QUANTIFICATION OF FORAGE PARTICLE LENGTH AND ITS EFFECT ON INTAKE AND CHEWING BEHAVIOR IN DAIRY CATTLE

by

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ABSTRACT

A method for the quantitation of the particle length distribution in processed forage was developed, tested, and used to investigate the effect of processing method and forage type on particle length distribution. The same method was also used to investigate the effect of forage particle length on voluntary feed intake (VFI) and chewing behavior in dairy cattle.

A simple vibrating tray forage particle separator (FPS) was constucted to separate forage particles on the basis of length alone. Although not completely accurate, the separator produced repeatable results in separating forage particles into six theoretical length fractions (<3.3, 3.3-8.25, 8.25-16.5, 16.5-33.0, 33.0-66.0 and >66.0 mm).

Cumulative sample weight undersize of separated orchardgrass hay was fitted by regression to a linear and two exponential equations, a lognormal distribution, and a modified Weibull function. Only the Weibull function closely fit these separation data. The median particle length (MPL) could be predicted by the inverse of the B parameter of the modified Weibull function while the use of the C parameter (named the Coefficient of Spread (CS)) was proposed as a measure of the spread of particle lengths around a given median.

Alfalfa and low and high quality orchardgrass hays were hammered through a 12.7 mm screen and chopped at 3 theoretical lengths of cut (3.18, 6.35 and 9.53 mm) and separated on the FPS to determine the respective dry matter (DM), crude protein (CP) and acid detergent fiber (ADF) MPL and CS. The MPL were based on the weight of each nutrient collected in each particle length fraction on the FPS. Different forages, processed by the same method, produced significantly different ($P < 0.05$) DM, CP and ADF MPL, and CS.

Furthermore, the differences in DM MPL and CS between forages were significantly different ($P < 0.05$) from those for CP and ADF. There were also significant differences ($P < 0.05$) between the DM and CP MPL, and the DM and ADF MPL, within each forage type.

Twelve lactating Holstein cows were fed orchardgrass hay chopped to two different MPL (7.3 and 18.1 mm) at two forage to concentrate ratios (40:60 and 60:40). The particle length of the forage did not significantly affect ($P > 0.05$) VFI or chewing behavior. Increasing the forage to concentrate ratio significantly ($P < 0.05$) decreased voluntary feed intake, increased the time spent chewing per kg of feed intake during eating and rumination and increased the number of boli regurgitated per kg of feed intake during rumination.

When dairy steers were fed timothy-brome hay chopped to 4 MPL (5.2, 9.0, 13.3 and 20.0 mm) at a 60:40 forage to concentrate ratio, an increase in the MPL of the forage in the diet significantly ($P < 0.05$) decreased the time spent idle, increased the time spent ruminating and the total time spent chewing (eating plus rumination), and increased the number of boli regurgitated per kg of feed intake. These effects of forage MPL on chewing behavior were directly related to the logarithm of the forage MPL. Increasing the MPL of the forage significantly decreased ($P < 0.05$) the time spent chewing per bolus regurgitated during rumination.

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GENERAL INTRODUCTION

A lack of fibre in the diet of ruminants can lead to disorders such as fat cow syndrome, abomasal ulcers, acidosis, liver abscesses, displaced abomasums, rumenitis, and low fat content in the milk of lactating dairy cows (Sudweeks and Ely, 1979). To prevent these disorders, the National Research Council (National Research Council, 1978) has recommended that diets fed to lactating dairy cows should contain a minimum of 17% crude fiber. Research, however, has shown that excessive reduction of particle size in forages otherwise adequate in "chemical fiber" components (eg. crude fiber, neutral detergent fiber and acid detergent fiber) can reduce or even eliminate the effectiveness of the fiber in preventing the disorders listed above. For this reason, Jorgensen et al. (1978) recommended the feeding of a given amount of long hay in the rations of dairy cattle. However, the feeding of forages in a long form as a large proportion of the diet can have an inhibitory effect on voluntary feed intake and, therefore, can decrease productivity.

The particle size of feedstuffs, and especially that of forages, has been shown to have a direct effect on the digestion process and feed utilization in ruminants. Feedstuffs entering the rumen are subjected to microbial digestion, the products of which are absorbed through the rumen walls and intestinal tract. However, a variable proportion of a given feedstuff, predominantly the fiber fraction, is either indigestible or only slowly digested in the rumen. These undigested residues can only leave the rumen by passage through the reticulo-omasal orifice. The passage of these undigested or indigestible residues from the rumen, however, is limited by the physical size of the particles. This restriction to passage affects

rumen fill which, in turn, has an inhibitory effect on voluntary feed intake. The reduction of the particle size and the subsequent passage of the undigested residue from the rumen is primarily facilitated by chewing activity during eating and ruminating. Therefore the monitoring of chewing behavior has been used to study the effect of reducing the particle size of forage fed to ruminants on forage utilization and as a measure of the fibrousness of the feed.

Research has shown that the reduction of the particle size of forages fed to ruminants can have a direct effect on increasing voluntary feed intake by increasing the rate of passage of undigested residues from the rumen. Even though the increased rate of passage usually results in a concomitant decrease in digestibility an increased productivity can be realized from higher intake levels.

Unfortunately, the incremental effect of a decrease in forage particle size on increasing intake and rate of passage is not consistent over the full range of applicable particle sizes and between forage types. There appears to be no difference in utilization between most forages fed in a long or coarsely chopped form. Fine chopping and coarse grinding of more fibrous or mature forages will usually enhance voluntary feed intake, whereas little effect may be seen when feeding similarly processed good quality forages. Fine grinding of most forages, however, will generally result in the disappearance of normal rumination behavior and an increase in the incidence of nutritional disorders.

Therefore, there appears to be a relationship between the chemical fiber content and the particle size of feedstuffs fed to ruminants in providing a minimum level of "physical fiber" sufficient to prevent digestive disorders but not limit intake and productivity. Whereas the surface area of feedstuff

particles may have a direct effect on microbial digestion, it is likely that the passage of particles from the rumen is ultimately limited by the largest dimension of the particles. Consequently, it would be beneficial to quantify the effect of forage particle length on intake and digestion to be able to maximize forage utilization and productivity. This naturally necessitates the accurate quantification of the particle length distribution in processed forage; unfortunately, standard methods have not yet been developed.

The research presented in this thesis was therefore undertaken to develop a method for quantifying the particle length distribution of processed forage, and to determine the relationship between the median particle length of a forage and the voluntary feed intake and chewing behavior of dairy cattle. The research project consisted of five experiments, the results of which are presented in the following three chapters.

Chapter 1 describes the development and testing of a repeatable and accurate method for the analysis and description of the particle length distribution in chopped forage. Chapter 2 reports the results of an experiment to investigate the effect of processing method and forage species on the particle length and nutrient distribution of chopped and hammermilled forage. The objective of this part of the project was to determine if, in the preparation of dietary treatments of processed forage, different forages, processed by the same method, resulted in the production of similar particle length and nutrient distributions. Finally, Chapter 3 reports the results of two experiments which investigated the relationship between the median particle length of forage and the voluntary feed intake and chewing behavior of dairy cattle. The development of equipment, and a method for the automatic monitoring of chewing activity are also described.

CHAPTER I

DESCRIPTION OF THE PARTICLE LENGTH DISTRIBUTION OF CHOPPED FORAGE USING A SIMPLE VIBRATING TRAY FORAGE PARTICLE SEPARATOR AND A MODIFIED WEIBULL-TYPE FUNCTION

INTRODUCTION

The effect of particle size reduction in forages fed to ruminants on parameters of digestion including intake, digestibility, chewing behavior, and rate of passage is well documented. Until recently, the investigation of the effect of forage particle size on the process of digestion in ruminants did not involve the quantitative analysis of the particle size distribution of the forage. Traditional experimentation has examined the qualitative difference between the effects of feeding long, chopped and ground forages. To be able to quantitate the effects of reducing the particle size of forages it is necessary to have an objective method for the accurate measurement of particle size. Particle size, however, with respect to forage particles, can include a number of parameters such as length, width, breadth, diameter, cross sectional area, and volume. None of the existing methodology, for both the separation of particles and the description of the resulting particle size distribution, appears to quantitate a specific size parameter when applied to the separation of forage particles.

The selection of the appropriate parameter or parameters to be quantified should be based on their relationship to biological function. Since it appears that the maximum dimension of a particle may exert the greatest effect on forage utilization by limiting the passage of particles from the rumen, the development of a method for the quantitation of forage

particle length, defined as the maximum particle dimension, would be most appropriate.

Therefore, the present study was undertaken with the following objectives:

1) to design and construct a vibrating tray forage particle separator and test its accuracy and precision in separating chopped forage particles on the basis of particle length,

2) to mathematically define the distribution of particle lengths in chopped forage,

3) and to identify statistical parameters which would adequately describe the particle length distributions found in chopped forages.

LITERATURE REVIEW

MEASUREMENT OF FEEDSTUFF PARTICLE SIZE

Visual Separation

A number of methods have been used to separate samples of concentrates and processed forages into component particle size fractions. The simplest and most accurate method of particle size analysis is visual separation. If particles are sufficiently large enough, all dimensions of the particles can be measured using a ruler or a set of calipers. Measurement of very small particles, such as those in feces or finely ground feedstuffs, may require the use of a microscope, usually fitted with cross-hairs and a graduated scale (Moseley, 1984). From the data that are collected, the frequency distribution of any measured particle size parameter can be determined and then charac- terized. Furthermore, during visual separation, measured pieces of feedstuff can be collected in small containers which can then be weighed to determine the weight distribution of the particle sizes in a given sample. A major disadvantage of visual separation, however, is that it is very time consuming and tedious, and subject to large subsampling errors; a one kilogram sample of chopped forage may contain in excess of 500,000 pieces which prohibits the examination of all but the smallest subsamples (O'Dogherty, 1982). Therefore, the use of some form of automated method is usually required.

Sieving

Both wet sieving and dry sieving techniques have been used to measure the particle size distribution of feedstuffs. Dry sieving employs a stacked

series of screens having different apertures which decrease in size from the top to the bottom of the stack. A representative sample is placed on the top sieve and agitation of the sieve stack causes sorting of particle sizes by the limitation of passage through each progressive screen in relation to particle size. Wet sieving is similar to dry sieving except that a stream or spray of solvent (usually water) is added to wash the particles through the stack of sieves.

Standard sieving methods, developed primarily for use in the chemical and mineral related fields, have been adopted by the American Society of Agricultural Engineers (ASAE) (American Society of Agricultural Engineers, 1969a, 1983), the American Society of Animal Science (ASAS) (American Society of Animal Science, 1969) and the American Society of Dairy Science (Ensor et al., 1970) for the measurement of particle size in feedstuffs comprised of spheroidal or cuboidal shaped particles as found in concentrates. When sieving spheroidal particles, the range of particle sizes retained on a given sieve is determined by the maximum diameter of the sieve aperture and the diameter of the sieve aperture directly above. Even though sieving has been described by the developers of sieving methodology for spheroidal particles as being inappropriate for the "sizing" of elongated particles (American Society of Agricultural Engineers, 1983), researchers have extensively used these techniques for particle size measurement in chopped and ground feedstuffs, rumen samples, duodenal samples and fecal samples. The particles in these substances, however, have been shown to be predominantly elongated (Mosely, 1984; McLeod et al., 1984).

The major problem with the sieving of elongated particles is that the size parameter which controls the separation process has not been fully elucidated. Uden and Van Soest (1982) found that a larger mean particle size

was obtained from wet sieving than was obtained by dry sieving. Since particles are free to bounce around during dry sieving, the researchers concluded that dry sieving mainly measured diameter while wet sieving measured particle length. Jones and Mosely (1977) wet sieved rumen particles collected from sheep fed hay and clover diets using wet sieving and then visually measured the actual length and width of particles retained on each sieve. The lengths of particles retained were about 3 to 4 times larger than the aperture of the sieve, while the width of the particles were about 1/2 to 3/4 the size of the sieve aperture. There was also a difference between the two forages in the dimensions of the particles that were retained on each sieve. The average length to width ratio of all the particles was about five to one. Since the particle sizes retained on each sieve varied with the size of the sieve apertures that were being used and the feedstuff that was being separated, Moseley (1984) suggested that it may be useful, by visually separating sieve fractions, to convert sieve fractions into particle length fractions. McLeod et al. (1984) found that following wet sieving, the coefficient of variation for the particle length to aperture size ratios for particles collected on different sieves with different forages ranged from 20 to 41 percent, whereas that for the particle width to aperture size ratios ranged from 19 to 28 percent. Since the values and range of the coefficient of variation for the ratio of width to aperture size were smaller, the researchers concluded that their wet sieving method was separating forage particles predominantly on the basis of particle width, and not length. The width to aperture size ratios, however, were always less than one. Therefore, it is still unclear as to which size parameter(s) is being quantified when elongated particles are separated by sieving.

Vibrating Tray Separators

Vibrating tray separators that are capable of measuring the particle length in feedstuffs predominantly comprised of elongated particles have been developed (Finner et al., 1978; Gale and O'Dogherty, 1982). The principle of the separation of particles on the basis of length by these machines assumes that the particles exhibit a length to width ratio greater than 1:1, are longitudinally symmetrical, and exhibit a constant length to weight ratio within a particle. If such a particle is conveyed horizontally and longitudinally over a gap, instability occurs when the center of gravity of the particle reaches the edge of that gap. Further movement of the particle results in overbalancing and the particle falls through the gap. Therefore, elongated particles passing over a gap of width X will fall through the gap if the length of the particle is 2X or less. If particles are conveyed over a cascading series of gaps, starting at the smallest gap and progressing to the largest, the particles can be separated into length fractions. The theoretical length of particles collected below a given gap will range from the maximum length capable of falling through the immediately preceding gap to twice the width of the designated gap.

Moller (1975) designed such a separator for measuring the length of forage particles in cobs and wafers. Moller's separator consisted of a single corrugated sheet of metal on which particles were longitudinally oriented and evenly dispersed. An eccentric, mounted on an electric motor, agitated the corrugated sheet which was mounted on spring steel straps. Particles were automatically applied to one end of the corrugated sheet and propelled over a series of holes of increasing diameter (1.4, 2, 4, 6, 8, and 10 mm.) which had been drilled at set intervals through the bottom of each channel in the corrugated metal sheet. Particles longer than 20 mm in

length were separated at the end of the tray by a series of three plates placed perpendicular to the bottom edge of the corrugated sheet to produce gaps of 15, 30 and 55 mm.

Finner et al. (1978) developed a separator which operated on the same principle. The researchers, however, used a cascading series of corrugated trays separated by progressively larger gaps. All the trays were inclined at a 10 degree angle and were vibrated by an electric vibrator. Forage particles were applied by hand to the top sorting tray and were propelled by gravity over each of the corrugated trays. Each successive tray was placed 0.5 times the gap width lower than the previous tray to enable a smoother passage of particles and a more efficient overbalancing of the particles.

Gale and O'Dogherty (1982) designed a unique vibrating tray separator which also used corrugated trays but the separation process operated in reverse to those above with longer particles being separated first, and progressively shorter particles being separated as they travelled down the series of trays. Particles were applied to the first tray by an aspirator column such that single pieces of forage were applied and oriented longitudinally. A knife edge placed at a given distance perpendicular to the first tray separated the longest particles; all particles shorter than that required to pass over the gap passed through the gap on to the next tray. The next longest particles were then removed in a similar manner with the shorter particles passing to the next tray and so on. The separation of the longer particles from the shorter particles eliminated the clogging and other separation problems frequently encountered with the simple vibrating tray separators described previously.

Oscillating Screen Separators

A modified form of sieving uses oscillating screen separators (Finner et al., 1978; Feller and Foux, 1975). Unlike sieving which uses wire screens, oscillating screen separators use large punched metal screens with larger apertures. These screens appear more suitable for separating chopped forages where greater numbers of the particles exceed 2 to 3 cm. in length. However, the relationship between screen size and particle size and the size parameter being measured using oscillating screen separators, as with sieving, has not been elucidated. Finner et al. (1978) bypassed this problem by measuring the particle length of particles retained on each screen directly using optical imaging.

Optical Imaging

The newest form of particle sizing involves optical imaging. Finner et al. (1978) described one system which used a Hewlett-Packard calculator plotter system and the University of Wisconsin Univac 1110 computer. Particles of forages were carefully spread over an X, Y grid on a horizontal glass screen such that no particles were touching each other. Particle endpoints were identified with the indicator arm of a digitizer and the coordinates transmitted to the calculator which determined and recorded the particle lengths. Hall et al. (1970) used the USDA Flying Spot Particle Analyzer (FSPA) to measure the cross sectional area of alfalfa stems. Measurements were made by photographing cross sectional views of stem sections on 35 mm film and measuring the resulting image areas on the FSPA using a flying spot film scanner. Luginbuhl et al. (1984) photographed samples of particles using a video camera and then digitized the image as a 256 x 256 array of points in an Apple IIe computer using an appropriate

interface. Using the binary image, the perimeter, length and breadth of each particle could be measured and the projected surface area of the particles calculated.

Optical imaging, once fully developed, will allow a more extensive analysis of particle size which could be done more accurately and more rapidly than using visual analysis. Optical imaging, however, still suffers from limitations in the size of sample (usually less than 1000 particles) that can be efficiently analyzed, necessitating either the analysis of very large numbers of samples or the development of extremely accurate subsampling techniques. A further drawback to the use of optical imaging is that the weight distribution of particle sizes is not measurable.

DESCRIPTION OF PARTICLE LENGTH DISTRIBUTIONS

Frequency data

The simplest method for describing the particle size distribution of a substance is to report the percentage of particles in a sample having a given size or range of sizes. Although the reporting of the complete sample particle length distribution in this manner provides the most complete information regarding the particle size distribution, and has been recommended (Kennedy, 1984), it does not lend itself easily to statistical testing and communication between research groups. A complicating factor exists that not all researchers use the same particle sizing methods, sieve sizes, or gaps on forage particle separators, to separate feedstuffs into component particle size fractions. Furthermore, there is little evidence that the expression of particle size in this manner aids in the elucidation

of the biological significance of specific particle size parameters for ruminant feedstuffs.

The quantitative description of the effect of particle size on parameters of digestion in ruminants necessitates the description of the whole particle size distribution by one or two parameters (namely a measure of central tendency and a measure of spread) which will be independent of the method of separation used.

Modulus of Fineness and Uniformity:

One of the earliest methods for the semi-quantitative description of the particle size distribution of ground feedstuffs was the Modulus of Fineness, originally devised at the University of Wisconson and later adopted by the ASAE as a recommended procedure (American Society of Agricultural Engineers, 1969b). The procedure involves the dry sieving of a 250 gram sample of ground feed through a set of standard sieve sizes (3/8, 4, 8, 14, 28, 48, and 100 mesh plus the bottom pan) for 5 minutes with a ro-tap or other similar method of shaking. The Modulus of Fineness is calculated by multiplying the percent weight of the sample retained on each sieve by the sieve position number (starting with a value of 0.0 for the pan), summing the results and then dividing by 100. An example of the calculations, given by the ASAE (1969b) recommendation, is illustrated in Table I.

A major problem exists when using the Modulus of Fineness in that two completely different distributions may have the same Modulus of Fineness depending upon how the material is distributed throughout the sieve stack. For this reason the Modulus of Uniformity was introduced as another recommendation of the ASAE as a descriptor of the spread of the particle size distribution (American Society of Agricultural Engineers, 1969b).

TABLE I: ASAE (1969b) example calculations for the determination of the Modulus of Fineness of ground feedstuffs by sieving.

Screen Mesh	Product of Percent of Material on Screen Times the Screen Position				
3/8	1.0	x	7	=	7.0
4	2.5	x	6	=	15.0
8	7.0	x	5	=	35.0
14	24.0	x	4	=	96.0
28	35.5	x	3	=	106.5
48	22.5	x	2	=	45.0
100	7.5	x	1	=	7.5
Pan	0.0	x	0	=	0.0
Total	100.0				312.0

Modulus of Fineness (312.0 / 100.0) = 3.12

The uniformity of a sample is expressed as the ratio of three numbers which represent the relative proportions of coarse, medium and fine particles in the sample. The sum of the figures always must equal 10 and the ratios range from 10:0:0 to 0:0:10 giving 66 possible combinations. Particles collected on the 3/8, 4 and 8 mesh sieves are designated as coarse, 14 and 28 mesh as medium and 48 and 100 mesh plus the pan as fine particles. The Modulus of Uniformity is determined by summing the percentage weight of particles collected on the sieves of a given size category, dividing the value by ten and rounding to a whole number. An example given by the ASAE (1969b) recommendation is illustrated in Table II.

The Modulus of Fineness together with the Modulus of Uniformity adequately described the particle size distribution of ground feedstuffs in a semi-quantitative manner for preliminary investigation of the effects of feedstuff particle size on ruminant digestion. However, these methods are only applicable to the sieving of processed feedstuffs where the particle size reduction process yields spheroidal or cuboidal shaped particles. This

TABLE II: ASAE (1969b) example calculations for the determination of the Modulus of Uniformity of ground feedstuffs by sieving.

Screen Mesh (A)	Percent of Sample on Screen (B)	Totals in Column (B) Divided by 10 (C)	Column (C) Values Rounded (D)
	COARSE		
3/8	1.0		
4	2.5		
8	7.0	10.5 / 10 = 1.05	1
	MEDIUM		
14	24.0		
28	35.5	59.5 / 10 = 5.95	6
	FINE		
48	22.5		
100	7.5		
Pan	0.0	30.0 / 10 = 3.00	3

Modulus of Uniformity = 1:6:3

is not the case with the processing of forages. Furthermore,if a different set of sieves is required to evenly distribute the particles throughout the sieve stack, the resulting Modulus of Fineness and Uniformity values are not comparable with those values obtained using the standard set of sieves.

A measure similar to the Modulus of Fineness, known as Chop Modulus (cited by O'Dogherty, 1982), has been used to describe the particle length distribution of chopped forage which had been separated into four length fractions (<25, 25-50, 50-100, and >100 mm) on a vibrating tray separator. The percentage weight of the sample retained in each tray was multiplied by a weighting factor (1, 2, 4, or 8 respectively). The resulting values were then summed and divided by 100 to give the Chop Modulus. Unfortunately the Chop Modulus suffers from the same limitation as does the Modulus of Fineness in that widely different particle length distributions can have the same Chop Modulus and that the method is only semi-quantitative in nature.

Mathematical Distribution Functions

The ideal method for the description of the particle size distribution of processed forage involves the identification of the underlying mathematical distribution from which standard statistical parameters such as a mean, median and standard deviation (or other measure of spread) could be calculated. The majority of the distributions of particle sizes in processed feedstuffs are skewed to the right. As early as 1925, it was demonstrated that the particle sizes of some comminuted substances could be described as being lognormally distributed (Murphy and Bohrer, 1984). However, it was Kolomogoroff(1941) who first advanced a theoretical explanation for the lognormal distribution based on assumptions about comminution. The use of the lognormal distribution, instead of the Modulus of Fineness and Modulus of Uniformity, for the description of the particle size distribution in ground feedstuffs (see Headley and Pfost, 1970) was first proposed by Headley and Pfost in 1966 (Murphy and Bohrer, 1984). The procedure was later adopted by the ASAE as a recommended procedure (American Society of Agricultural Engineers, 1969a) and still later as a standard procedure (American Society of Agricultural Engineers, 1983) for the determination of the particle size in feedstuffs comprised of spheroidal or cuboidal particles. However, the procedure is not recommended to define the size of particles which are flaked or elongated such as are found in rolled grains or chopped forage.

The standard procedure involves the use of a standard set of sieve sizes starting with an aperture of 0.053 mm and each additional sieve getting progressively larger in a geometric progression (ie. the aperture of each additional seive is "root 2" times the aperture of the previous sieve). Sieving takes place on a suitable sieve shaker and progresses until there is

a constant distribution of particles between the sieves. Based on the assumption that the particles sizes are lognormally distributed, the following equations can be used to determine the geometric mean diameter and the geometric standard deviation.

$$d_{gw} = \log^{-1} \left((\Sigma (W_i \log \bar{d}_i) \; / \; \Sigma W_i) \right)$$

$$S_{gw} = \log^{-1} \left((\Sigma W_i (\log \bar{d}_i - \log d_{gw})^2 \; / \; \Sigma W_i)^{0.5} \right)$$

where: d_{gw} = geometric mean diameter

S_{gw} = geometric standard deviation

d_i = aperture diameter of the i'th sieve

d_{i+1} = aperture diameter of the sieve placed just above the i'th sieve

$\bar{d}_i$ = geometric mean diameter of particles on the i'th sieve $(d_i \times d_{i+1})^{0.5}$

W_i = weight of material on the i'th sieve

Graphical methods can also be used to determine the geometric mean diameter and standard deviation, and to test the goodness of fit of the particle size distribution to the lognormal distribution. If a distribution is lognormally distributed, plotting the cumulative percent weight of the sample retained on each sieve against the logarithm of the diameter of the aperture of that sieve on logarithmic probability paper will yield a straight line. A close fit of the data points to a straight line and a random distribution of residuals around the line indicates a good fit of the data to the lognormal distribution. If the data adequately fits a straight line, the geometric mean diameter can be read from the graph as the geometric diameter at the 50% probability point and the geometric standard deviation calculated as the geometric diameter at the 84% probability point

divided by the the geometric mean diameter. The geometric standard deviation can also be calculated by dividing the geometric mean diameter by the geometric diameter at the 16% probability point.

Another method of calculating the geometric mean diameter and standard deviation was presented by Waldo et al. (1971). The distribution of particle sizes was expressed as the cumulative percent of particles by weight passing through a sieve aperture of size X (in microns). The percent weight of the sample capable passing through each sieve was transformed to normal equivalent deviates (Y) and regressed on the base ten logarithim of the sieve aperture size (X) using the equation $Y = a + b\log_{10}X$. In standardized normal form

$$Y = (\log X - \log u) / \log S$$

$$= (-\log u / \log S) + 1/\log S \times \log X$$

where logu is the geometric mean diameter and logS is the geometric standard deviation. The geometric mean diameter could therefore be estimated by -a/b and the geometric standard deviation by 1/b.

The benefit of using the lognormal distribution is that the particle size distribution can be described completely by two parameters, the geometric mean diameter and the geometric standard deviation. Furthermore, once the geometric mean diameter and standard deviations by weight are known, the distributions of particle numbers and surface area of spheroidal and cuboidal shaped particles can also be described, and all three distributions will have the same geometric standard deviation (Headley and Pfost, 1970).

Whereas the lognormal distribution methods described above are only applicable for the description of the particle size distribution of sieved spheroidal and cuboidal particles, similar procedures can be used if

particle length is measured on a vibrating tray separator (O'Dogherty,1984). Where applicable in each analytical procedure above, the sieve diameter is replaced by the minimum or maximum theoretical particle length capable of falling through each gap on the separator. The results of the calculations will then yield the geometric mean particle length and standard deviation. Any subsequent calculations of the distribution of particle numbers and surface area are, however, no longer valid.

Other distributions which have been fitted to particle size data obtained from the sieving of feedstuffs include the Gamma probability density function and the Rosin-Rammler or Weibull function. These are exponential functions which exhibit great flexibility when fitted to probability density functions or sigmoidal shaped cumulative frequency distributions of particle sizes such as are found in processed feedstuffs and other substances.

Exponential distributions such as the Weibull function are fitted to the data using non-linear regression of the percent cumulative weight undersize on sieve size, or particle length as determined by vibrating tray separators. The median particle size or particle length of the distribution is calculated by solving the regression equation for the cumulative percent undersize equal to 50%. Unfortunately, computational procedures have not been put forward for a measure of the spread of the distribution. The Gamma probabiltity density function, though highly flexible, involves a recursive gamma function which makes the parameterizing process computationally formidable (Yang et al., 1978). Allen et al. (1984), however, fit the Gamma probability density function using a procedure involving maximum liklihood estimators for the parameters in the function.

Herdan (1960) recommended the use of the Rosin-Rammler (or Weibull)

function when the distribution of particle sizes deviated from normality to the point that the lognormal distribution could not be adequately fitted to separation data. Furthermore, Rose (1954) demonstrated that for an exponential distribution, the distribution of particle sizes on a number or weight basis was independent of the sample size and the shape or density of the particles being separated. Therefore, the use of an exponential distribution to describe the weight distribution of processed feedstuff particles by sieving does not require any assumptions regarding particle geometry or density as it does when the lognormal distribution is used (Pond et al., 1984).

Since the size parameter that is measured by the sieving of elongated particle has not yet been elucidated, none of the procedures described above is valid for the measurement of particle size of elongated particles by sieving. However, researchers have used these procedures for the description of particle size in processed forages, boluses collected through esophageal fistulas, rumen contents, duodenal digesta, and fecal samples, all of which are predominantly comprised of elongated particles. The procedures do have some validity if the measurement of a size parameter is not implied and the results are simply expressed as the percentage of particles capable of passing a given size of sieve aperture (Kennedy, 1984).

The goodness of fit of the lognormal distribution to the results of the sieving of feedstuffs comprised of elongated particles has been variable. Waldo et al. (1971) found that the assumption of lognormality for the distribution of particle sizes in fecal samples was adequate, but that the distribution of particle sizes in chopped and pelleted orchardgrass hay significantly differed from lognormal. The researchers concluded, however, that the fit was adequate for many practical and scientific purposes. Allen

et al. (1984) also found a significant lack of fit of separation data to the lognormal distribution when the particle size distribution of ground forages and fecal samples was examined by the procedure of Waldo et al. (1971). A better fit was obtained when the lognormal probability density function was fitted to the data by maximum likelihood estimators of the log mean and standard deviation: this is similar to the method of calculating the geometric mean diameter and standard deviation described above using the weights of particles retained on each sieve. The best overall fitting of the data, however, was obtained using the Gamma probability density function.

Pond et al. (1984) sieved samples of grazed coastal Bermuda grass taken from the esophagus, upper and lower rumen strata, and feces of cattle, and then fit the particle distribution data to the lognormal distribution and an exponential distribution based on a modified Rosin-Rammler or Weibull function. The researchers concluded that the use of the lognormal distribution was inappropriate for describing the particle size distribution of all the samples because the fitted curves exhibited significant kurtosis and skewness. They also concluded that the exponential distribution more closely fit the observed data and that its use was therefore more appropriate in describing the particle size distribution in samples comprised of elongated particles.

Smith et al. (1984) found that when the cell wall particle size distribution of digesta samples (procedure of Smith and Waldo, 1969) from alfalfa, orchardgrass and corn silage fed cattle was determined by sieving, the exponential distribution used by Pond et al. (1983, 1984) offered no advantages, and did not improve the fit of the data, as compared to the lognormal distribution. The extraction of the samples with a neutral detergent solution prior to sieving may, however, have altered the particle

size distributions of the samples. Furthermore, the researchers based their comparison of the goodness of fit between the lognormal and Weibull distributions on the comparison of the coefficients of determination, distribution of residuals, and residual sums of squares for two dissimilar regression equations. The lognormal regression was performed by linear regression of probit transformed cumulative percent weight undersize on the logarithm of sieve size, while the fitting of the Weibull function was performed by nonlinear regression of the cumulative percent weight undersize on sieve size.

Murphy and Bohrer (1984) examined some tenable assumptions regarding the comminution of elongated particles which could lead to the lognormal or Rosin-Rammler particle size distributions. The researchers' assumptiions did not lead to the generation of a lognormal distribution. However, even though they admitted that the Rossin-Rammler distribution would fit the results better, Murphy and Bohrer (1984) concluded that resolving the lognormal distribution of its components would provide more information than would "glossing" over the differences between the data and the lognormal distribution with the use of another distribution such as the Rosin-Rammler. One could argue that the use of any parameters derived from a mathematical distribution that did not correctly fit the observed data could introduce error into experimental results that rely on the accurate quantification of particle size.

Little information is available regarding the mathematical definition of the distribution of particle lengths in processed feedstuffs. Gale and O'Dogherty (1982) found that the particle length distribution of chopped forage separated on a vibrating tray separator could be approximated by a lognormal distribution, but showed no statistical testing to prove the

point. The graphical representation of an observed particle length distribution, however, exhibited a sinusoidal distribution of residuals around the regression line. Such a distribution of residuals would indicate a lack of fit. O'Dogherty (1984) found that some observed particle length distributions diverged from lognormality in the "tails" of the distribution, but concluded that the distributions were, in general, an adequate approximation of a lognormal distribution over much of the particle length range. No other examples of the fitting of particle length distributions, determined using vibrating tray separators, to known distributions are available.

MATERIALS AND METHODS

SEPARATION OF FORAGE PARTICLES

A vibrating tray Forage Particle Separator (FPS) was developed to enable the separation of chopped forage particles on the basis of length (see Figure 1); its design was based on the vibrating tray separator developed by Finner et al. (1978). The FPS was comprised of a tray bed, bed frame and base frame.

The tray bed was comprised of a cascading series of seven corrugated trays made from enamel coated sheet steel mounted on a tray frame made from 50.4 cm angle iron. The first tray, for the application and alignment of particles, was 61 cm long followed by one 25 cm and then five 20 cm long separation trays, each measuring 76 cm in width. The trays were separated by gaps measuring 2, 2, 5, 10, 20, and 40 mm respectively and each successive tray was positioned one half the gap size lower than the preceeding tray. Two 2 mm gaps were used because the smallest length fraction comprised a large part of the forage samples and was the most difficult to separate. The corrugated trays were strengthened and aligned by wood and metal supports which were attached to the tray frame by 15 cm long pieces of 12.7 mm threaded rod. Slotted holes in the tray frame and the use of threaded rod permitted unlimited adjustment of the trays. The tray bed (trays plus tray frame) was bolted at a 13 degree angle to the bed frame. The bed frame in turn was bolted to the four cantilever supports of the base frame. The bed frame and base frame were both constructed from 7.62 cm channel iron. A 2.54 cm pneumatic piston vibrator was mounted to the front of the bed frame. The frequency and amplitude of the vibration was adjusted by an air pressure

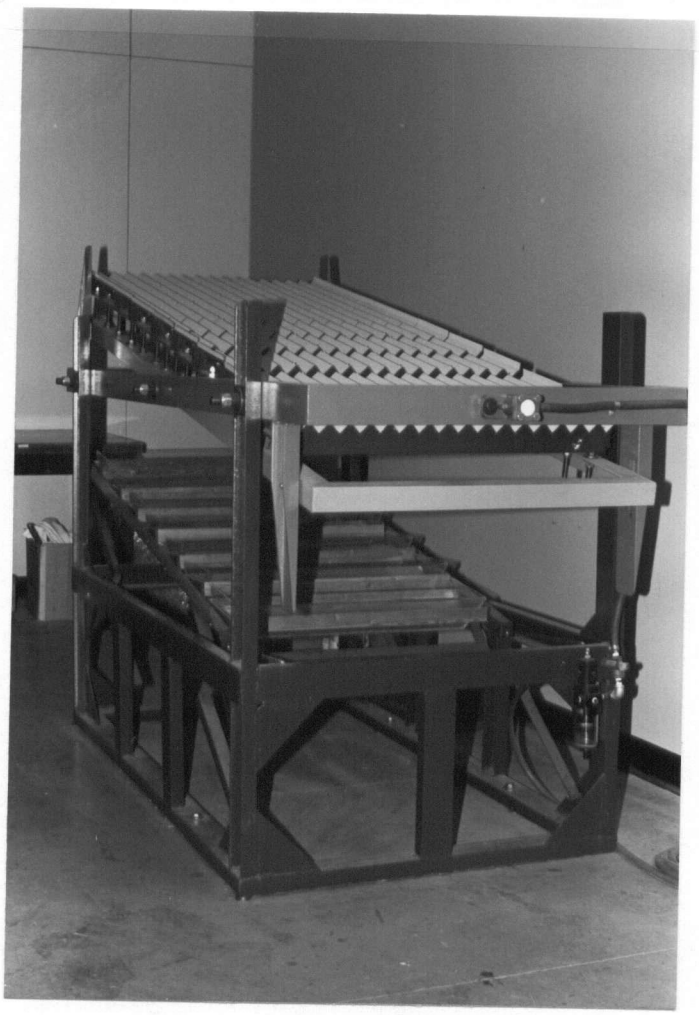

FIGURE 1: Forage Particle Separator

regulator mounted on the base frame.

The design of the separator was such that when the correct vibration frequency was applied to the bed frame, it would vibrate horizontally at the natural harmonic frequency of the cantilever supports. This vibration was transmitted evenly to the separator trays by the mounting of the tray bed to the bed frame and caused the forage particles to "flow" down the grooves in the trays without bouncing or jumping the gaps between trays.

During separation the forage particles were applied by hand to the top application and alignment tray such that there was no clumping of particles. Particles falling through each gap were collected below in mounted plexiglass collection trays. The arrangement of separation trays that was used theoretically resulted in the separation of the following six particle length fractions according to the "overbalancing principle": <4, 4-10, 10-20, 20-40, 40-80, and >80 mm. Once a sample had been separated, the particles collected in each of the collection trays were transferred into tared plastic bags and weighed. The results of the separation were expressed as the percent of sample weight, on an air dry basis, that was collected in each of the theoretical particle length fractions.

FORAGE PARTICLE SEPARATOR TESTING

FPS Separation of Hand Chopped Alfalfa Hay

A sample of baled alfalfa hay was chopped by hand on a paper cutter such that a wide distribution of particle lengths was produced. The chopped alfalfa was then subdivided into four samples which comprised the total amount of alfalfa chopped. Each subsample was separated on the FPS into

particle length fractions which were then weighed.

To test the effect of method of separation on the reproducibility of FPS results, the particle length fractions collected from the separation of a given subsample were then reseparated consecutively, starting with the shortest length fraction and ending with the longest. The particle length fractions resulting from reseparation were then weighed. This reseparation was performed a second time resulting in three separations of each subsample.

The effect of the method of separation on the percent of subsample weight collected in each particle length fraction was tested by the following General Linear Hypothesis using the BMD:10V package program of the University of British Columbia:

$$Y_{ijk} = u + F_i + R_{ij} + S_{ik} + E_{ijk}$$

where: Y_{ijk} = the dependent variable: percent of subsample weight collected.

u = the overall mean.

F_i = the effect of the i'th gap in the FPS (ie. particle length fraction).

R_{ij} = the effect of the j'th separation run nested within the i'th fraction.

S_{ik} = the effect of the k'th subsample nested within the i'th fraction.

E_{ijk} = the residual error associated with the interaction between the j'th separation run and the k'th subsample within the i'th fraction.

Differences in the percent weight of sample collected in each particle length fraction, between samples and separation runs within particle length fractions, were tested using Duncan's Multiple Range test ($\alpha = 0.05$).

FPS vs. Visual Separation of Machine Chopped Orchardgrass Hay

Three bales of mature orchardgrass hay were broken open and the bale sheaves randomly allocated into three piles. Each pile of sheaves, selected at random was then chopped at one of three theoretical lengths of cut (TLC = 3.18, 6.35, or 9.54 mm) on a John Deere Model 35 Forage Harvester fitted with 6 Blades. The TLC was changed by altering the infeed gear ratios according to machine specifications. The chopped hay was blown into an array of four groups of three subsampling boxes arranged as shown in Figure 2. One box from each of the groups was randomly allocated to one of three samples. The chopped forage contained in similarly numbered subsample boxes was composited and then subsampled by quartering into a 50g sample (approx 1.0 litre volume) before being separated on the FPS.

After the particle length fractions of each sample were weighed, similar length fractions within each sample of a given TLC were composited and then divided into two subsamples. These subsamples were visually separated to determine the actual particle length distribution for each particle length fraction within a given TLC. The particles were measured with a ruler and separated manually into as many as 26 length fractions which were then weighed. The first two fractions contained particles that ranged in length from 0-4 and 4-10 mm respectively. Particles ranging from 10 to 80 mm were separated in 5 mm increments. The remaining longer particles were separated in 10 mm increments.

The actual particle length distribution for each particle length fraction collected on the FPS was calculated by multiplying the visually determined percent weight of a given range of particle lengths in the fraction by the weight of all the particles collected in that fraction on the FPS. The actual particle length distribution for each TLC was then

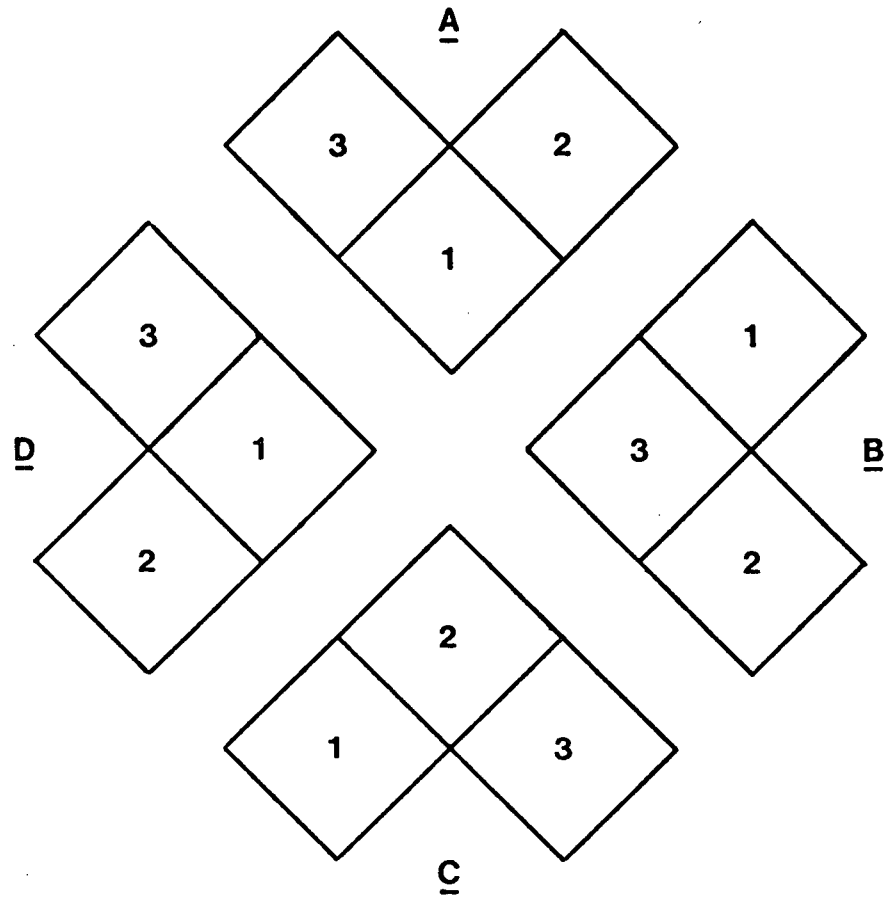

FIGURE 2: Arrangement of 4 groups of subsampling boxes for obtaining 3 representative samples of a chopped forage.

determined by summing the visually determined particle length distributions of the particle length fractions that were collected from the samples of a given TLC. This method of visual separation resulted in the determination of a single actual particle length distribution for each set of TLC samples separated on the FPS. Both the visually and FPS determined particle length distributions were expressed as the percent of air dry sample weight comprising a given range of particle lengths. The visual separation data were also used to calculate the percentage weight of particles in each TLC sample, and in each length fraction of the sample collected on the FPS, that was correctly and incorrectly classified on the basis of length by the FPS.

The particle length distributions determined using the FPS were compared with those determined visually by the Chi squared goodness of fit test (Choi, 1978) using the visual data as the expected particle length distribution. The consistency of FPS particle sizing accuracy of different lengths of particles and of particles in each particle length fraction collected on the FPS was tested using a Chi squared contingency table (Choi, 1978). Differences in the degree of undersizing and oversizing error by the FPS between particle length fractions and between TLC, for all particle lengths as a whole, were tested by the Chi squared comparison of several proportions test (Choi, 1978). The difference between the degree of oversizing and undersizing by the FPS was then used to calibrate the theoretical particle length fractions that were being collected on the FPS.

DESCRIPTION OF PARTICLE LENGTH DISTRIBUTIONS

The visual and FPS separation data for chopped mature orchardgrass hay described above were converted to the percent cumulative weight of sample

particles that were shorter than the maximum length theoretically capable of passing through each gap on the FPS (ie. Percent Cumulative Weight Undersize). For all but the last collection tray, the maximum length of particle capable of passing through a given gap was determined from the calibration of the FPS above. The maximum particle length collected in the last collection tray was determined by measuring the longest particle in the that tray. The cumulative percent weight of particles undersize (Y) was then regressed on particle length (X) using each of the following mathematical equations:

1: $Y = a + bX$

2: $Y = a + b\log X$

3: $\log Y = a + b\log X$

4: $Y = a + b\log X$ (Y in standard probability units- Waldo et al., 1971)

5: $Y = 100 \times (1 - e^{-(BX)^{C}})$ (Modified Weibull or Rossin-Rammler type function- Yang et al., 1978)

Equations 1, 2, 3, and 4 were fitted to the data by linear regression using the BMD:P1R packaged program of the University of British Columbia. The Weibull function (equation 5) was fitted to the data by non-linear regression using the BMD:PAR packaged program of the University of British Columbia. The coefficients of determination and distribution of residuals for each regression line were compared to determine goodness of fit of each data set to the lines predicted by each regression equation.

Regression equations 2, 4 and 5 were used to predict the percent weight of sample particles that were collected in each particle length fraction on

the FPS. To compare the goodness of fit between the regression equations, the predicted particle length distribution from each regression equation was compared with the observed particle length distribution using the Chi squared goodness of fit test (Allen et al, 1984).

The median particle lengths (the length of 50% Cumulative Weight Undersize) for visual and separation data were predicted using regression equations 2, 4 and 5. The predicted median particle lengths were subjectively compared for accuracy and consistency between regression equations, TLC samples, and method of separation; lack of replication of visual separation data did not permit statistical testing of any differences in the predicted median particle lengths.

RESULTS AND DISCUSSION

OPERATION OF THE FORAGE PARTICLE SEPARATOR

The ease of separation of chopped forage particles on the FPS ranged from effortless to very difficult. Similar separation problems to those described by Finner et al. (1978) and Gale and O'Dogherty (1982) were encountered. Ideally shaped particles resembling uniform rods separated effortlessly as theorized. Chopped forage samples, however, contain a variable proportion of irregularly shaped particles. "U" shaped particles and particles that lack structural rigidity could thread their way through gaps that were smaller than those which they should theoretically have been able to fall through. "L" shaped particles and particles with rough edges could get snagged in gaps as they passed down the separator. This snagging would dramatically increase the time required to separate a sample by causing the gaps to become clogged which, in turn, caused appropriately sized particles to flow over the gap that they otherwise would have fallen through.

Because of these separation problems, constant surveillance was necessary to unclog gaps between trays. Most trapped particles were pushed through the gap they were clogging with the exception of obviously long particles which were saved and reoriented to continue down the separator. These major separation problems were successfully avoided in the machine designed by Gale & O'Dogherty (1982). However, the construction cost and complexity of design of that separator precluded a similar design in this study.

Because the alfalfa hay contained more irregularily shaped particles, it

was consistently more difficult to separate than was the orchardgrass hay. With both forages, shorter particles tended to separate more easily than did longer particles because these particles tended to be more ideally shaped and more rigid. Therefore, orchardgrass hay chopped at the short TLC was easier to separate than that chopped at the long TLC. Separation times for all samples ranged from 15 minutes to 2 hours with the average time for separation being about 30 minutes.

FORAGE PARTICLE SEPARATOR TESTING

FPS Separation of Hand Chopped Alfalfa Hay

The results of the separation of hand chopped alfalfa hay are shown in Table III. The subsample being separated had a significant effect ($P < 0.05$) on the proportion of sample weight collected in each particle length fraction on the FPS. This effect, however, was consistent over the three

TABLE III: Average percent of sample weight (n = 4) of hand chopped alfalfa hay collected in each particle length fraction after each of three separation runs on the Forage Particle Separator.

		THEORETICAL RANGE OF PARTICLE LENGTHS (mm)					
		<4	4-10	10-20	20-40	40-80	>80
RUN#	1	10.1[a]	15.4[a]	34.7[b]	23.0[b]	13.7	3.2
	2	11.7[b]	16.7[b]	33.7[a]	21.0[a]	13.8	3.2
	3	12.2[b]	17.2[b]	33.1[a]	20.6[a]	13.7	3.3

[a-b] Means within each particle length fraction having different superscripts were significantly different ($P < 0.05$).

[#] Run 1; each sample was separated as a whole sample.
Runs 2 & 3; the particle length distribution for each sample was determined by consecutively separating the particle length fractions collected in the previous run.

runs. Since each subsample should have had a similar particle length distribution this effect must have been caused by subsampling error. The method of separation also had a significant effect on the proportion of sample weight collected in each length fraction. There was a significant increase ($P < 0.05$) in the amount of particles in the shorter particle length fractions (<4, 4-10 mm) and a decrease in the 10-20 and 20-40 mm fractions when the samples were reseparated from the particle length fractions collected in the first run; the 40-80mm and >80mm fraction weights did not change significantly ($P > 0.05$). There was no significant difference ($P > 0.05$), however, between the second and third runs in the particle length distribution of the samples when they were reseparated from the particle length fractions collected in the second run. Finner et al. (1978) separated each sample of a chopped forage, as a whole, three times on their simple vibrating separator and found that the standard deviation for the percent sample weight collected through each gap among the three runs was only about one percent; the average coefficient of variation was about three percent. Therefore, it appears that the results of separating chopped forage on a simple vibrating separator are very reproducible as long as a single method of application of forage particles to the separator is used.

The movement of particles from the middle length fractions to smaller length fractions between runs 1 and 2 indicated that there could have been an interaction between the two length groups which caused shorter particles to pass over the correct gaps when the sample was separated as a whole. On the other hand, since the greatest proportion of sample particles was of medium length, separation of these fractions as a unit may have increased the opportunity for these particles to pass through the smaller gaps. This

question of particle sizing accuracy was investigated in a separate experiment.

FPS vs. Visual Separation of Machine Chopped Orchardgrass Hay

After the machine chopped orchardgrass hay had been separated on the FPS, the resulting particle length fractions were separated visually to determine the accuracy of the FPS in separating chopped forage particles on the basis of length. A mature grass hay was used because it contained a high proportion of ideally shaped particles when chopped. There was no significant difference ($P > 0.05$) between the particle length distributions determined using the FPS and those determined visually (Table IV). There was, however, a consistent trend with all TLC towards an underestimation of the weight of particles in the 4-10 mm fraction and an overestimation of the weight of particles in the 20-40, 40-80 and >80 mm fractions when the particle length distributions were determined using the FPS.

The proportion of material, comprising each theoretical particle length

TABLE IV: Particle length distributions (percent of sample weight) of mature orchardgrass hay, chopped at three theoretical lengths of cut (TLC), determined by the FPS and by visual (VIS) separation.

		THEORETICAL RANGE OF PARTICLE LENGTHS (mm)						
TLC (mm)		<4	4-10	10-20	20-40	40-80	>80	CHI^2
3.18	FPS	15.9	18.7	30.3	22.8	10.5	2.0	5.350
	VIS	18.1	25.9	27.1	20.8	7.1	1.0	
6.35	FPS	10.8	15.5	35.1	23.5	12.8	2.5	10.625
	VIS	8.4	29.7	30.1	21.3	8.8	1.7	
9.53	FPS	7.5	9.7	37.6	29.2	13.9	2.1	7.647
	VIS	6.2	18.4	39.6	22.5	10.9	1.3	
mean	FPS	10.9	14.1	34.7	25.6	12.6	2.2	6.254
	VIS	10.4	24.0	33.0	21.6	9.6	1.3	

fraction collected on the FPS, that was correctly and incorrectly classified by length is given in Table V. The distribution of correctly and incorrectly classified particles in each particle length fraction was not significantly different ($P > 0.05$) between TLC samples. There was, however, a significant difference ($P < 0.05$) between particle length fractions in the percent weight of particles that was correctly and incorrectly classified. The 4-10 mm fraction contained the greatest proportion of correctly classified particles (65.9%) which was significantly higher ($P < 0.05$) than the proportion correctly classified in the 20-40 mm and the >80 mm fractions, not significantly different ($P > 0.05$) from the proportion correctly classified in the remaining fractions. The >80 mm fraction contained the lowest proportion of correctly classified particles (39.6%) which was significantly less ($P < 0.05$) than the proportion correctly classified in the other fractions, with the exception of the 20-40 mm fraction.

The proportion of particles that were incorrectly sized were classed as being either oversized or undersized; oversized particles were particles that should have fallen into a shorter length fraction whereas undersized

TABLE V: Percent weight of particles collected in each theoretical particle length fraction on the Forage Particle Separator (FPS) that were correctly and incorrectly sized.

THEORETICAL FPS LENGTH FRACTION	OVER SIZED	CORRECTLY SIZED	UNDER SIZED
<4 mm	0.0	56.8^{bc}	43.2
4-10 mm	23.1	65.9^{c}	11.0
10-20 mm	33.1	58.3^{bc}	8.7
20-40 mm	42.9	52.1^{ab}	5.0
40-80 mm	42.9	53.4^{bc}	3.7
>80 mm	64.5	39.6^{a}	0.0

[a-c] Values for correctly sized particles with different superscripts were significantly different ($P < 0.05$).

particles were particles that should have been classified into a longer length fraction. As the gap size on the FPS increased there was a significant increase in the proportion of oversized particles and a decrease in the proportion of undersized particles collected in the respective particle length fractions. These results are consistent with observations made while operating the FPS. Logically it was impossible for any particle to be oversized in the smallest length fraction or undersized in the longest length fraction. However, since many particles had to cross a number of gaps before arriving at the correctly sized gap, one would expect an increased incidence of undersizing in the smaller length fractions. This undersizing usually resulted from longer, irregularly shaped particles initially clogging and then threading their way through the smaller gaps. Conversely, as the particles passed down the FPS, the proportion of long to shorter particles increased, increasing the probability of oversizing from smaller particles being "carried" over the correct gap and falling into the longer particle length fractions.

Table VI shows the proportions of actual particle lengths in the chopped forage samples, by weight, that were correctly and incorrectly classified by the FPS. The TLC did not have a significant effect ($P > 0.05$) on the accuracy of particle length classification. The proportions of <4, 10-20, 20-40, 40-80 and >80 mm particles that were correctly classified were not significantly different ($P > 0.05$) from each other but only averaged 63.5 percent. The proportion of correctly classified 4-10 mm particles (38.7%) was significantly lower ($P < 0.05$). No explanation for this difference could be found. As particle length increased the incidence of undersizing increased whereas the incidence of oversizing decreased. Since longer particles had to travel over a greater number of gaps than did shorter

TABLE VI: Percent weight of sample forage particles of the given actual ranges of particle length that were correctly and incorrectly sized by the Forage Particle Separator.

ACTUAL SAMPLE PARTICLE LENGTHS	UNDER SIZED	CORRECTLY SIZED	OVER SIZED
<4 mm	0.0	59.8[b]	40.2
4-10 mm	11.2	38.7[a]	50.2
10-20 mm	8.3	61.2[b]	30.6
20-40 mm	15.6	61.6[b]	22.9
40-80 mm	18.6	69.9[b]	11.5
>80 mm	35.2	64.8[b]	0.0

[a-b] Values for correctly sized particles with different superscripts were significantly different ($P < 0.05$).

particles, before being separated, there was a greater probability for these particles to erroneously fall through small gaps and be undersized. On the other hand, smaller particles were more easily carried or pushed by larger particles over the correct gap causing them to be oversized.

The accuracy of particle length classification in the forage samples as a whole, by weight, is summarized in table VII. The proportions of incorrectly classified particles were divided into groups that passed through the first gap (1), or other gap (2), immediately preceding (-) or following (+) the correct gap. There was no significant difference in the accuracy of classification between TLC. An average of 56.6% of all particles were classified correctly. Of the remaining incorrectly sized particles, 32.38% passed over the correct gap and through later gaps while 11.0% passed through gaps prior to reaching their intended gap. Of those particles passing over the correct gap, 91.1% fell through the immediately following gap while 75.0% of those dropping prematurely fell through the gap immediately preceding the correct gap. This imbalance between over and undersizing by the FPS, on average, resulted in a net 21 percent oversizing of particle length.

TABLE VII: Percent weight of all particles falling into the correct tray (T_o) and into trays before (-) and after (+) the correct tray on the FPS for mature orchardgrass hay chopped at three theoretical lengths of cut (TLC).

	TRAY				
TLC (mm)	-2^+	-1	T_o	+1	$+2^+$
3.18*	2.6	8.8	54.9	29.9	3.8
6.35*	3.0	7.9	55.7	30.8	2.7
9.53*	2.5	8.4	58.5	28.2	2.4
mean*	2.7	8.3	56.6	29.5	2.9

* Percentage of particles falling into trays after the correct tray was significanly greater ($P < 0.05$) than that falling into trays before the correct tray.

Gale and O'Dogherty (1982) also found a higher incidence of oversizing with their separator but it was not as pronounced; the proportion of particles correctly classified by their separator ranged from 65 to almost 100% in some length fractions. These researchers also demonstrated with their separator, that the horizontal setting of each gap width had to be 14.2% larger than half the maximum length of particle intended to be separated by that gap. Therefore, if a gap is set at 5 mm, the theoretical maximum length of particle capable of being separated will not be 10 mm but somewhat less than 10 mm depending on the characteristics of the separator. For this reason, a separator can be calibrated by calculating the theoretical range of particle lengths being separated based on the degree of under or oversizing.

Based on the results above, the FPS was recalibrated to correct for the 21% oversizing. The calibration was based on particles having an equal probability of being undersized or oversized. Therefore the theoretical lengths of particles collected in each particle length fraction on the FPS were reduced by 21% to the following: <3.3, 3.3-8.25, 8.25-16.5, 16.5-33.0,

33.0-66.0, and >66.0 mm. By reducing the upper limits of particle size by 21%, the net adjustment in the range of particle lengths collected is 10.5%. For example, with two consecutive gaps set to theoretically separate particles up to 10 mm and 20 mm in length respectively, the 20 mm fraction loses 3.50 mm of larger particle lengths but gains 1.75 mm of smaller particle lengths resulting in an overall adjustment of 10.5% on either side. The actual proportion of sample particles in each of these new particle length fractions was then calculated by interpolating the results from visual separation.

After calibration of the theoretical length of particles collected in each fraction on the FPS, there was no significant difference ($P > 0.05$) between the FPS and visually determined particle length distributions of all samples tested (Table VIII). In general the Chi squared values for goodness of fit were considerably reduced indicating a greater similarity between the two distributions.

There was, however, still a significant difference ($P < 0.05$) between FPS particle length fractions in the proportion of correctly classified particles in each fraction (Table IX). The accuracy of classification tended to be more uniform, however, with a significant decrease ($P < 0.05$) in the accuracy of classification in the shorter particle length fractions and a significant increase ($P < 0.05$) in the accuracy in the longer particle length fractions. The distribution of undersized, correctly sized, and oversized particles within fractions was shifted significantly ($P < 0.05$) from oversizing to undersizing in the 3.3-8.25, 8.25-16.5, 16.5-33.0 and 33.0-66.0 mm fractions. This shift was consistent with the objective of calibration. There was a similar increase in oversizing and decrease in undersizing as gap size increased as there was before calibration.

TABLE VIII: Particle length distributions (percent of sample weight) of mature orchardgrass hay, chopped at three theoretical lengths of cut (TLC), determined by the Forage Particle Separator(FPS) and by visual (VIS) separation after calibration of the FPS.

		CALIBRATED PARTICLE LENGTH RANGE (mm)						
TLC (mm)		<3.3	3.3-8.3	8.3-16.5	16.5-33.0	33.0-66.0	>66.0	CHI^2
3.18	FPS	15.9	18.7	30.3	22.8	10.5	2.0	1.204
	VIS	15.0	21.5	26.4	25.1	9.7	2.4	
6.35	FPS	10.8	15.5	35.1	23.5	12.8	2.5	5.043
	VIS	6.9	22.5	30.5	24.3	12.1	3.7	
9.53	FPS	7.5	9.7	37.6	29.2	13.9	2.1	3.210
	VIS	5.1	14.1	33.1	30.0	14.9	2.8	
mean	FPS	10.9	14.1	34.7	25.6	12.6	2.2	2.551
	VIS	8.6	18.9	30.3	26.8	12.5	3.0	

Table X gives the proportions of the new ranges of actual particle length in a whole sample that were correctly and incorrectly classified by the FPS. The accuracy of classification of each of these ranges of particle

TABLE IX: Percent weight of particles, collected in each theoretical particle length fraction on the Forage Particle Separator (FPS) that were correctly and incorrectly sized after calibration.

THEORETICAL FPS LENGTH FRACTION	OVER SIZED	CORRECTLY SIZED	UNDER SIZED
<3.30 mm	0.0	46.8^{a}	53.2
3.30- 8.25 mm	19.1	50.1^{a}	30.9*
8.25-16.50 mm	24.1	55.0^{ab}	21.0*
16.50-33.00 mm	24.2	63.4^{b}	11.9*
33.00-66.00 mm	23.3	65.4^{b}	11.3*
>66.00 mm	33.7	66.3^{b}	0.0

$^{a-b}$ Values for correctly sized particles with different superscripts were significantly different ($P < 0.05$).

* Distribution of correctly and incorrectly sized particles within particle length fraction was significantly different than that before calibration ($P < 0.05$).

TABLE X: Percent weight of sample forage particles of the given actual ranges of particle length that were correctly and incorrectly sized by the Forage Particle Separator after calibration.

ACTUAL SAMPLE PARTICLE LENGTHS	UNDER SIZED	CORRECTLY SIZED	OVER SIZED
<3.30 mm	0.0	59.8[bc]	40.2
3.30- 8.25 mm	15.9	38.0[a]	46.2
8.25-16.50 mm	19.2	62.9[c]	18.0*
16.50-33.00 mm	29.0	60.9[bc]	10.1*
33.00-66.00 mm	30.0	65.7[c]	4.5
>66.00 mm	51.1	48.9[ab]	0.0*

[a-c] Values for correctly sized particles with different superscripts were significantly different ($P < 0.05$).

* Distribution of correctly and incorrectly sized range of particle length was significantly different than that before calibration ($P > 0.05$).

length was not significantly different ($P > 0.05$) from that for the previously given ranges of particle length (Table VI), with the exception of the longest particles for which the proportion of correctly classified particles declined from 64.8 to 48.9%. This fraction, however, represented less than 4% of all particles that were separated. Within the ranges of particle length there was a significant shift ($P < 0.05$) from oversizing to undersizing with particles ranging in length from 8.25-16.5 mm and 16.5-33.0 mm. Undersizing of the largest particle lengths (>66 mm) also significantly increased ($P < 0.05$). There was a similar increase in undersizing and decrease in oversizing as particle length increased as there was before calibration.

The accuracy of length classification of all particles in the samples as a whole, by weight, after calibration is summarized in Table XI. Calibration did not significantly change ($P > 0.05$) the proportion of particles correctly classified (57.3%) by the FPS. There was, however, a significant shift ($P < 0.05$) from oversizing, to undersizing of particles such that

TABLE XI: Percent weight of all particles falling into the correct tray (T_o) and into trays before (-) and after (+) the correct tray, for mature orchardgrass hay chopped at three theoretical lengths of cut (TLC), after calibration of the Forage Particle Separator.

	TRAY				
TLC (mm)	-2^+	-1	T_o	+1	$+2^+$
3.18	3.8	18.5	54.7	20.2	2.9
6.35	4.3	17.4	56.8	19.4	2.1
9.53	3.4	18.2	59.6	17.2	1.7
mean	3.8	18.0	57.3	18.7	2.1

there was no significant difference ($P > 0.05$) between the proportion of particles that were oversized and those that were undersized. Of the total weight of chopped forage that was separated, 57.3% of the particles were classified correctly with 21.8% being undersized and 20.9% being oversized after calibration.

It was therefore concluded that the simple vibrating tray separator suffers from an inherent inability to accurately classify all the particles in a sample of chopped forage by length. The over and undersizing errors which occur, are in part due to the design of the machine and in part due to the difficulty of separating irregularly shaped particles using the principle of overbalancing. On the other hand, due to the reproducibility of results and the ability to calibrate the theoretical lengths of particles that the separator classified into each fraction, it was concluded that the FPS could be used to accurately and quantitatively determine the particle length distribution of chopped forage.

DESCRIPTION OF PARTICLE LENGTH DISTRIBUTION

Goodness of Fit of Mathematical Functions

The coefficients of determination for the regression of percent cumulative weight undersize on particle length using the five regression equations are shown in Table XII. The modified Weibull function (5) consistently gave the highest R^2 values, followed by the regression of "probit" Y on particle length (4). All coefficients of determination were significant ($P < 0.05$) with the exception of those resulting from simple linear regression (1) with the data collected using the Forage Particle Separator.

Figures 3a through 7b show the fit of the predicted regression lines in

TABLE XII: Average R^2 values for the five regression models fitted to the data resulting from the Forage Particle Separator (FPS) and visual (VIS) separation of mature orchardgrass hay chopped at three theoretical lengths of cut (TLC).

		REGRESSION EQUATION#				
METHOD	TLC	1	2	3	4	5
FPS	3.18	0.600*	0.942	0.874	0.955	0.998
	6.35	0.616*	0.942	0.870	0.956	0.995
	9.53	0.630*	0.933	0.875	0.960	0.994
VIS	3.18	0.503	0.886	0.778	0.955	0.998
	6.35	0.479	0.876	0.695	0.976	0.995
	9.53	0.445	0.848	0.685	0.981	0.994

1: $Y = a + bX$
2: $Y = a + b\log X$
3: $\log Y = a + b\log X$
4: Probit $Y = a + b\log X$
5: $Y = 100(1 - e^{-(BX)^C})$

* R^2 value not significant ($P > 0.05$).

relation to the observed data, and the distribution of residuals for each regression equation for the FPS separated orchardgrass hay that was chopped at a TLC of 3.18 mm. From these graphs it is clear that equations 1 through 4 displayed a systematic lack of fit to the observed data. The residuals resulting from the use of equations 1, 2 and 3 were consistently distributed in an inverted "U" shape while those resulting from the use of equation 4 were consistently distributed in a normal "U" shape. When the data was fitted to the modified Weibull function, however, the residuals were randomly distributed around the predicted regression line indicating a consistent goodness of fit of the data to the predicted cumulative curve.

A further goodness of fit test was performed by comparing the derived particle length probability density distributions predicted from regression equations 2, 4 and 5 with those observed using FPS and visual separation. The Chi squared values from the analysis are shown in Table XIII. There was a consistent lack of fit ($P < 0.05$) between the observed and predicted particle length probability density distributions using equation 2. The same lack of fit was seen using equation 4 but only for the distributions that were determined using the FPS. This result indicates that the actual distribution of particle length in chopped forage may approximate a lognormal distribution. A similar lack of fit to the lognormal distribution observed in the data from FPS separation has been observed when distributions of elongated particles were determined by sieving chopped forage (Waldo et al., 1971; Allen et al., 1984), rumen contents (Pond et al., 1984) and fecal samples (Allen et al., 1984; Pond et al., 1984). The above results also suggest that a high coefficient of determination is not sufficient, by itself, to indicate a goodness of fit to a given distribution if the R^2 value is below 0.99. R^2 values between 0.90 and 0.95 have in the

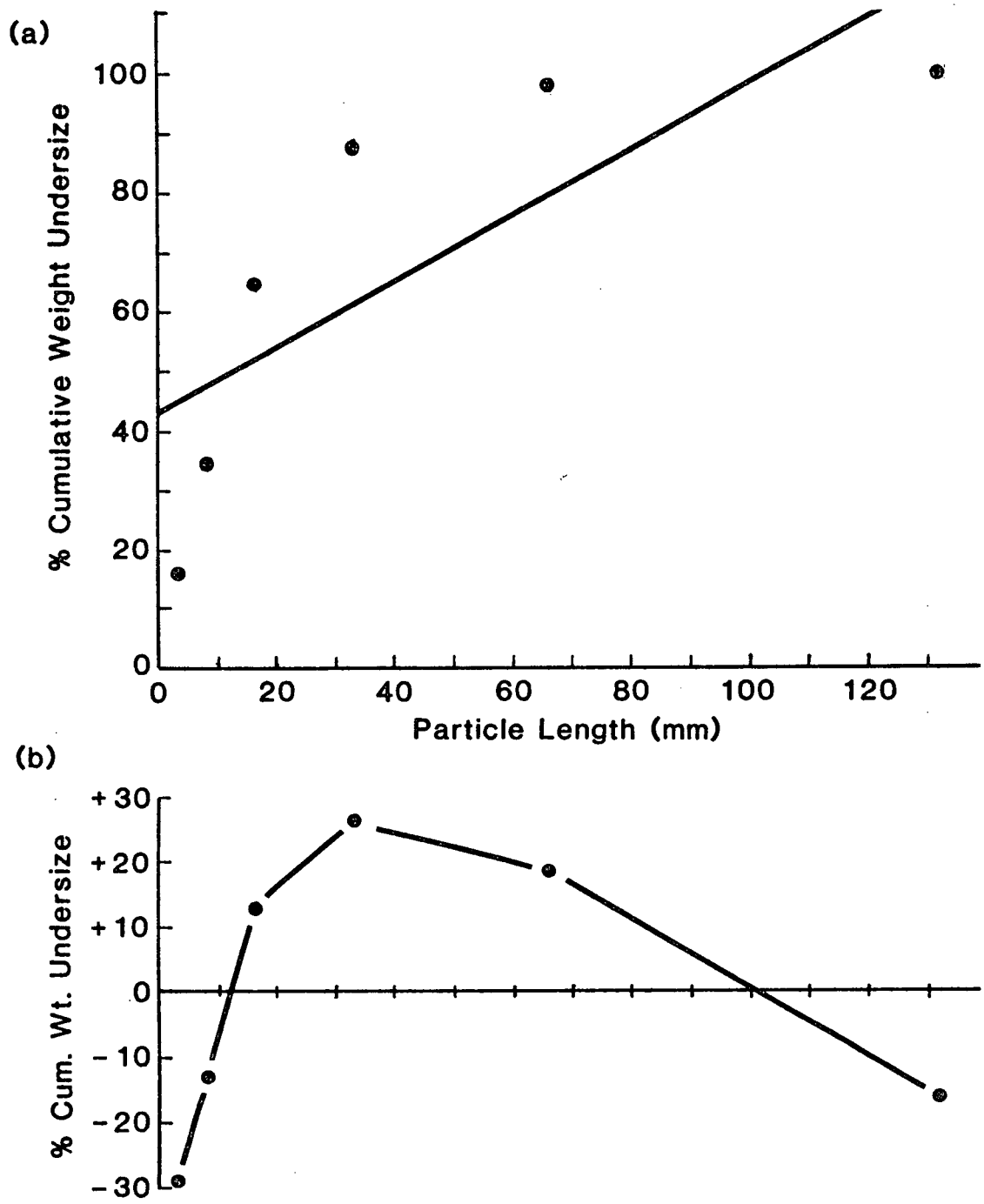

FIGURE 3: Plots of FPS separation data for low quality orchardgrass hay chopped at a TLC of 3.18 mm showing the fit of the observed points to the predicted line (a) and the distribution of residuals (b) using the regression equation $Y = a + bX$.

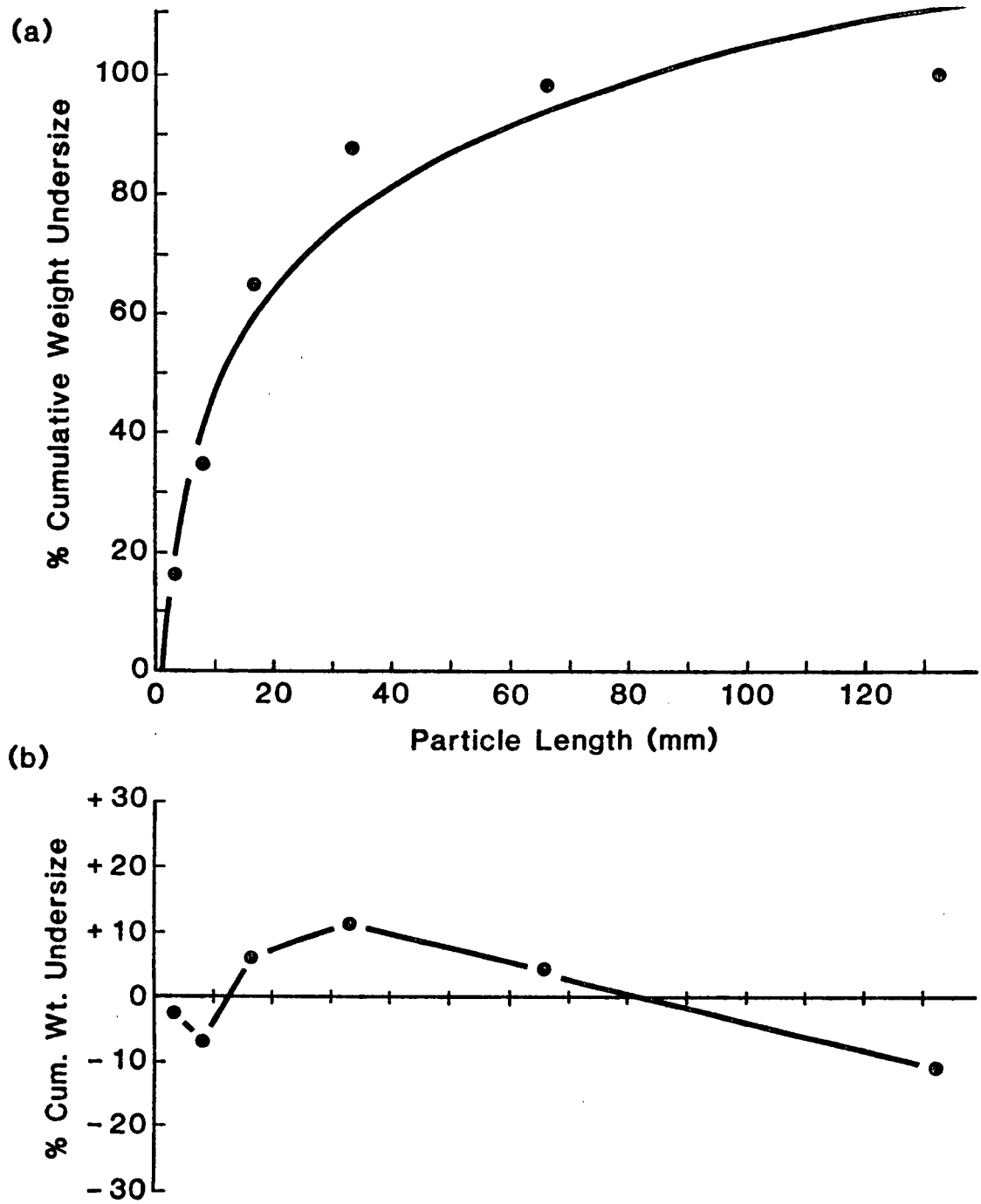

FIGURE 4: Plots of FPS separation data for low quality orchardgrass hay chopped at a TLC of 3.18 mm showing the fit of the observed points to the predicted line (a) and the distribution of residuals (b) using the regression equation $Y = a + b\log X$.

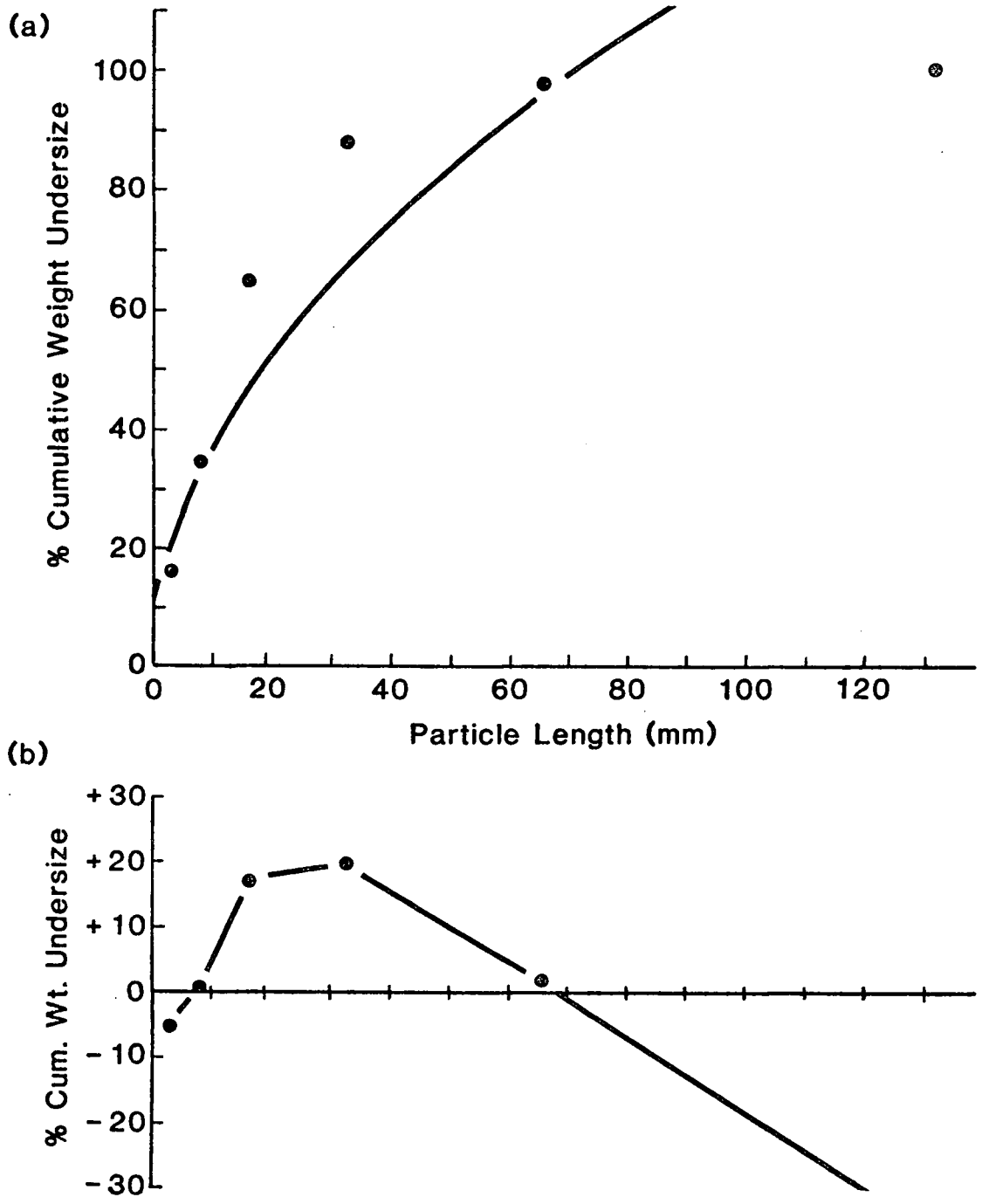

FIGURE 5: Plots of FPS separation data for low quality orchardgrass hay chopped at a TLC of 3.18 mm showing the fit of the observed points to the predicted line (a) and the distribution of residuals (b) using the regression equation logY = a + blogX.

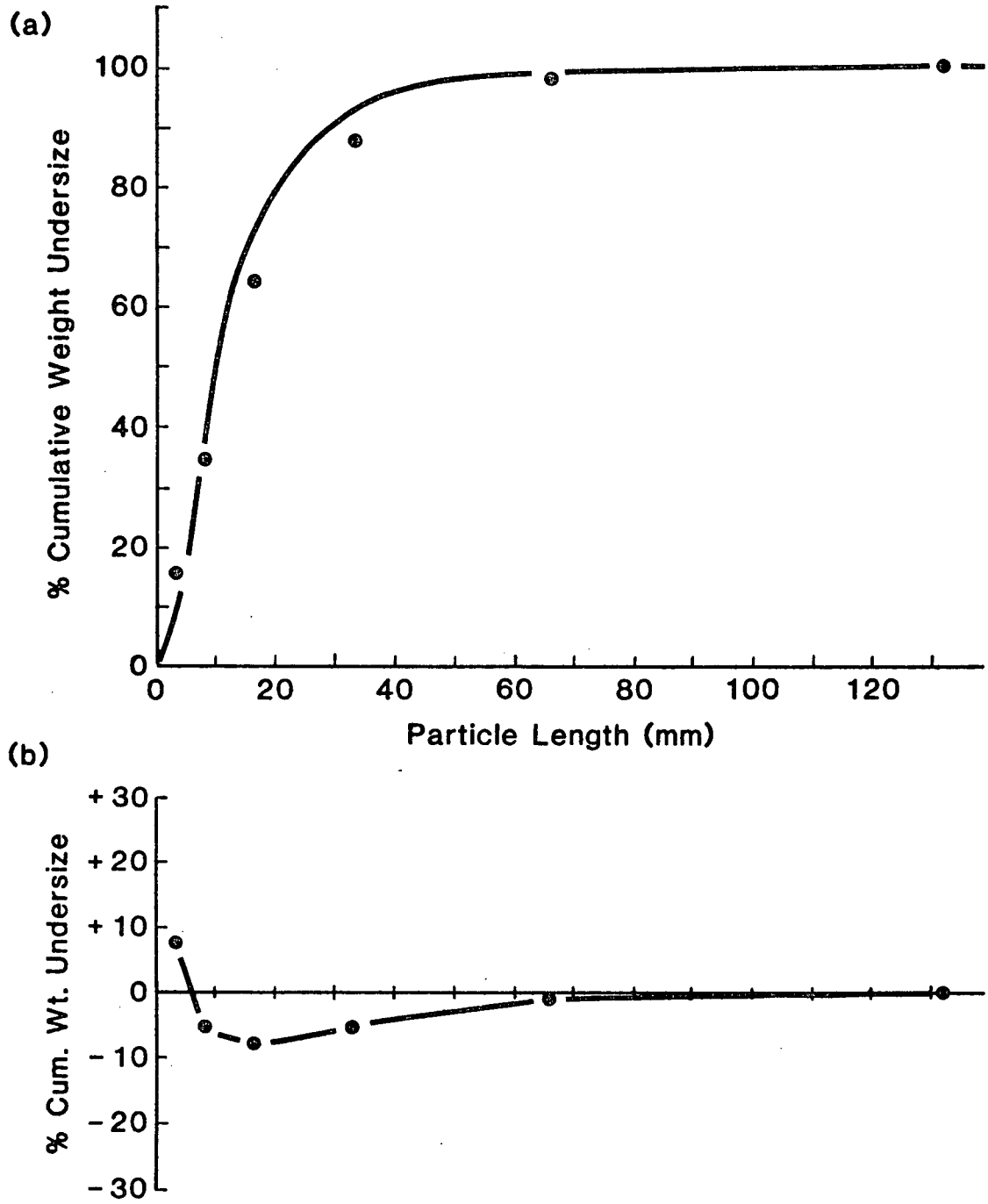

FIGURE 6: Plots of FPS separation data for low quality orchardgrass hay chopped at a TLC of 3.18 mm showing the fit of the observed points to the predicted line (a) and the distribution of residuals (b) using the regression equation Probit Y = a + blogX.

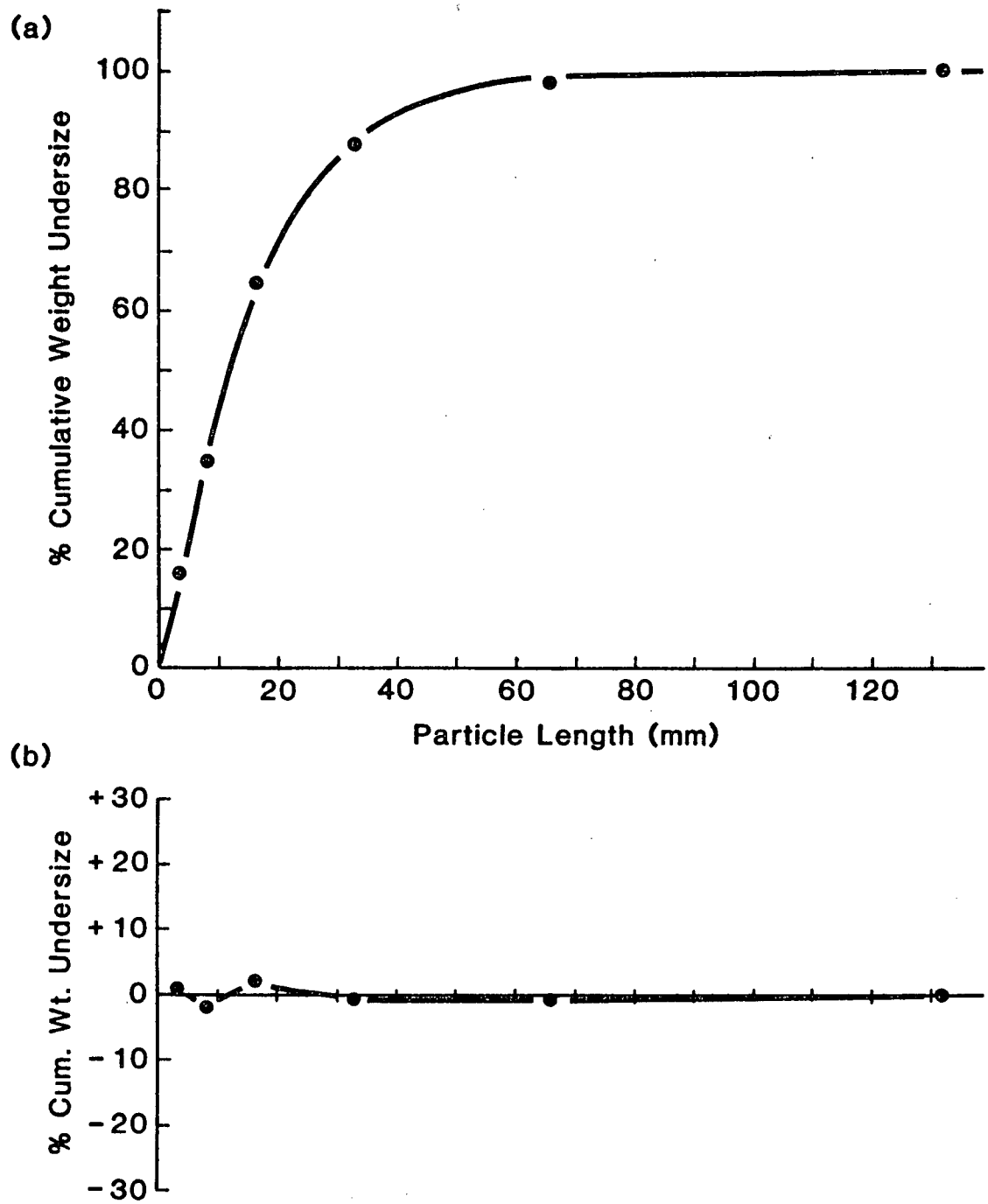

FIGURE 7: Plots of FPS separation data for low quality orchardgrass hay chopped at a TLC of 3.18 mm showing the fit of the observed points to the predicted line (a) and the distribution of residuals (b) using the modified Weibull function.

TABLE XIII: Chi squared values for the goodness of fit of the derived particle length probability density distributions, predicted by three regression equations, to those observed after FPS and visual (VIS) separation of orchardgrass hay chopped at three theoretical lengths of cut (TLC).

		REGRESSION EQUATION#		
METHOD	TLC	2	4	5
FPS (n=6)	3.18	18.24*	15.62*	1.40
	6.35	41.30*	15.36*	4.67
	9.53	63.87*	23.71*	8.20
VIS (n=24)	3.18	29.38*	8.61	0.87
	6.35	60.90*	2.01	10.33
	9.53	73.90*	6.32	8.77

2: $Y = a + b\log X$

4: Probit $Y = a + b\log X$

5: $Y = 100(1 - e^{-(BX)^C})$

* CHI squared value significant ($P < 0.05$).

past been used as proof that certain data approximated a lognormal distribution (Smith et al., 1984). There was no significant difference ($P > 0.05$), however, between the observed and predicted probability density distributions for both the FPS and visual separation data when the modified Weibull-type function (5) was used.

Prediction of Median Particle Length

Table XIV gives the median particle lengths predicted by equations 2, 4 and 5 for the separation of the hay by the FPS and visual separation. The median particle lengths predicted from FPS data were based on the calibrated ranges of particle length that were collected on the FPS. Due to the goodness of fit of the modified Weibull function for both the cumulative particle length and particle length probability density distributions, the

TABLE XIV: Median particle lengths predicted by three regression equations for FPS and visually (VIS) separated orchardgrass hay chopped at three theoretical lengths of cut (TLC).

		REGRESSION EQUATION#		
METHOD	TLC	2	4	5
FPS (n=6)	3.18	11.5	10.2	12.0
	6.35	13.7	11.7	14.1
	9.53	15.8	13.2	16.4
VIS (n=24)	3.18	8.9	11.9	11.8
	6.35	10.9	14.0	13.8
	9.53	12.6	16.1	16.4

2: $Y = a + b\log X$

4: Probit $Y = a + b\log X$

5: $Y = 100(1 - e^{-(BX)^C})$

predicted median particle lengths for the visually separated hay, determined using the Weibull function, were assumed to be the "correct" values, and the other values were subjectively compared with them. Lack of adequate replication in this case did not permit statistical testing of any differences.

There was a good agreement between the median particle length values predicted from the FPS data and those predicted from visual separation data when the modified Weibull function was used. This result further indicated that the FPS could be used to accurately quantitate the particle length distribution in chopped forage. There was also good agreement between the median particle length values predicted by regression equations 4 and 5 when applied to the visual separation data. However, the fitting of the lognormal distribution to FPS determined particle length distributions tended to underestimate the median particle lengths of these distributions due to a consistent lack of fit as indicated in Table XIII. These results support

other research that has shown that the goodness of fit of the lognormal distribution to sieving data by linear regression may be affected by the selection of sieves sizes that are used during separation or when points are missing from either end of the cumulative distribution (Allen et al., 1984). These researchers demonstrated that a better fit to separation data may be obtainable by using maximum liklihood estimators of the lognormal distribution parameters. Fitting of data by non-linear regression as is done using the Weibull function or the Gamma function is not subject to the same fitting errors as is linear regression (Allen et al., 1984). Although the median particle lengths predicted by equation 2 were similar to the "correct" values, the lack of fit of this equation to the data suggests that the results were obtained by coincidence.

Only regression using the modified Weibull function resulted in predicted particle length probability density functions that were similar to those that were observed using either FPS or visual separation data. Murphy and Bohrer (1984) have argued that no explicit theory exists regarding comminution leading to the production of a Rosin-Rammler (or Weibull) distribution of particle sizes and for that reason concluded that its use was inappropriate for describing the particle size distribution of comminuted substances. However, as these researchers also pointed out, the Rosin-Rammler or Weibul function is also the solution of the differential "hazard rate" equation and the probability function proposed by Weibull (1951) for material failure; both of these characteristics are involved in the comminution of feed particles by hammering, grinding, chopping and chewing. Therefore, the use of the Weibull function appears to be appropriate for describing the particle length distribution in chopped forages when they have been separated on a simple vibrating tray separator.

No methods, however, have been proposed for the description of the spread of particle lengths in a sample of chopped forage using this function.

Description of Spread Using the Weibull Function

One of the major benefits of using the lognormal distribution is that the distribution of particle lengths can be described by two parameters, the log mean and log standard deviation. However, since the lognormal distribution did not satisfactorily fit the data from FPS separation, a method of describing the spread of particles using the Weibull function was required.

If one examines the action of the parameters in the Weibull function (Figure 8), one can see that the B parameter controls the shift of the curve (ie. change in curve position from left to right on the X axis) while the C parameter controls the shape (ie. the relative slope and symmetry of the curve). When base "e" is used in the function, a change in the shape parameter (C) causes the curve to pivot around the 63.2 percentile point. Therefore, both the B and C parameters must change when either the median of a given particle length distribution changes or the distribution of particle lengths around a given median changes. However, when base 2 is used in the Weibull function (Figure 9), the pivot point for changes in the shape of a curve becomes the 50 percentile point or the median particle length value for a given distribution. The use of a different base changes the values of the two parameters but does not alter the fit of the function. By using base 2, changes in the shape parameter (C) do not alter the value of the shift parameter (B) which can then be used to calculate the median particle length, the value of which is determined by 1/B.

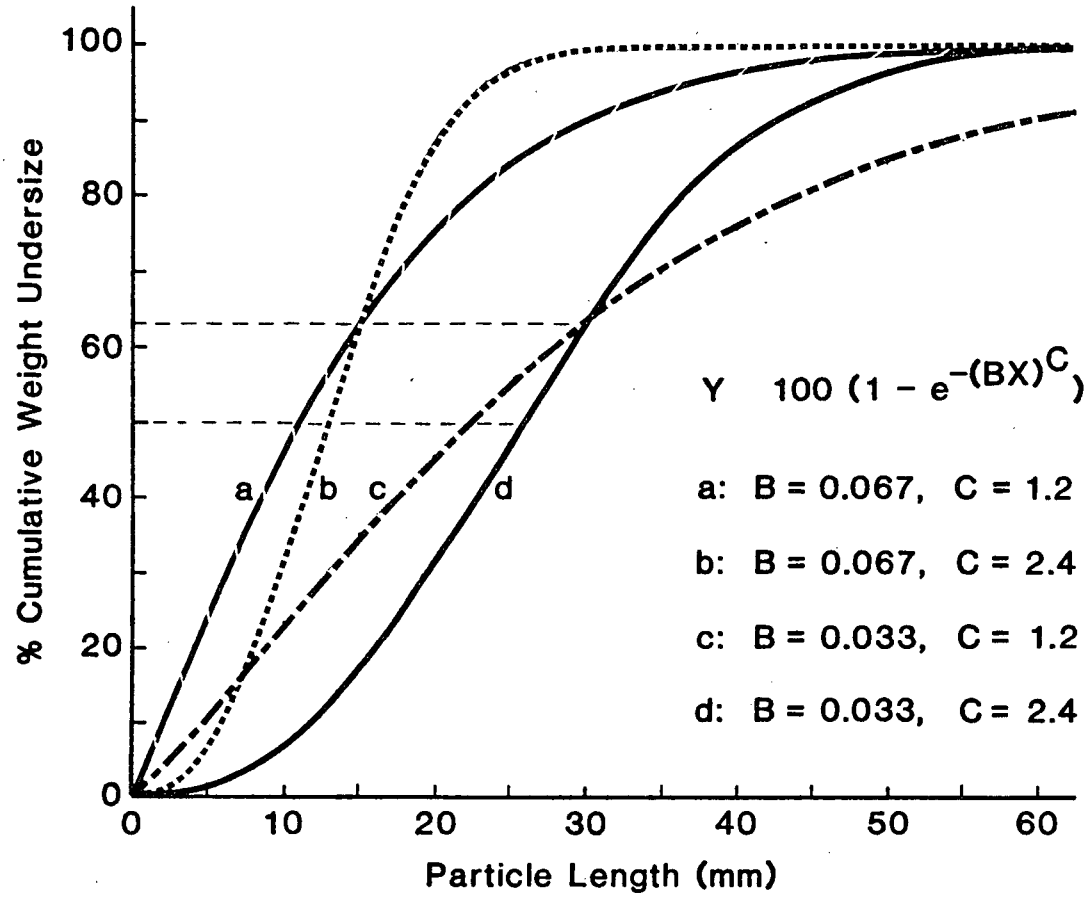

FIGURE 8: Changes in shape of the modified Weibull cumulative frequency distribution with various B and C parameter values when "base e" is used in the equation.

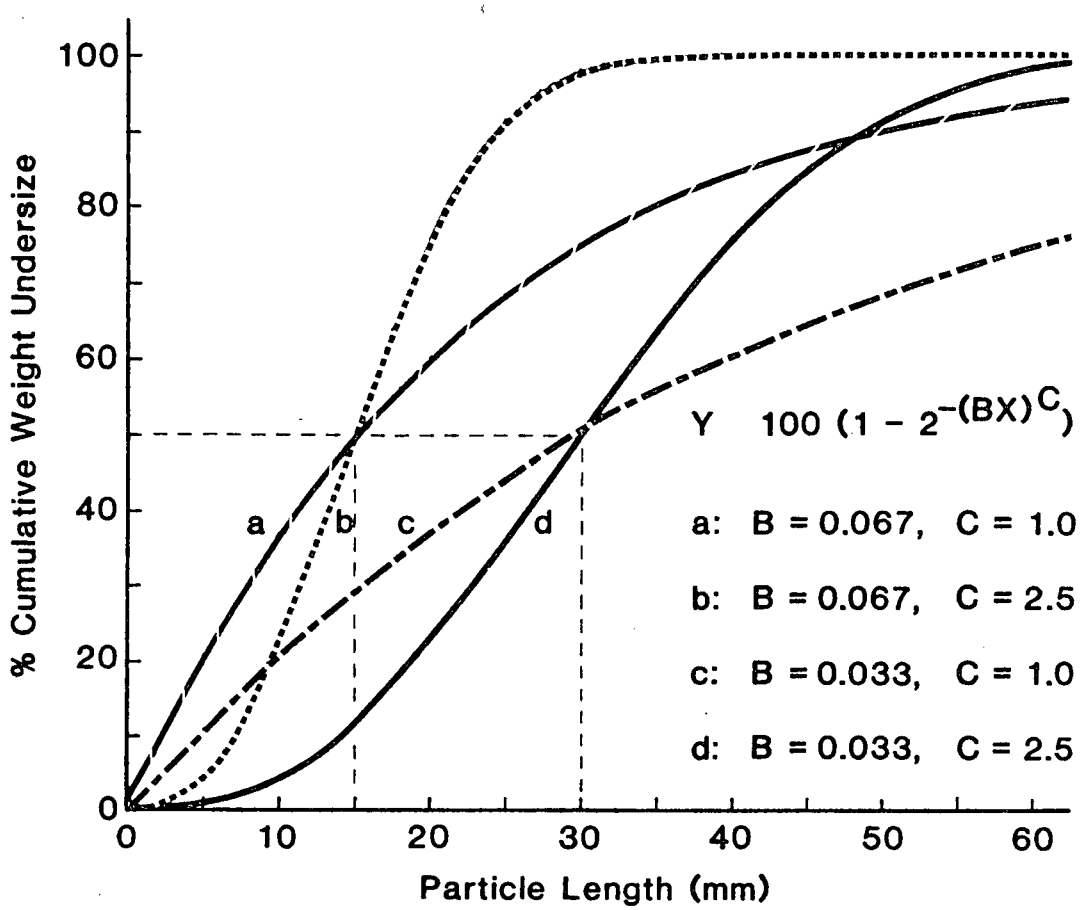

FIGURE 9: Changes in shape of the modified Weibull cumulative frequency distribution with various B and C parameter values when "base 2" is used in the equation.

The shape of a cumulative curve is determined by the shape of the associated increment or density function. Therefore when base 2 was used in the Weibull function, the value of the C parameter could be used to describe the shape of the particle length distribution when applied to separation data. The effect of changing the value of the C parameter on the shape of the cumulative and derived increment (density) curves when base 2 was used in the function is shown in Figures 10 and 11 respectively; all the curves have the same value for B and therefore predict the same median particle length. With C equal to 1.0, the cumulative curve is the same as a simple exponential curve. However, as the value of the C parameter increases, one can see that the incremental distribution becomes less skewed to the right such that when C is equal to 3.212, a normal distribution is approximated. If the value of C becomes even larger, the distribution then becomes skewed to the left. Therefore, if two particle length distributions have the same median, but different C values, the spread of the particles around the mean must be different; and therefore, the two distributions must be different. Furthermore, as can be seen from Figure 10, as the value of C increases to 3.212, the relative spread of the particles around the median decreases.

If two distributions have different median values, but similar values of C, the relative spread of particles around each mean is equal. For example, two distributions have median particle lengths of 10 and 20 mm respectively and the value of C is 1.5 for both distributions. Using the values of B (0.1 and 0.05) and the value of C in the Weibull function, one can calculate the range in length of particles collected between the 25 and 75 percentile points of the cumulative distribution using the following equation:

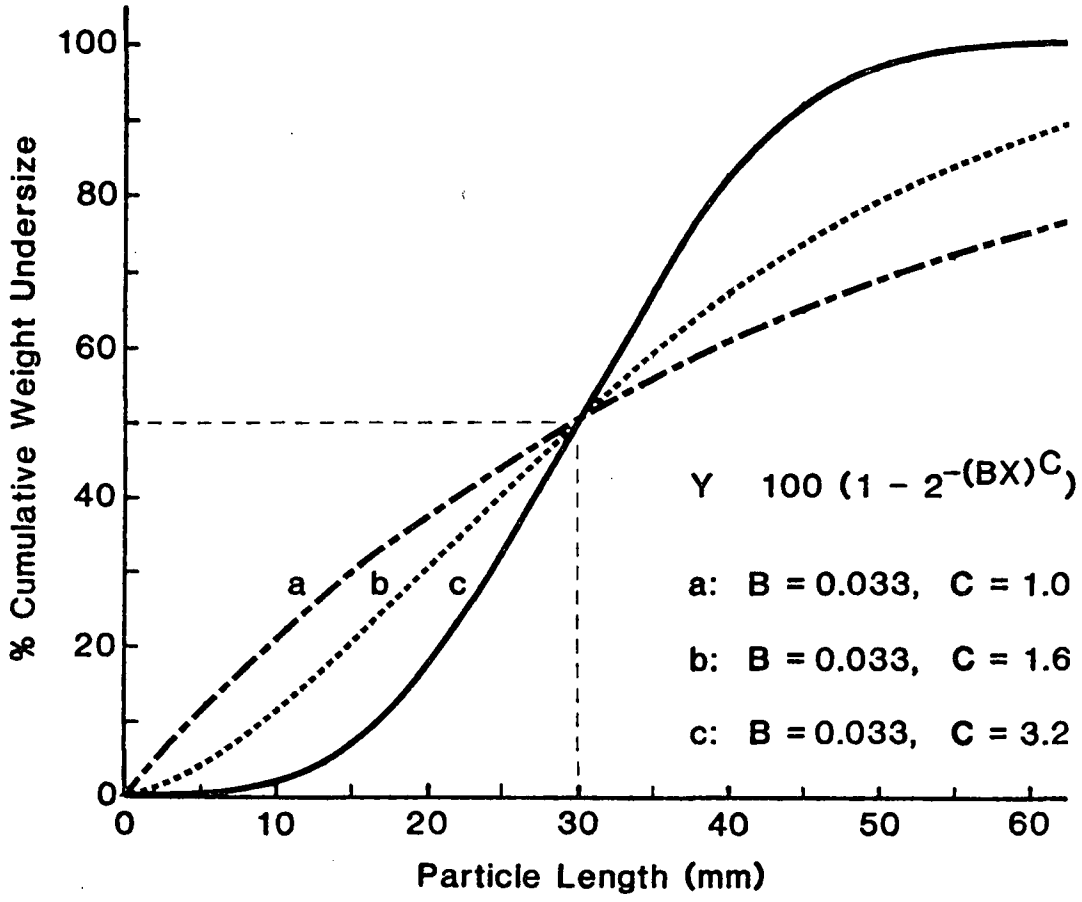

FIGURE 10: Changes in shape of the modified Weibull cumulative frequency distribution given a fixed B parameter value and three C parameter values when "base 2" is used in the equation.

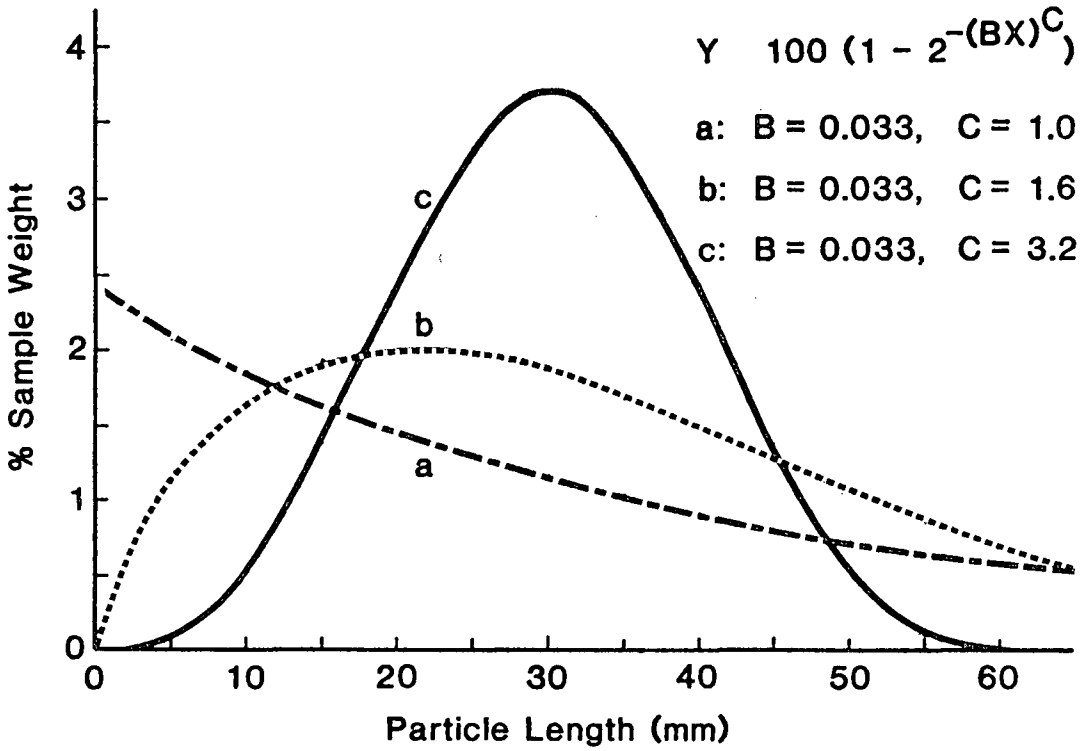

FIGURE 11: Changes in shape of the modified Weibull probability density distribution given a fixed B parameter value and three C parameter values when "base 2" is used in the equation.

$$X = \frac{10^{\left|\frac{\log\left(-\left(\log\left(Y-1\right)/\log 2\right)\right)}{C}\right|}}{B}$$

where: X = the length of particles at the 25 or 75 percentile point.

Y = the percentile point divided by 100

C = the shape parameter

B = the shift parameter which is equal to the inverse of the median particle length.

The range of particle lengths between the 25th and 75th percentile points for the two example particle length distributions are 5.56 - 15.87 mm and 11.13 - 31.75 mm respectively. Expressing the range of lengths as a single value (10.31 and 20.62 mm) and dividing by the respective median particle length gives the relative spread of particle lengths around the mean (1.031 and 1.031) which are equivalent for the two particle length distributions.

Therefore, the C parameter acts not only as an indicator of the shape of the distribution (normal vs. degree of skewness) but in a manner similar to the coefficient of variation in describing the relative spread of distributions having the same or dissimilar median particle lengths. For this reason the C parameter can be used to describe and test the relative spread of particle lengths around the median particle length of chopped forages and was therefore named the coefficient of spread.

Table XV gives the coefficients of spread from the FPS and visual separation of chopped orchardgrass hay. FPS separation tended to overestimate the coefficient of spread for the particle length distributions. This indicated that although the FPS could be used to accurately determine the median particle lengths of the distributions, some error may occur in the determination of shape of the distribution. It is

TABLE XV: Coefficients of spread for orchardgrass hay chopped at three theoretical lengths of cut (TLC) as determined from FPS and visual (VIS) separation.

	THEORETICAL LENGTH OF CUT (mm)		
	3.18	6.35	9.53
FPS	1.142	1.275	1.524
VIS	1.068	1.132	1.289

more likely, however, that the separation into many more particle length fractions by visual separation may have resulted in a more accurate fitting of the Weibull function to the distributions.

SUMMARY

The research in this chapter investigated the accuracy of a simple vibrating tray Forage Particle Separator (FPS) in separating forage particles on the basis of length, and the description of the resulting particle length distributions using mathematical functions. By comparison with visual separation, the FPS correctly classified only 57.3 percent of the separated particles, by weight, on the basis of length. However, after calibration of the theoretical particle lengths being separated into fractions on the FPS, there was an equal degree of oversizing and undersizing such that the FPS accurately described the particle length distribution in the chopped forage that was separated.

Of the mathematical functions that were tested, the lognormal distribution and the Weibull function both significantly fit the particle length distributions that were determined by visual separation. Based on the distribution of residuals from regression, however, the Weibull function gave the best fit to the data. When using FPS separation data, the determined particle length distributions did not approximate a lognormal distribution. This was probably due to problems associated with fitting the lognormal distribution by simple linear regression. The Weibull function, on the other hand, fit the FPS and visual separation data equally well. Therefore it was concluded that the Weibull function was more appropriate than the lognormal distribution for use in describing the particle length distribution in chopped forage. A method for describing the spread of particle length distributions using the C parameter of the modified Weibull function was described.

CHAPTER II

THE EFFECT OF PROCESSING METHOD AND FORAGE TYPE ON THE PARTICLE LENGTH DISTRIBUTION OF DM, CP AND ADF IN PROCESSED FORAGES

INTRODUCTION

The reduction of particle size in forages fed to ruminants by chopping and grinding reduces feed wastage, can increase voluntary feed consumption, and has been shown to have an effect on digestion and rate of passage of these feeds. Processing of different forages using identical methods, has therefore routinely been used in experimentation investigating the digestibility of different forage types and the effect of particle size on digestion processes. Little research, however, has been done to see if similar particle size distributions are produced when different forages are processed using the same method.

Recent research has shown that different forages, ground under identical conditions, can result in the production of significantly different particle size distributions (Osbourn et al., 1981), and that the crude protein (CP) and fiber fractions of the forage can be differentially distributed throughout the range of particle sizes that are produced (Jaster and Murphy, 1983). If these differences in particle size distribution of dry matter (DM), CP, and fiber are large enough within or between forages when processed under identical conditions, lack of quantification of the particle size distributions could introduce uncontrolled variation into experimental results.

Therefore, the objective of the following study was to quantitatively determine the effect of processing method (hammermilling or chopping at

three theoretical lengths of cut [TLC]) and forage type (alfalfa and high and low quality orchardgrass hay) on the particle length distribution of DM, CP, and acid detergent fiber (ADF) in processed forage.

LITERATURE REVIEW

Research has shown that the rate of microbial digestion, rate of passage and, therefore, the extent of digestion of feedstuffs fed to ruminants may be directly affected by the particle size distribution in the feed. Robles *et al.* (1980) found that decreasing the particle size of forages increased the rate of *in vitro* cell wall digestion in alfalfa. When various concentrates were subjected to *in vitro* and *in situ* digestion, Ehle *et al.* (1982) found that the particle size of linseed meal had an effect on the rate of DM digestibility whereas the particle size of the other concentrates did not. Particle size, however, did not appear to affect the *in vitro* or *in situ* digestion of CP.

The particle size of feedstuffs appears to have its greatest effect on the rate of passage of particles from the rumen, which in turn affects the digestibility of the diet. Jaster and Murphy (1983), when feeding alfalfa hay to Holstein heifers, found that reducing the median particle length from 2160 to 1440 um (determined by sieving) significantly decreased DM and ADF digestibility. Osbourn *et al.* (1981) found that differences as small as 0.2 in the Moduli of Fineness for different ground forages significantly altered the organic matter and cell wall digestibility of the forages when fed to lambs. Therefore, under certain conditions, a relatively small difference in particle size can significantly affect the digestibility and rate of passage of some feedstuffs in ruminants.

Any study of the effect of forage particle size on parameters of digestion and rate of passage in ruminants usually requires that the feedstuff first be processed. Processing of forages is also used to reduce feed wastage and increase voluntary feed consumption when conducting

research studying the effect of different forage characteristics on forage utilization. In most of these trials, the different feedstuffs have been processed using the same method, but the actual particle size distributions of the processed feedstuffs have not been determined; only the methods employed, including screen size used in grinding or hammermilling, or the theoretical length of cut (TLC) used during chopping, are reported. Osbourn et al. (1981), however, found that different forages, harvested with the same equipment, milled through the same size screen and/or passed through the same pelletizer had significantly different Moduli of Fineness. The researchers also found that the differences in the particle size distributions between forages processed by an identical method significantly affected the comparison of the digestibility of these forages. Similar research involving the chopping of forages could not be found.

The particle size distributions of forages reported in the literature are based on the distribution of DM. If protein and fiber are evenly distributed, by weight, throughout the range of particle sizes in a sample of processed forage, the particle size distributions of DM, CP and ADF will be similar. If the concentration of CP or ADF changes as particle size changes, the distribution of these nutrients on the basis of particle size will be different from the particle size distribution of DM.

The processing of different feedstuffs using the same method does appear to differentially affect the distributions of CP and ADF in relation to particle size. Ehle (1984) found that the concentration of cell wall components increased with increasing particle size within a sample of coarse chopped alfalfa and two maturities of smooth bromegrass hay. He also found that the rate of increase was greater in the alfalfa hay than it was in the bromegrass hays, within which the rate of increase was greater in the more

mature bromegrass hay. Jaster and Murphy (1983) also found that the ADF concentration of chopped alfalfa hay particles within a given sample increased as particle size increased. They also demonstrated that crude protein concentration decreased with increasing particle size. Therefore, the particle size distributions of DM, CP and ADF may differ within samples of processed forage and between forages processed under identical conditions. If these differences are large enough, they also could have a significant effect on the comparison of the digestibility and rate of passage of different forages and the determination of the effect of reducing forage particle size on the process of digestion in the ruminant.

MATERIALS AND METHODS

PROCESSING AND PARTICLE LENGTH SEPARATION OF FORAGE

Approximately 100 kilograms each of baled alfalfa (ALF) and high and low quality orchardgrass hay (OGH and OGL) were chopped at three theoretical lengths of cut (TLC) (3.18, 6.35 and 9.53 mm), with a John Deere, Model 35 forage harvester, and hammer-milled through a 12.7 mm screen in a Haybuster. The bales of each forage were broken open and the sheaves equally and randomly distributed between the four processing treatments in a balanced three by four factorial design. The sheaves for each chopped forage treatment were then chopped and sampled three times using the same procedure that was described in Chapter 1. Hammermilled forage was collected directly below the hammermill screen, mixed and then sampled three times by "grab sampling" with a small shovel. Each hammermilled sample was a composite of not less than six randomly selected subsamples. Grab samples of all processed forage were also taken and composited for each forage type to be used for chemical analysis. All samples, excluding those for chemical analysis, were then separated into 6 particle length fractions (<3.3, 3.3-8.25, 8.25-16.5, 16.5-33.0, 33.0-66.0 and >66.0 mm) on the Forage Particle Separator (FPS) as described in Chapter 1.

CHEMICAL ANALYSIS

After separation, similar particle length fractions from samples within each treatment combination were composited to yield a single set of particle length fractions for each treatment combination. These composite particle

length fractions and the unseparated forage samples were then ground through a 1.0 mm screen in a Wiley mill before being analyzed for dry matter (DM) (oven drying at 65 degrees Celsius), crude protein (CP) (Parkinson and Allen, 1975) and Acid Detergent Fiber (ADF) (Waldern, 1971) content.

CALCULATIONS

The weight of CP and ADF in each particle length fraction of a given sample was calculated by multiplying the weight of the sample collected in each particle length fraction on the FPS by the respective nutritional content of the fraction. The percent weight of CP and ADF in each fraction was then calculated.

The median particle length (MPL) and coefficient of spread (CS) of DM, CP, and ADF for each sample were determined by the methods described in Chapter 1 using the Modified Weibull function. The MPL for each nutrient in a forage sample is defined as the length at which 50% of the cumulative percent weight of the nutrient is found. For example, if the DM MPL is 10 mm, 50% of the total weight of DM in the sample is located in the particles that are less than 10 mm in length and 50% of the DM is located in the particles greater than 10mm in length. The same applies for CP or ADF. If the CP MPL is 7 mm, 50% of the total weight of CP in the sample is located in the particles that are less than 7 mm in length and 50% of the CP is located in the particles greater than 7 mm in length. The determination of the cumulative distribution of CP and ADF was the same as that for DM except that the percent weight of each nutrient was used in place of the percent weight of DM.

The MPL of each particle length fraction of a given sample separated on

the FPS was determined by solving the appropriate regression equation for the independent variable X when the cumulative percent weight undersize (Y) was equal to the mid point of the cumulative sample weight collected in a given particle length fraction. For example, if the range of percent cumulative weight collected in a given tray was 65 to 79%, the mid point (Y) was 72% ((65 + 79) / 2).

STATISTICAL ANALYSIS

The effect of treatment combination on the MPL and CS of DM, CP and ADF was tested by General Linear Hypothesis using the BMD:10V packaged program of the University of British Columbia. The General Linear Hypothesis was as follows:

$$Y_{ijk} = u + F_i + P_j + FP_{ij} + E_{ijk}$$

where: Y_{ijk} = the dependent variable: MPL or CS.

u = the overall mean.

F_i = the effect of the i'th type of forage.

P_j = the effect of the j'th method of processing.

FP_{ij} = the effect due to the interaction between the i'th type of forage and the j'th method of processing.

E_{ijk} = the unexplained residual error associated with each sample.

Differences between means for the treatment combinations were tested using Duncan's Multiple Range test ($\alpha = 0.5$).

The relationship between particle length and nutritional content within each treatment combination was tested using linear regression. Both simple

linear ($Y = a + bX$) and curvilinear regression ($Y = a + b\log X$) were used. The particle length fraction MPL was the independent variable (X) and the percent nutrient content of the fraction was the dependent variable (Y). Regression analysis was performed using the BMDP:1R packaged program available at the University of British Columbia. The effect of treatment combination on the relationship between particle length and nutrient content was tested by homogeneity of regression coefficients using the U.B.C. Computing Center packaged program, SL:TEST. Differences between regression coefficients and regression lines were separated by Scheffe's multiple range test which was also part of the same program.

The effect of treatment combination on the deviation of CP and ADF median particle lengths and coefficients of spread from those of DM within each forage was tested using the same General Linear Hypothesis as was used above. The difference between the MPL for DM and that for CP or ADF within each sample was calculated by subtracting the value determined for DM from that determined for CP and for ADF. Individual t tests were used to test the null hypothesis that the difference between the DM and CP, and the DM and ADF median particle lengths, within each treatment combination, was not significantly different from zero.

RESULTS AND DISCUSSION

FORAGE NUTRITIONAL COMPOSITION

Forage CP and ADF Content

The nutritional composition of the three forages is given in Table XVI. The three forages that were processed had significantly different ($P < 0.05$) CP contents; the OGH hay had the highest CP content, OGL hay the lowest, while the CP content of ALF was intermediate. OGL and ALF had similar ADF contents which were significantly higher ($P < 0.05$) than that for OGH.

Relationship Between Particle Length and Nutrient Content

Figures 11 and 12 show the CP and ADF content of the particle length fractions in each of the processed forages as an average of the values determined with each method of processing. Regressing the percent nutrient content of the particle length fractions on the logarithm of the median particle lengths of those fractions gave a better fit than did simple linear regression.

TABLE XVI: Percent crude protein (CP) and acid detergent fiber (ADF) content (DM basis) of the alfalfa (ALF) and high (OGH) and low (OGL) quality orchardgrass hay used in the experiment.

	HAY		
	ALF	OGH	OGL
CP	17.0[b]	25.8[c]	5.8[a]
ADF	34.1[b]	20.8[a]	33.2[b]

[a-c] Means within rows with different superscripts were significantly different ($P < 0.05$).

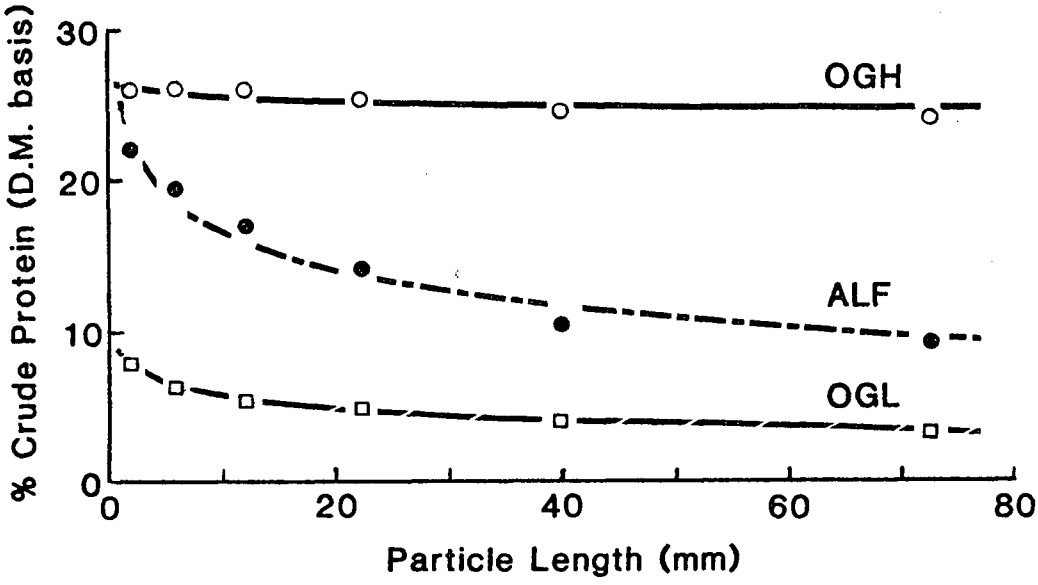

FIGURE 12: Plot of the average observed values and predicted regression lines (Y = a + blogX) for the relationship between crude protein content (Y) and particle length (X) in processed alfalfa (ALF) and high (OGH) and low (OGL) quality orchardgrass hays.

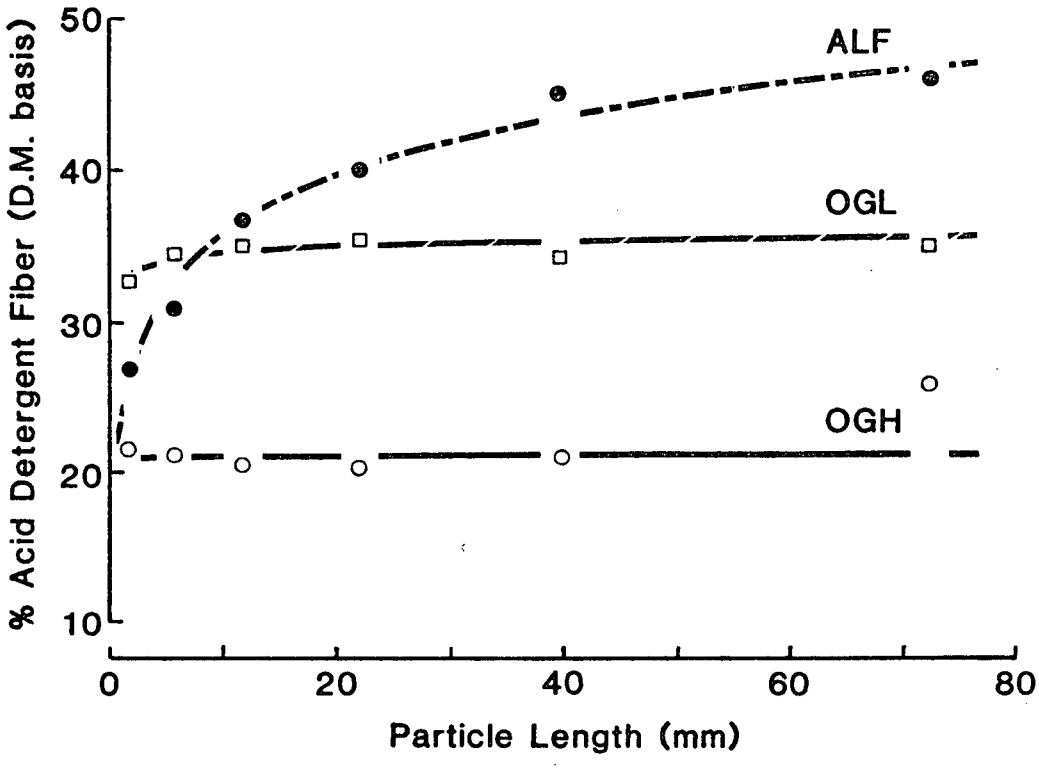

FIGURE 13: Plot of the average observed values and predicted regression lines (Y = a + blogX) for the relationship between acid detergent fiber content (Y) and particle length (X) in processed alfalfa (ALF) and high (OGH) and low (OGL) quality orchardgrass hays.

TABLE XVII: Regression coefficients (b) for the regression[#] of percent CP and ADF content of particle length fractions on the DM median particle length of the fraction for the forages hammered through a 12.7 mm screen (H) and chopped at three theoretical lengths of cut (TLC).

		FORAGE		
NUTRIENT	TLC	ALF	OGH	OGL
CP	H	-9.543^{c}	-1.635^{ab}*	-3.461^{ab}
	3.18	-7.144^{bc}	-0.817^{a} *	-2.872^{ab}
	6.35	-8.359^{c}	-1.793^{ab}	-2.380^{ab}
	9.53	-8.240^{c}	0.330^{a} *	-2.674^{ab}
ADF	H	14.250^{bc}	-3.033^{a} *	0.700^{a} *
	3.18	10.890^{bc}	1.459^{a} *	1.840^{a} *
	6.35	14.510^{c}	0.176^{a} *	1.230^{a} *
	9.53	14.210^{c}	0.233^{a} *	3.860^{ab}

[#] $Y = a + b\log X$

[a-c] Means with different superscripts within nutrient rows were significantly different ($P < 0.05$).

* Regression coefficient not significantly different from zero ($P > 0.05$).

The regression ($Y = a + b\log X$) coefficients for CP and ADF are given in Table XVII. Not all of the regression coefficients were significant. Within each forage, the regression coefficients for CP and ADF content were not significantly affected ($P > 0.05$) by the method of processing that was used.

The regression coefficients for CP for all but one treatment combination were negative. This indicated that CP content of the forage particles declined with increasing particle length. The CP content of forage particles declined at a significantly greater rate ($P < 0.05$) with increasing particle length in the processed ALF hay than it did in the orchardgrass hays. The regression coefficients for CP in OGL were larger, but not significantly different ($P > 0.05$) than those for OGH. The regression coefficients for CP resulting from three of the processing

methods used on OGH, however, were not significantly different from zero ($P > 0.05$), indicating that CP in this forage was uniformly distributed on the basis of particle length.

The regression coefficients for ADF for all but one treatment combination were positive indicating that the ADF content of forage particles increased as particle length increased. This increase in ADF content with increasing particle length was significantly greater ($P < 0.05$) in processed ALF than it was in the orchardgrass hays. There was, however, no significant difference ($P > 0.05$) between the regression coefficients for OGH and OGL, and, with the exception of OGL hay chopped at a TLC of 9.53 mm, all of the ADF regression coefficients for these forages were not significantly different from zero ($P > 0.05$).

PARTICLE LENGTH DISTRIBUTIONS

Fitting of the Weibull Function

The coefficients of determination for the fitting of the Weibull function to the cumulative particle length distribution, by weight, of DM, CP and ADF in all chopped forage were consistently greater than 0.99. There was also a random distribution of residuals around the regression lines indicating a good fit of the function to the data. The coefficients of determination for the fitting of the Weibull function to the cumulative nutrient particle length distributions in the hammered forage ranged from 0.97 to 0.99, which is considered low for the prediction of median particle length (MPL) and coefficient of spread (CS) (see Chapter 1). The use of the Weibull function, however, resulted in a random distribution of residuals, and gave a better fit to the data than did the lognormal distribution. It

was concluded, therefore, that the fit of the Weibull function to the hammermilled forage data was adequate for the prediction of MPL and CS in this experiment.

DM Median Particle Length

In most research involving the feeding of processed forage to ruminants, the particle size distributions of different forages, processed using the same method, have been assumed to be similar. In this study, however, there was a significant interaction ($P > 0.05$) between the effects of forage type and method of processing on the DM MPL produced in the processed forage (Table XVIII).

Firstly, the screen size used in hammering or the TLC used in chopping

TABLE XVIII: DM, CP and ADF median particle lengths (mm) of the forages hammered through a 12.7 mm screen (H) and chopped at three theoretical lengths of cut (TLC).

		FORAGE			
NUTRIENT	TLC	ALF	OGH	OGL	SEM[#]
DM	H	4.7^{a}	5.6^{a}	8.1^{b}	0.6
	3.18	11.2^{cd}	8.6^{b}	11.9^{cde}	
	6.35	10.9^{c}	11.9^{cde}	14.1^{f}	
	9.53	13.4^{ef}	12.9^{def}	16.4^{g}	
CP	H	3.7^{a}	5.4^{b}	6.2^{b}	0.5
	3.18	8.2^{c}	8.4^{c}	8.5^{c}	
	6.35	8.3^{c}	11.6^{de}	10.6^{d}	
	9.53	10.3^{d}	12.6^{e}	13.1^{e}	
ADF	H	5.9^{a}	5.3^{a}	8.2^{b}	0.5
	3.18	13.2^{de}	8.0^{b}	11.9^{cd}	
	6.35	12.9^{de}	11.0^{c}	14.0^{ef}	
	9.53	15.2^{fg}	11.9^{cd}	16.2^{g}	

[#] Standard error of the mean for the values in each nutrient row.

[a-g] Means with different superscripts within nutrient rows were significantly different ($P < 0.05$).

was not an accurate predictor of the MPL that was produced when the forages were processed. In every case, the MPL of the hammered forage was less than the screen size (12.7 mm) used, while the MPL of the chopped forage was greater than the TLC used during chopping. The net result was that for each nutrient, within each forage, hammering through a 12.7 mm screen produced a significantly smaller ($P < 0.05$) MPL than did chopping at any TLC.

Differences in the mechanism of particle size reduction between hammering and chopping determine the relationship between the screen size or TLC and the MPL produced in processed forage. The process of hammering forages involves pulverization of particles to a size capable of passing through a given size of screen. Because pulverization results in the production of a variable proportion of very small particles, and there is a limit to the maximum size of particle which can pass through the screen, the MPL of hammered forage will be less than the size of the screen aperture. When forages are chopped in a precision cut forage harvester, however, the MPL of the processed forage is usually greater than the TLC (O'Dogherty, 1982). The calculation of a TLC assumes that particles entering tha chopper pass through the blades end first and perpendicular to the cutting surface. In practice, forage particles entering a chopper can be randomly oriented with respect to the cutting surface. Particles that do not pass through the blades perpendicular to the cutting surface will be cut longer than the TLC. Therefore, the MPL of chopped forages usually exceeds the calculated TLC used during chopping.

Processing of the different forages using the same methods did not always result in the production of similar DM MPL between forages. There was no significant difference ($P > 0.05$) in the DM MPL between ALF and OGH when the forages were hammered or chopped at a TLC of 6.35 and 9.53 mm. When OGL

was processed by the same methods, however, the DM MPL produced in each case was significantly larger ($P < 0.05$) than that produced when the other forages were processed. When the forages were chopped at a TLC of 3.18 mm, the relationship between the DM MPL of the forages was changed; there was no significant difference ($P > 0.05$) in the DM MPL between ALF and OGL whereas the MPL produced when OGH was chopped was significantly smaller ($P < 0.05$). With each method of processing, the DM MPL produced when OGL was processed was significantly larger ($P < 0.05$) than that produced when OGH was processed.

The reasons for the differences in the DM MPL between forages processed by the same method are unclear. Robles et al. (1980) found that the geometric mean diameter of ground forages generally increased with increasing cell wall content of the forages. The higher ADF content of OGL as compared with that of OGH may therefore have contributed to the production of larger MPL in the processed OGL. The morphological structure of forages may also contribute to differences in MPL. Legumes are comprised of leaves and hollow stems which are more brittle than are the same components in grasses (Hall et al., 1970). Therefore, especially when hammered, processed legumes should produce smaller MPL than that produced when grasses are processed by the same method. Finally, the presentation of particles to the cutting surface in a forage harvester has a direct effect on the length of particles that are produced. Since each forage was chopped from the baled form, differences between forages in the structural composition and orientation of particles in the bales may have contributed to differences in the DM MPL between different forages processed by the same method.

No matter what the reason for the production of different MPL in forages

processed by the same method, small differences between the DM particle size of forages fed to ruminants have been shown to have an effect on rate of passage, digestibility and chewing behavior. Santini et al. (1983) found that differences as small as 1 mm in forage MPL directly and linearly affected chewing time in Holstein cows when they were fed chopped alfalfa hay and silage. Elimam and Orskov (1984) found that decreasing the Modulus of Fineness of ground dried grass from 2.77 to 2.15 reduced the outflow of Chromium treated fish meal from the rumen. Decreasing the median particle length of chopped hay by approximately 5 mm, when fed to high producing dairy cattle, decreased the amount of time the animals spent chewing and the ruminal acetate:propionate ratio (Van Beukelen et al., 1985). Jaster and Murphy (1983), when feeding alfalfa hay to Holstein heifers, found that reducing the geometric mean diameter from 2160 to 1440 um significantly decreased DM and ADF digestibility but not total chewing times. Osbourn et al. (1981) found that differences as small as 0.2 in the moduli of fineness for different ground forages significantly altered their O.M. and cell wall digestibility when fed to lambs.

The differences in DM MPL between the forages processed by the same method in this study ranged from 0.5 to 3.5 mm. These differences in MPL fall within the range of sizes discussed above that have been shown to significantly affect forage utilization when processed forage is fed to ruminants. Therefore, lack of quantification of forage particle size in research using different forages processed by the same method may introduce uncontrolled experimental error. The above applies equally to research investigating the effect of reducing particle size on the ruminant digestion process, and to research investigating the utilization of different species and qualities of forage where processing is used to reduce feed wastage and

increase voluntary feed intake. The above results, however, clearly show that with quantification of forage particle size, different processing methods can be used to produce similar MPL in different forages and thus reduce uncontrolled experimental error.

The above results also showed that during chopping, each increase in TLC did not always result in an increase in the DM MPL of chopped forage. When OGL was chopped, there was a significant increase ($P < 0.05$) in DM MPL with each increase in TLC. There was also a significant increase in DM MPL when the TLC of ALF was increased from 6.35 to 9.35 mm and when the TLC of OGH was increased from 3.18 to 6.35 mm. However, increasing the TLC of ALF from 3.18 to 6.35 mm and the TLC of OGH from 6.35 to 9.53 mm did not result in the production of significantly different DM MPL ($P > 0.05$) between the TLC. Therefore, the preparation of dietary particle length treatments by chopping, on the basis of TLC alone, may not always ensure that a difference exists between the particle length distributions of the dietary treatments.

CP and ADF Median Particle Length

As with DM MPL, there was a significant interaction ($P < 0.05$) between the effects of forage and method of processing on the CP MPL,. and the ADF MPL, produced in the processed forage. The effect of method of processing on the differences in DM, CP and ADF MPL within each forage was similar for each nutrient that was studied. The nutrient MPL produced when a forage was hammered was always significantly smaller ($P < 0.05$) than that produced when the forage was chopped at any TLC. As with DM MPL, each increase in the TLC of chopped OGL resulted in a significant increase ($P < 0.05$) in CP MPL and ADF MPL; there was also no significant difference ($P > 0.05$) between the MPL for each of the nutrients when ALF was chopped at a TLC of 3.18 and 6.35 mm

and when OGH was chopped at a TLC of 6.35 and 9.53 mm.

The effect of method of processing on the differences in DM, CP and ADF MPL between forages processed by the same method was different with each nutrient that was studied. Whereas the DM MPL of ALF and OGH were similar when the forages were hammered or chopped at a TLC of 6.35 or 9.53 mm, the CP MPL of ALF was significantly smaller ($P < 0.05$), and the ADF MPL significantly larger ($P < 0.05$) (except when hammered) than the respective nutrient MPL of OGH. The DM and the ADF MPL of OGL were significantly larger ($P < 0.05$) than the respective nutrient MPL of OGH but there was no significant difference ($P > 0.05$) in CP MPL between the two forages. When OGL and ALF were hammered or chopped at a TLC of 6.35 or 9.53 mm, the DM MPL and CP MPL of OGL were significantly larger ($P < 0.05$) than the respective nutrient MPL of ALF; the ADF MPL of the two forages, however, were not significantly different ($P > 0.05$) with each method of processing, except when the forages were hammered.

The difference in the effect of the treatment combinations on the DM, CP and ADF MPL produced in the processed forage was caused by differences between forages in the extent that nutrient MPL deviated from DM MPL within each foraqe. As with previous analyses, there was a significant interaction between the effect of forage type and the method of processing on the deviation of CP and ADF MPL from the DM MPL of the processed forage (Table XIX). With the exception of the ADF MPL deviation from that of DM in hammered OGH and OGL chopped at a TLC of 3.18 mm, all the deviations of CP or ADF MPL from that of DM within each processed forage were significantly different from zero. These deviations resulted from the unequal distribution of CP and/or ADF on the basis of particle length within each of the forages, as was discussed earlier. A negative deviation indicated that the nutrient

TABLE XIX: Deviation between the DM and CP, and DM and ADF median particle lengths (mm) of the forages hammered through a 12.7 mm screen (H) and chopped at three theoretical lengths of cut (TLC).

		FORAGE			
NUTRIENT	TLC	ALF	OGH	OGL	SEM[#]
C.P.	H	-1.065^{e}	-0.232^{f}	-1.944^{d}	0.119
	3.18	-2.933^{bc}	-0.280^{f}	-3.392^{a}	
	6.35	-2.694^{c}	-0.279^{f}	-3.471^{a}	
	9.53	-3.117^{ab}	-0.283^{f}	-3.328^{a}	
ADF	H	1.169^{f}	-0.239^{c} *	0.116^{e}	0.058
	3.18	2.051^{h}	-0.597^{b}	-0.018^{de}*	
	6.35	1.908^{gh}	-0.858^{a}	-0.098^{cd}	
	9.53	1.766^{g}	-0.934^{a}	-0.150^{cd}	

[#] Standard error of the mean for the values in each nutrient row.

[a-h] Means with different superscripts within nutrient rows were significantly different ($P < 0.05$).

* Deviation between ADF and DM MPL not significantly different from zero ($P > 0.05$).

was concentrated in the shorter lengths of forage particles whereas a positive deviation indicated that the nutrient was concentrated in the longer particles. A deviation that was not significantly different from zero indicated that the distribution of the nutrient was similar to that of the DM and that the nutrient was evenly distributed, by weight, throughout the various lengths of forage particles.

With all three forages, processing resulted in a concentration of CP in the shorter lengths of particles. The method of processing, however, did not significantly affect ($P > 0.05$) the deviation of CP MPL from DM MPL when OGH was processed. The CP MPL of ALF and OGL, on the other hand, deviated significantly less ($P < 0.05$) from the DM MPL when the forages were hammered than it did when the forages were chopped. The TLC used during chopping did not significantly affect ($P > 0.05$) the deviation of CP MPL from DM MPL in

OGL whereas the deviation with ALF was greater ($P < 0.05$) at a TLC of 9.53 mm than it was when the forage was chopped at the two shorter TLC. There was, however, no significant difference ($P > 0.05$) in the deviation of CP from DM MPL between ALF chopped at a TLC of 3.18 mm and that chopped at a TLC of 6.35 mm.

With the exception of ALF chopped at a TLC of 9.53 mm, there was a significant difference ($P < 0.05$) in the deviation of CP MPL from DM MPL between the three forages within each method of processing. The deviation was the greatest with OGL, the smallest with OGH and intermediate with ALF. At a TLC of 9.53 mm, the difference in the deviation of CP MPL from DM MPL between ALF and OGL was not significantly different ($P > 0.05$) . These deviations, however, were significantly greater ($P < 0.05$) than that found when OGH was chopped at a TLC of 9.53 mm.

Processing had an inconsistent effect on the location of ADF in relation to particle length between the three forages. The deviations of ADF MPL from that of DM suggest that the ADF in hammered OGL and all processed ALF was concentrated in the longer lengths of particles whereas the ADF in chopped OGL and all processed OGH was somewhat concentrated in the shorter particle lengths. The deviation of ADF MPL from DM MPL in ALF and OGH was significantly less ($P < 0.05$) when the forages were hammered than it was when they were chopped. With OGL, the deviation was positive when the forage was hammered and negative when it was chopped. There was, however, no significant difference ($P > 0.05$) in the deviation of ADF MPL from DM MPL between hammered OGL and OGL chopped at a TLC of 3.18 mm.

There was a consistent trend towards a lesser degree of ADF concentration in the longer particle length fractions in all three forages as the TLC used in chopping increased. There was, however, no significant

difference ($P > 0.05$) in the deviation of ADF MPL from DM MPL between TLC in chopped OGL; in chopped ALF, the positive deviation significantly decreased ($P < 0.05$) as TLC increased. The negative deviation of ADF MPL from DM MPL significantly increased ($P < 0.05$) when OGH was chopped at a TLC of 6.35 mm as compared with chopping at a TLC of 3.18 mm; there was, however, no significant change ($P > 0.05$) in the deviation when the TLC was increased from 6.35 to 9.53 mm.

There was a significant difference ($P < 0.05$) in the deviation of ADF MPL from DM MPL between the three forages within each method of processing. The deviation was the largest, and positive, in processed ALF, the smallest and close to zero in processed OGL, and intermediate, but negative, in processed OGH.

The negative deviation of ADF MPL from that of DM in OGH and OGL indicates an opposite relationship between nutrient concentration and particle length to that found when particle length fraction ADF content was regressed on the MPL of each fraction (see Table XVII). The positive relationship seen in Table XVII would suggest that there should have been a positive deviation between the ADF and DM MPL in the orchardgrass hays. There are two possible explanations for the finding of a negative ADF deviation. Small fluctuations occurred in the ADF content of the particle length fractions such that some smaller length fractions had a higher ADF content than did some longer length fractions within a given forage sample. If the shorter length, higher ADF fraction cumulatively contained more than 50% of the sample DM, which did occur, a negative deviation could result when the cumulative ADF distribution was calculated. It seems more probable, however, that, consistent with the results found in Table XVII, there was no "actual" difference between the ADF and DM MPL within each of the

orchardgrass hays. The negative deviation that was found could simply have resulted from differences in the fitting of the Weibull function due to the cumulative effect of very small differences in the ADF content of the different particle length fractions.

In research investigating the effect of forage particle size on forage utilization, the digestibility of nutritional components has always been related to the DM particle size of the forage. However, the results of this study indicate that the effect of the treatment combinations on the DM, CP and ADF MPL of forages processed by the same method was different depending on which nutrient was examined. Furthermore, the differences in CP and ADF MPL between forages processed by the same method ranged from 0.2 to 3.3 mm and 0.6 to 5.2 mm respectively. It was also found that the deviation of CP or ADF MPL from that of DM within a given forage ranged from nearly zero to 3.5 mm. Some of these differences in MPL, as with DM MPL were in the range that has been shown to affect rate of passage from the rumen. Different nutrients within a given processed forage may therefore have different rates of passage which may directly affect the ruminal digestibility of the nutrient. Furthermore different forages with similar DM MPL may have different CP or ADF MPL and vice-versa. Therefore, the digestibility of a given nutrient component in processed forage should be related to the median particle size of that nutrient to avoid the introduction of uncontrolled experimental error from relating CP or ADF digestibility to DM median particle size.

Coefficients of Spread

The CS of a particle length distribution (see Chapter 1) is a measure of the relative dispersion of particles lengths around the MPL. It is possible

for two samples of processed forage to have the same MPL but have different CS. As the value of the CS increases from 0 to 3.212, the relative dispersion of particle lengths decreases and the particle length distribution becomes less skewed to the right (see Chapter 1).

As with MPL, there was a significant interaction between the effect of forage type and method of processing on the DM, CP and ADF CS of the particle length distributions that were produced during processing (Table XX). The significant differences between the CS of the various treatment combinations suggest that the nature of the particle length distribution (eg. normal vs. lognormal) that is produced by different processing methods with different forages is not constant. These differences in the nature of the particle length distribution may partially explain the observed lack of

TABLE XX: DM, CP and ADF coefficients of spread of the forages hammered through a 12.7 mm screen (H) and chopped at three theoretical lengths of cut (TLC).

		FORAGE			
NUTRIENT	TLC	ALF	OGH	OGL	SEM[#]
DM	H	1.020^{ab}	0.954^{a}	1.301^{c}	0.043
	3.18	1.088^{ab}	1.087^{ab}	1.142^{b}	
	6.35	1.138^{b}	1.344^{c}	1.275^{c}	
	9.53	1.276^{c}	1.384^{c}	1.524^{d}	
CP	H	0.899^{a}	0.935^{ab}	1.066^{bcd}	0.043
	3.18	1.089^{cd}	1.121^{cd}	1.020^{abc}	
	6.35	1.093^{cd}	1.337^{e}	1.194^{d}	
	9.53	1.183^{d}	1.424^{e}	1.417^{e}	
ADF	H	1.157^{bc}	0.959^{a}	1.337^{d}	0.047
	3.18	1.137^{bc}	1.047^{ab}	1.138^{bc}	
	6.35	1.241^{cd}	1.288^{cd}	1.313^{d}	
	9.53	1.375^{d}	1.368^{d}	1.572^{e}	

[#] Standard error of the mean for the values in each nutrient row.

[a-e] Means with differnt superscripts within nutrient rows were significantly different ($P < 0.05$).

fit when some particle size distributions have been fitted to the lognormal distribution (see Chapter1).

Different forages that had the same MPL when processed by the same method did not always have similar CS. ALF and OGL had similar D.M MPL when the forages were chopped at a TLC of 6.35 mm and similar ADF MPL when the forages were chopped at a TLC of 9.53 mm. In both of these cases, however, the CS of OGL was significantly greater ($P < 0.05$) than that of ALF. The CP MPL of OGH and OGL were similar when the forages were chopped at a TLC of 6.53 mm whereas the CS of OGH was significantly greater ($P < 0.05$) than that of OGL. When ALF and OGH were hammered, similar ADF MPL were produced, but the CS of ALF was significantly greater ($P < 0.05$) than that of OGL. Therefore, even if similar MPL are produced in different forages processed by the same method, the particle length distributions of the processed forages may not be similar. On the other hand, in every case where different processing methods used on the same forage produced similar MPL, the CS of the processed forage were also not significantly different ($P > 0.05$).

When each of the forages was chopped, a significant increase in the DM, CP or ADF MPL was accompanied by a significant increase ($P < 0.05$) in the CS. Between forages processed by the same method there was no consistent relationship between a difference in MPL and a difference in CS. For example, there was no significant difference in the ADF CS of the three forages when they were chopped at a TLC of 3.18 or 6.35 mm. At the same TLC, the ADF MPL of OGH was significantly smaller ($P < 0.05$) than those of ALF and OGL which were not significantly different ($P > 0.05$) from each other. Conversely, there was no significant difference in both CP MPL and CP CS between the three forages when they were chopped at a TLC of 3.18 mm.

Finally, there were also cases where different forages processed by different methods had similar MPL but had different CS. For example, the DM MPL of hammered OGL was not significantly different ($P > 0.05$) from that of OGH chopped at a TLC of 3.18 mm, whereas the DM CS of the OGL was significantly smaller ($P < 0.05$) than that of the OGH. The opposite was also evident in that different forages processed by different methods had different MPL but had similar CS. The ADF MPL of OGL chopped at a TLC of 3.18 mm was significantly larger ($P < 0.05$) than that of hammered ALF whereas the CS for the two processed forages were not significantly different ($P > 0.05$).

The differences in the effect of treatment combination on the DM, CP and ADF CS, and the deviation of CP and ADF CS from the DM CS were not analyzed due to the confounding effects of the associated changes in DM, CP and ADF MPL. For the particle length distributions of a given forage, the length at which 100 % cumulative weight undersize occurs, is the same for all three nutrient distributions (ie; the length of the longest particle in the sample). Because each distribution has the same endpoint, a decrease in the MPL of a nutrient, due to a higher concentration of the nutrient in the shorter lengths of particles, will result in a smaller CS for that nutrient as compared with the DM CS. Conversely, an increase in the MPL of a nutrient, due to a higher concentration of the nutrient in the longer lengths of particles, will result in a increased CS for that nutrient as compared with the DM CS. Therefore, differences in the effect of forage and method of processing on nutrient CS, and the deviation of nutrient CS from the DM CS, are a function of the difference between the DM and nutrient MPL of each processed forage.

Although it is recognized that the median particle size of processed

forage can have a direct effect on the utilization of forages fed to ruminants, it is still unclear as to what effect the distribution of particle sizes around the median has on forage utilization. Moseley (1984) found that DM intake, disappearance of digestible organic matter from the rumen and dry matter flow in the abomasum were more consistently correlated with the proportion of forage particles passing a 1 mm sieve plus that of soluble dry matter than they were with the geometric mean diameter of the forage. Therefore, differences between forages in the distribution of particle sizes around a common median particle size may have an effect on forage utilization.

The results of this study have shown that for DM, CP and ADF, the CS of different forages processed by the same method may not be similar. Furthermore, different processed forages that have similar MPL may not necessarily have similar CS. Therefore, in the preparation of dietary treatments of processed forage, failure to equalize or otherwise control the differences in CS between treatments, may, as could differences in MPL, introduce uncontrolled experimental error into the results of research in which processed forage is fed.

SUMMARY

The study reported in this chapter was undertaken to determine if similar DM, CP and ADF particle length distributions were produced when different forages were processed by the same method. Alfalfa and high quality and low quality orchardgrass hay were hammered through a 12.7 mm screen and chopped at 3 theoretical lengths of cut (TLC: 3.18, 6.35 and 9.53 mm). The effect of forage type and method of processing on the particle length distribution of the processed forage was determined by comparing the DM, CP and ADF median particle lengths (MPL) and coefficients of spread (CS) of the particle length distributions that were produced.

Different forages that were processed using the same method did not always result in the production of similar DM, CP or ADF MPL, or similar CS. Furthermore, processed forages that did have similar DM MPL, or similar CS, did not always have similar CP and/or ADF MPL, or similar CS. There were also significant differences between the MPL of different nutrients within a given forage. These differences between the MPL of different forages that were processed by the same method, and of different nutrients within a given forage, were of a magnitude that has been shown to significantly affect chewing behavior, rate of passage and digestibility of some forages when fed to ruminants.

CHAPTER III

THE EFFECT OF FORAGE PARTICLE LENGTH AND FORAGE TO CONCENTRATE RATIO ON INTAKE AND CHEWING BEHAVIOR IN DAIRY CATTLE

INTRODUCTION

Voluntary feed intake by ruminants is limited by the rate of digestion and the rate of passage of undigested feed particles from the rumen. The passage of the particles is in turn limited to those particles that have been sufficiently reduced in size, by mastication during eating and rumination, to a size that is capable of passing through the reticulo-omasal orifice. Research has shown, however, that the reduction of the particle size in feedstuffs fed to ruminants (especially forages) decreases the time required for particle size reduction by chewing (Santini et al., 1983) and increases the rate of passage of digesta from the rumen (Rode et al., 1985).

The particle size of a feedstuff, over and above the chemical fiber content of the feed, is also important in providing physical stimulation of normal rumen function. Excessive reduction of particle size has been shown to adversely affect intake by decreasing rate of passage, to reduce fat levels in the milk of lactating dairy cows by altering rumen fermentation, and to promote nutritional disorders such as ruminitis, displaced abomasum and liver abscess. The excessive reduction of particle size is characterized by an almost complete cessation of rumination activity.

Unfortunately, much of the research on the effects of particle size on ruminant digestion and forage utilization has not involved the quantification of particle size in the feedstuffs that were fed. Identification of the quantitative relationship between feedstuff particle

size and parameters of ruminant digestion is required for the maximization of feedstuff utilization and the prevention of nutritional disorders.

The monitoring of chewing behavior is one of the simplest methods for determining the effect of particle size on ruminant digestion. Therefore, using the method described in Chapter 1 for the quantification of forage particle length, the objectives of the following study were to:

1. determine the effect of forage particle length on the chewing behavior of lactating dairy cows when an orchargrass hay, chopped to two different median particle lengths, was fed at two forage to concentrate ratios.

2. determine the relationship between forage particle length and chewing behavior in dairy steers fed a timothy-brome hay chopped to four different median particle lengths.

LITERATURE REVIEW

DIGESTION AND PASSAGE OF FEED PARTICLES IN THE RUMEN

The disappearance of feedstuff from the rumen can be described by the processes of digestion, absorption and removal by passage through the reticulo-omasal orifice. The microbial digestion of feedstuff in the rumen is accomplished by microbial attachment to and chemical degradation of the feed particles in the ration. However, not all components of feedstuffs are degradable by microbial digestion. Researchers using *in vitro* and *in situ* techniques have demonstrated that there exists a "potentially digestible" fraction which is limited in size by the size and composition of the cell wall fraction (Robles *et al.*, 1980). The potentially digestible fraction of feedstuffs generally consists of 90 to 100 % of the cell content fraction, plus varying proportions of the cell wall fraction. Part of the potentially digestible fraction includes a rumen fluid soluble fraction which does not require microbial degradation to leave the rumen. Products of solublization and microbial digestion are either absorbed through the rumen wall, expelled as gases by eructation or passed from the rumen through the reticulo-omasal orifice as part of the fluid fraction of the digesta, or as microbial cells attached to feed particles. In total, disappearance of feedstuff from the rumen due to solublization and microbial digestion can range up to about 70 % under practical feeding conditions.

The undigested or indigestible fraction of ingested feed is removed from the rumen by passage through the reticulo-omasal orifice. Such passage, however, is limited by the size of the particles. Uden and Van Soest (1982) demonstrated that retention time of chromium mordanted fiber particles in

the rumen increased with increasing particle size. Poppi et al. (1980) showed that when particles of digesta attempted to leave the rumen there was an increasing resistance to passage as the size of the particles increase. These researchers found an inflection point in particle size "resistance" to passage curves equivalent to a sieve size of 1.18 mm for sheep. This means that particles capable of passing through a 1.18 mm sieve have a higher probability of passage than do particles that will be retained on a 1.18 mm sieve. They therefore concluded that there existed a critical particle size above which passage may be possible, but that the probability for passage was low. Smith et al. (1983) also supported the 1.18 mm sieve size as being critical for passage in sheep since, in their work, only 0.2% of particles passing to the doudenum would have been retained on a sieve of that size. The researchers also showed that particles of natural logarithim mean size 5.3 (.2mm) passed from the rumen without being reduced in size. Their work, however, was only based on results from one animal. Welch and Smith (1978) measured the passage of four lengths of polypropylene ribbon (0.5, 1.0, 1.5 and 2.0 mm) from the rumen in cattle and three lengths in sheep (0.25, 0.5 and 1.0 mm). The recovery of unchewed particles in the feces was inversely proportional to the length of the particles. The researchers also found, in both species of animals, that the longest lengths would pass from the rumen unchewed. This length fraction, however, only amounted to about 1.0% of those particles placed in the rumen.

The passage of undigested feed residues from the rumen is facilitated by the reduction of particle size by microbial degradation, chewing during eating and ruminating and detrition from reticulo-rumen motility (Reid et al., 1977). Once particles pass from the rumen, there appears to be no further reduction in particle size (Poppi et al., 1980; Smith et al., 1983).

REDUCTION OF FEEDSTUFF PARTICLE SIZE IN THE RUMEN

Microbial Degradation and Detrition in the Rumen

Microbial digestion has been shown to have a direct effect on the reduction of particle size of feedstuffs and an indirect effect by increasing the 'brittleness' of digesta feed particles. Murphy and Nicolleti (1984) incubated coarsely ground alfalfa hay in vitro for 48 hrs and found that although the median particle size did not change, the $\log_{10}$ standard deviation of the particle size distribution increased linearly with time of incubation. This would indicate a uniform chemical degradation of all particle sizes. When the same hay was incubated in situ, there was a 19% reduction in mean particle size after 96 hours of incubation with no change in standard deviation. Welch (1982) incubated 2 cm alfalfa and first and second cut grass hay stems in situ for ten days and observed no apparent change in the physical appearance of the stems other than an increase in the brittleness of the particles. This increase in brittleness may have been responsible for the reduction of particle size seen in situ by Murphy and Nicollet (1984) by making the particles more susceptible to detrition from rumen movement.

Unfortunately, no research has as yet been attempted to quantify the effect of rumen movement on comminution of ingested feedstuffs. Although it has been demonstrated that microbial degradation and detrition from rumen movement contributes directly to particle size reduction in the rumen, it is more likely that the increase in brittleness from microbial digestion increases the effectiveness of particle size reduction by chewing during rumination.

Chewing Behavior

Chewing during eating and rumination is the primary mechanism for the reduction of particle size of undigested and indigestible feed residues in the rumen to a size capable of passing through the reticulo-omasal orifice. The process of chewing during eating involves prehension, mastication, salivation and swallowing. Mastication during eating serves a triple purpose. Firstly, mastication is required for the reduction of particle size which, along with salivation, permits food to be swallowed. Secondly, the reduction in particle size increases the surface area of the ingested particles which enhances microbial attachment and the rate of digestion in the rumen. The salivation which takes place during eating is also important for the maintenance of rumen pH which has a direct effect on the rate of microbial digestion and reticulo-rumen motility. Finally, the reduction of particle size during eating increases the probability of direct passage of newly ingested particles from the rumen.

Considerable reduction in particle size is accomplished by chewing during eating. Reid et al. (1979) fed wethers chaffed alfalfa in which 97% (w/w) DM of the particles offered to the animals were too large to pass through a 1 mm screen. After chewing during eating, 52% of the particles passed through the same screen. Lee and Pearce (1984) found that chewing during eating in steers reduced the proportion of particles retained on a 1 mm screen by 30 to 40 percent. In terms of Modulus of Fineness, particle size of ingested feed was reduced by 46 to 52 percent. There is, however, a great variation in the extent to which animals reduce particle size during eating (Lee and Pearce, 1984; Gill et al, 1966).

It appears that the extent of comminution required during eating may be limited to that required for bolus formation and lubrication prior to

swallowing. Welch and Smith (1978) found that 99% of one centimeter long particles of polypropylene ribbon were recovered unchewed in the rumen of a fistulated steer fed a mixture of the ribbon and concentrates. Balch (1958) found that the rate of feed ingestion, weight of saliva produced and rate of salivation during eating were not consistent with all types of feedstuffs. Hay, which had a larger particle size and a higher level of fiber, was consumed at a faster rate than was concentrate. Swallowed boluses of hay contained 12-16% dry matter whereas those of coarsely ground concentrates contained 35-40% dry matter. Calculations revealed that 3-4 times the amount of saliva was secreted per unit weight of hay consumed as compared with concentrates. On the other hand, the rate of saliva secretion was approximately doubled when the animals were fed concentrates. The differences in bolus dry matter content was caused by a more rapid ingestion rate of the concentrates as compared with that of hay. Therefore, initial particle size and resistance to particle size reduction may have a regulating effect on eating rate.

Although, the amount of comminution occurring during eating may be limited to that required to enable swallowing, the reduction of particle size during eating directly enhances the passage of particles from the rumen. Baily and Balch (1961) studied the effect of chewing during eating on the removal of particulate matter from the rumen by comparing the rumination times of a cow fed hay normally, or by placement of hay directly into the rumen through a fistula. Time spent ruminating was increased by close to 50% with "fistula feeding". These results were supported by Bae et al. (1981) who found that decreased time spent eating per kg of cell wall intake was associated with increased time spent ruminating.

Particle size reduction and salivation from chewing during rumination,

as with eating, is important for enhancing microbial digestion. However, chewing during rumination is the final and most important mechanism for the reduction of particle size enabling passage from the rumen through the reticulo-omasal orifice.

The essentiality of rumination for the passage of undigested particles has been classically demonstrated by the prevention of rumination by muzzling in sheep. Pearce and Moir (1964) found that prevention of rumination increased retention times and subsequently increased DM, OM and crude fiber apparent digestibilities. However, muzzling did not completely inhibit particulate passage from the rumen, which lead the researchers to conclude that microbial digestion must account for a substantial degree of particle size reduction. Unfortunately, complete prevention of rumination was not accomplished by the muzzles which meant that the effect of the prevention of rumination may have been underestimated. Welch (1982) accomplished complete prevention of rumination using steers. At each feeding, the animals had access to hay for 2 hours after which they were muzzled until the next feeding period. Intake of hay was markedly reduced by muzzling. Towards the end of the feeding periods, the muzzled animals preferred to ruminate rather than eat. In another trial, the researcher had animals die of esophageal and pharynx impaction when the animals attempted to ruminate while muzzled.

Therefore, factors that affect the disappearance of feedstuff from the rumen, either by affecting digestibility or rate of passage through the reticulo-omasal orifice, also affect the chewing behavior of the animal. For this reason, Balch (1971) proposed the use of the total time spent chewing (eating plus rumination) as an index of the fibrousness of feedstuffs fed to ruminants.

FACTORS AFFECTING CHEWING BEHAVIOR

Feedstuff Particle Size

The reduction of particle size in feedstuffs fed to ruminants has an effect on the rate of feed ingestion, rate and extent of microbial digestion, chewing behavior and rate of passage of digesta particles from the rumen. A change in the rate of passage of particles from the rumen in turn has an effect on the site of feedstuff digestion in the gastro-intestinal tract.

It is well documented that the reduction of particle size of feedstuffs can be associated with an increase in voluntary intake (Weston and Kennedy, 1984). This effect, however, has been shown not to be consistent for all species and maturities of forage. For example, Campling et al. (1963) and Campling and Freer (1966) found that coarse grinding of an artificially dried grass hay or a medium quality ryegrass hay did not significantly affect intake. However, Campling and Freer (1966) found that grinding and pelleting oat straw increased intake by 26% compared with feeding in the long form. Lee and Pearce (1984) found significant correlations between the intake of some feeds and the modulus of fineness and percent of particles retained on a 1 mm screen. This correlation, however, was not significant for all feeds tested. In general, the effect of particle size reduction on increasing intake appears to have little effect with high quality forages and concentrates and an increasing effect when the fibrousness of the feed increases (Weston and Kennedy, 1984).

The reduction of particle size of forages fed to ruminants appears to exert its greatest effect by increasing the rate of passage of digesta particles from the rumen. Campling and Freer (1966) found that grinding of

ryegrass hay did not significantly increase voluntary feed intake but significantly decreased the retention time of stained particles in the rumen. The reduction in retention time was also associated with a considerable reduction in the extent of digestion. In the same study, grinding of oat straw also significantly reduced the retention time of particles in the rumen and the digestibility of the forage. The reduction in digestibility was, however, not as pronounced as with the hay diet. This difference may have been due to the smaller size of the potentially digestible fraction that is normally found in straws as compared with that found in grass hays.

The effect of feedstuff particle size on the process of digestion in ruminants has been shown to be reflected in the chewing behavior of the animals. As early as 1935, Kick and Gerlaugh (1935) showed that reducing the particle size of good quality alfalfa hay by chopping and grinding reduced the amount of time steers spent eating and ruminating and was associated with a decreased retention time of digesta in the rumen. This effect, however, was not consistent over all treatments. There was no significant difference in the amount of time spent chewing between a hay fed in the long form and that chopped to an estimated median length of 24.7 mm. The amount of time spent chewing declined when the forage was chopped to approximately 6.4 mm in length and then declined further when the forage was ground. The feeding of ground hay also caused a marked amount of pseudo-rumination which indicated that the forage had lost its ability to stimulate normal rumination activity.

Since the work of Kick and Gerlaugh (1935), the majority of the research on the effect of particle size on chewing behavior has predominantly used qualitative treatments involving the feeding of forage in the long, coarsely

chopped and ground form or just the long and ground forms. The results of this research have in general supported the research of Kick and Gerlaugh (1935) in that there appears to be no significant reduction in the amount of time spent chewing when forage is coarsely chopped as compared with feeding in the long form (eg. Kick et al., 1937; Gordon, 1958) and that grinding significantly reduces both the amount of time spent eating and ruminating (Kick et al., 1937; Balch, 1952; Gordon, 1958; Freer and Campling, 1965; Campling and Freer, 1966).In many cases the fine grinding of forages has led to an almost complete ceassation of normal rumination activity and a marked occurrence of pseudo-rumination.

Therefore, the particle size of feedstuffs is important in stimulating normal rumination activity. The need for physical stimulation of the rumen wall by digesta particles in promoting normal rumination has been classically demonstrated. Balch (1952) restored normal rumination activity in a cow fed ground hay by placing a bristle brush in the reticulum of the animal. Welch (1982) found a large reduction in normal rumination activity when lactating cows were fed alfalfa meal pellets and concentrates. Normal rumination activity was restored when 200 grams of polypropylene ribbon was introduced into the diet. Balch (1952) found that although grinding of forage did not always inhibit the triple contraction of the reticulum seen during normal rumination, the lack of physical stimulus of the rumen wall caused by grinding inhibited the regurgitation reflex required for normal rumination. The same lack of stimulus has also been seen when diets predominantly comprised of concentrates have been fed. (Freer and Campling, 1965).

Level of Intake

As discussed above, most feedstuffs contain a fraction that is not potentially digestible in the rumen. Therefore, as intake increases, the amount of indigestible material that must be cleared from the rumen also increases. Subsequently, increased intake results in an increase in time animals spend eating and ruminating. The relationship between intake and time spent eating and ruminating, however, is not constant.

Welch and Smith (1969b) studied the effect of increasing hay intake on the rumination time in sheep previously fasted for 48 hours. A 100% increase in hay intake, from 500 to 1000 grams fed as a single meal, increased the time the animals spent ruminating by only 67%. Increasing single meal intake from 250 to 1000 grams in 250 gram intervals gave a statistically significant linear increase in rumination time. However, the incremental increase between the 750 and 1000 gram intakes was about one half the difference between the lower intake levels. When the increments between intake levels remained the same but intakes ranged from 250 grams to a maximum of 1800 grams per day, and the animals were fed continuously, there was a non-linear increase in rumination time with increased intake; the amount of rumination per kg of intake subsequently decreased as intake increased. Bae et al. (1981) also found that rumination time per kg intake decreased with increasing level of intake when dry Holstein cows were fed hay at 50, 75, 100, and 125 % of daily NRC recommended dry matter intake and results were expressed as chewing time per kg of cell wall intake. However, at the higher levels of intake the cows significantly increased their chewing rate during rumination which may have compensated for the reduction in time spent ruminating. The researchers also found that eating time per kg of cell wall intake increased with increasing intake. Subsequently the total

time chewing per kg cell wall intake did not differ significantly with level of intake. Bae et al. (1981) concluded that their results indicated that ingested roughages required a constant amount of comminution by the combined action of eating and rumination.

The increase in time spent chewing during eating, per kg of intake, with increased levels of intake may be due to a decrease in intake and an increase in chewing activity per bolus swallowed towards the end of a meal. Gill et al. (1966) studied the eating behavior and particle size of swallowed hay in dairy cattle fed at two levels of intake. As intake increased from 5 to 7.5 kg per day, there was an increase in the time spent eating from 15.4 to 18.3 min per kg of intake. Increasing the amount of feed offered per meal did not significantly affect the chewing rate per minute but increased the number of chews per bolus swallowed. The researchers also found that with both levels of intake, the number of chews per bolus increased and the rate of bolus swallowing decreased as the meal progressed. Gill et al. (1966) also found that a higher number of chews per bolus swallowed during eating was associated with a reduced mean particle size in the swallowed boluses.

Therefore, increasing the level of intake increases the amount of time required to consume the feed while the increased number of chews per bolus swallowed and decreased rate of swallowing as a meal progresses causes an increase in eating time per kg of intake. However, the greater reduction in particle size associated with increased time spent eating results in a decreased requirement for time spent ruminating per kg of intake as the level of intake increases. Due to the effects of changes in intake level on chewing behavior described above, results from experiments, where intake levels between animals are not equal, must be analyzed on the basis of the

total amount of chewing activity that occurs per kg of intake.

Chemical Composition of Feedstuff

The amount of time animals spend ruminating is related to the amount of undigested feed residue in the rumen. Welch and Smith (1968) found that immediately after the removal of feed from sheep being fasted there was a rapid decline in rumination activity which fell to zero after 36 hours. Examination of rumen contents of a sacrificed sheep showed that the rumen contents contained insufficient fibrous constituents required for stimulation of rumination. Upon refeeding, normal rumination commenced within 24 hours. Therefore any factor directly affecting the digestibility of feedstuffs in the rumen will have a direct effect on the amount of time spent ruminating.

The chemical composition and the size of the potentially digestible fraction of feedstuffs has been shown to be the most important factor determining the rate of digesta disappearance from the rumen (Fonnesbeck et al., 1981). Since the cell contents of feedstuff approach 100% digestibility (Fonnesbeck et al., 1981), the size and composition of the fiber fraction appear to control the level of undigested residues in the rumen and, therefore, has an effect on the amount of time an animal spends ruminating.

Robles et al. (1981) fed mature wethers orchardgrass hay which varied in cell wall content from 60 to 78 percent. These researchers found that as cell wall concentration increased, DM and DE intake, and DM digestibility and excretion rate decreased while cell wall intake, rumen volume and rumen cell wall content and retention time increased significantly. They also found that on different diets, the animals ate to a constant indigestible cell wall intake. An increase in cell wall intake and increased retention

time with feedstuffs of increasing cell wall content has been shown to increase amount of time spent ruminating. Welch and Smith (1969a) fed sheep early-cut orchardgrass hay, late cut mixed grass hay, weedy oat straw, 2nd cut mixed alfalfa grass hay, and oat straw containing 22.8, 8.0, 7.3, 17.8 and 5.4 percent crude protein and 27.1, 36.4, 39.2, 28.3, and 42.9 percent crude fiber respectively. They found that the simple correlation between rumination time and forage cell wall intake was 0.99 whereas the simple correlation between rumination time and crude protein intake was only 0.24. Therefore, as the digestibility of a ration is increased, the amount of residue remaining to be cleared from the rumen decreases which has a direct effect on reducing the amount of time spent ruminating.

The fibrousness of feedstuffs may also have an effect on the eating behavior in ruminants. Freer et al. (1962) found that Friesian and Shorthorn cattle required more time to eat oat straw than they did to eat hay. Balch (1971) also found that less fibrous feedstuffs required significantly less time to be consumed by cattle than did higher fiber feeds. Lee and Pearce (1984) demonstrated that different forages required different grinding energies to produce the same modulus of fineness and that grinding energy was related to the ADF content of the forage. If swallowing is limited by a maximum particle size, feedstuffs that are more resistant to comminution would require longer chewing times during eating.

The moisture content of feedstuffs may also have an effect on eating behavior. Gill et al (1966) found that although there was no significant difference in eating time per kg DM intake, there was a significant increase in the number of chews per minute, and a significant decrease in the number of chews per bolus swallowed during eating when fresh herbage was fed to cattle as compared with the feeding of the forage as a hay. Feeding of fresh

cut herbage also increased the rate of bolus swallowing and the wet weight of the boli. The dry weights of the boli from the two diets, however, were not significantly different. These reaserchers also found that when mature ryegrass was fed in the fresh form, as opposed to a hay, the median particle size of the swallowed boli increased from 1314 um to 2070 um and the particle size of the boli did not decrease as the meal progressed as it did when the hay was fed.

Forage to Concentrate Ratio

It has been shown that an increase in the forage to concentrate ratio in a ration is associated with an increase in the amount of time ruminants spend chewing during eating and ruminating (Balch, 1958; Sudweeks et al., 1975). Concentrates generally contain less fiber than do forages. Therefore, an increase in the forage to concentrate ratio of a ration results in an increase in fiber intake and the level of indigestible residues in the rumen. As discussed above, such an increase in the fiber content of rations normally causes an increase in the amount of time the animals spend eating and ruminating. The particle size of concentrates also tends to be smaller than that of most forages. As the proportion of forage in the diet increases, the particle size of the diet increases and, therefore, the requirement for comminution of particles by chewing during eating and rumination also increases. The lower requirement for comminution of concentrates is reflected in the higher rate of passage of concentrates from the rumen as compared with that of forages (Rode et al., 1985).

The proportion of concentrates in a ration also has an effect on the eating behavior of ruminants. Balch (1958) found that when animals ate concentrates the recordings had a wavy appearance indicating the mouth was

not opened wide; hay eating gave a more regular pattern with a level baseline. The rate of jaw movements when eating concentrates was also somewhat higher (88-90 per min) than that for hay (72-82 per min). These chewing rates did not significantly change during the course of a meal.

Particle Density

The specific gravity of particles in the rumen appears to have a direct effect on the selection of particles for rumination and passage from the rumen. Evans et al. (1973) found that in cattle fed pasture hay, rumination commenced at the time of maximum concentration of low density particles and minimum concentration of high density particles in the rumen. Rumination activity then ceased at the point where the concentration of high density particles was maximum and low density particles were at a minimum concentration in the rumen. Since the increase in specific gravity of feed particles in the rumen is likely a result of microbial digestion and hydration of feed particles (Hooper and Welch, 1985) it is possible that differences in the rate of change of the specific gravity of different feeds will have an effect on the time after feeding that rumination commences. Welch and Smith (1969a) found that the peak rumination time in sheep fed diets of varying nutritional composition occured at different times depending on the diet fed.

Passage from the rumen, once particle size is sufficiently reduced, appears to be fastest for particles with specific gravities in the range of 1.1 to 1.2 (King and Moore, 1957; Campling and Freer, 1962). Hooper and Welch (1985) found that the specific gravity of forages increased at a greater rate when immersed in rumen fluid than it did when the forage was immersed in water. These researchers also found that forage particles in

buffer solution increased in specific gravity at a faster rate than did particles in water. Thomson et al. (1977) found that the addition of salivary salts to the rumen increased the liquid dilution rate. Therefore, salivation during rumination may increase the specific gravity of comminuted particles and increase the rate of passage of these particles.

It is not known, however, whether the specific gravity of feedstuffs will affect the amount of comminution particles will require before passage is possible. It is likely that the specific gravity of feedstuffs will have its greatest effect on the passage of particles already reduced to a size capable of passing through the reticulo-omasal orifice. Therefore, the specific gravity of feedstuffs would probability exert a greater effect on rumen fill and the level of intake rather than on the amount of time animals spend ruminating.

Body Weight

Bae et al. (1983) found that chewing time per kg of cell wall intake in different breeds of dairy cattle significantly decreased with increasing metabolic body weight; differences in body weight accounted for 52% of the variability in time spent chewing between animals. Differences in cell wall intake between animals accounted for an additional 22% of variability. Breed of animal did not significantly affect chewing time over and above the effect of body size. There was also no correlation between body size and speed of chewing. Lea and Pearce (1984) hypothesized that anatomical differences in the animal in mouth size, jaw movement, teeth area and grinding action may account for differences in particle size reduction of ingested feed.

METHODS OF MONITORING CHEWING BEHAVIOR

As with most behavioral studies, the most complete information on animal chewing behavior is obtainable by visual observation and recording. Unfortunately, the amount of information required in chewing studies, including total times of different behaviors and the counting of individual chews, makes this task almost impossible to be accomplished by the visual observation of even one animal at a time. Since many of the experiments being designed today to study the effects of various dietary treatments on chewing behavior require simultaneous observation of a number of animals, the manpower requirements and the cost of that labor prohibit the use of visual observation (Penning, 1983). Furthermore, visual observation of chewing behavior can become tedious and tiring, resulting in errors and inaccuracies in the recorded information (Castle et al., 1975). To overcome the difficulties of visual observation, a number of automated methods have been developed to record the jaw movements of animals. The accurate observation of chewing behavior requires the development and use of one of these methods since none are commercially available. Any method that is developed should ideally satisfy the following criteria:

1: be accurate in the recording of chewing activity, making it possible to distiguish between chewing activity involved in eating and rumination and non-chewing activity such as drinking, licking, and bawling.

2: require a minimum of labor and/or supervision during recording and analysis of data.

3: be easily interchangeable between animals and very resistant to damage by animal activity and other operational failure.

4: be easily constructed at a minimum of expense.

5: be adaptable to telemetry or other remote recording to enable observation of grazing and eating in all forms of animal confinement and housing.

6: be adaptable to electronic analysis of recorded data by data loggers and computers.

The earliest method of automatic chewing montitoring utilized an expandable rubber tube which was placed under the jaw or over the nose of the animal (Johnstone-Wallace, 1953; Oltjen et al., 1962). The expandable tube was then connected via another tube to a pressure tambour on which a pen was mounted. Jaw movements by the animal would stretch the rubber tube which was placed around the jaw causing an increase in pressure in the closed system which in turn moved the recording pen. Balch (1971) designed a similar system but used a lightly inflated tube made from thin walled rubber tubing supported on a perforated brass tube to prevent problems of kinking. This device was used both to monitor jaw movement when placed beneath the cheek strap of a leather head stall and reticulo-rumen motility when anchored in the rumen. Activity increased the pressure in the closed system by decreasing the volume of the device, similar to the sqeezing of a balloon. Pressure changes were recorded by movement of the tambour pen on a moving chart recorder. Although the above systems have been used

successfully, they suffer from the need for animals to be partially restrained to prevent kinking of the tube which connects the jaw pneumatic device to the tambour, and from temperature changes which also alter pressure in the system thus rendering it non-functional.

The problems with the above system have been overcome with the use of pressure transducers which eliminate the need for a connecting length of tube (Law and Sudweeks, 1975). Pressure impulses from a pneumatic device are converted to electrical impulses which can be recorded on an electronic moving chart recorder. These researchers found that their system operated with less than 1/2 percent error over the range of 1/4 to 16 impulses per second. The use of electronic transducers also enables remote recording of chewing activity on tape by radio telemetry.

Grazing behavior has been studied using Vibricorders which record movement by the motion of a pendulum which is recorded on a circular disk of paper by a pen attached to the pendulum (Castle et al., 1975). This system alone, however, can only discern animal motion associated with body movement during grazing. Ruckebush and Bueno (1973) (cattle) and Bechet (1978) (sheep) removed the pendulum from a Vibricorder and adapted a pneumatic control to the pen which received impulses from a rubber bulb situated in the submandibular space of the grazing animal. This latter method improved the accuracy of recording with Vibricorders, increased the amount of information recorded and did not require the use of expensive telemetry when used with grazing animals.

Another form of transducer recorder has been employed which completely removes the need for pneumatics. Leveille et al. (1979) developed a variable induction gauge by winding copper wire around a length of tube, flattening the tube and wire, and covering the assembly with a polymer to

protect it. The transducer was mounted around the nose band on sheep similar to the mounting of pneumatic tubes. Electrical impulses caused by changes in resistance in the transducer due to jaw movement were interpreted by a data logger and analyzed by computer. Penning (1983) developed an almost identical system except that the transducer was made by packing a silicon tube with carbon granules and implanting electrodes at each end. The transducer was mounted in a similar manner with the impulses recorded on tape and later analyzed by a microprocessor.

Chewing behavior has also been recorded without the need for pneumatics using various forms of microswithches (Duckworth and Shirlaw, 1955; Stobbs and Cowper, 1972; Chambers et al., 1981). These types of "event recorders" are mounted directly under the jaw and activated by direct pressure or mounted on a halter and activated by a chain or rope slung under the jaw of the animal. Microswitch impulses, however, record only a single fixed amplitude stroke when the jaw of the animal opens far enough to activate the switch. Therefore, the adjustment of this type of system is critical; damage to the microswitch can also be a major problem (P.M. Kennedy, personal communication). This method also gives no information on the amplitude of the jaw movements which are important in identifying many non chewing activities such as bawling, licking and drinking. Both the inclusion of these activities as chewing and any damage to the microswitch could introduce considerable error.

Two methods for direct measurement of jaw movement and chewing behavior have been developed. Nichols (1966) attached special electrodes to the masseter muscles of sheep. Changes in the electrical potential received from the skin over the muscles were amplified by a transmitter which relayed the signals to a receiver which recorded the signals on an electric chart

recorder. Kydd and Mullins (1963) developed a method for fitting a very small pressure transducer to a tooth and connecting it to a transmitter embedded in a tooth borne partial denture. This method would have a great advantage in that the actual grinding energy and chewing activity could be measured directly. However, use of both of the above methods on a large scale is limited by the difficulty of fitting the transducers, the lack of easy interchangeability between animals and the cost of animal preparation.

MATERIALS AND METHODS

DAIRY COW TRIAL

Twelve Holstein dairy cows, all in mid lactation, were randomly allotted to four dietary treatments in a balanced two period changeover design (Gill and Magee, 1976). Each animal received two of the four treatments during the experiment. The dietary treatments comprised good quality orchardgrass hay chopped to two different median particle lengths (10 mm and 20 mm) fed at two forage to concentrate ratios (40:60 and 60:40) in a two by two factorial arrangement; the cows were fed ad libitum in two meals per day. Each four week experimental period consisted of three weeks adaptation followed by one week of sample collection.

During the adaptation period, the cows were housed with the rest of the herd in a free stall barn but fed individually using electronically activated doors. At the beginning of the sampling period, six of the cows on trial were transferred to the research area for electronic monitoring of chewing behavior (see Figure 14). The animals were adapted to stanchions for 24 hours after which chewing behavior was monitored continuously for 24 hours. The cows were then returned to the free stall barn for the next adaptation period and the second group of six cows was transferred to the research area. Chewing monitoring commenced immediately following the afternoon milking and terminated just prior to the next afternoon milking. During the early morning of each monitoring period, it was necessary for the cows to be released from the stanchions to permit parlor milking. Any chewing activity that occurred during that time was monitored visually. During the sampling period, milk, rumen fluid, and fecal samples were also

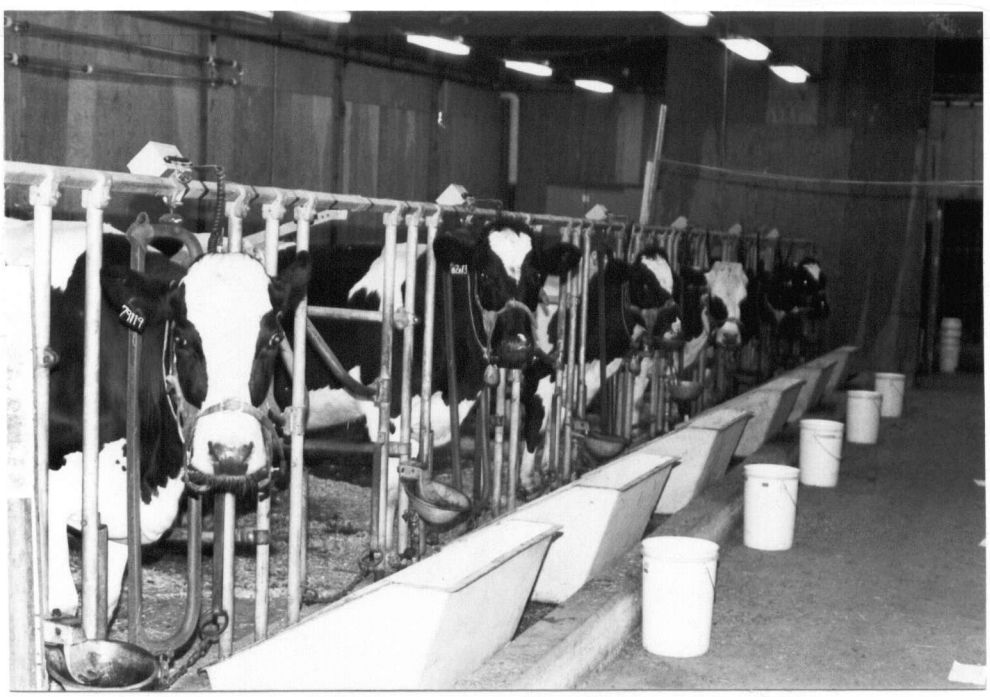

FIGURE 14: Dairy cattle in stanchion stalls in research area during the monitoring of chewing behavior.

taken to be analyzed in relation to objectives of another trial.

DAIRY STEER TRIAL

Three Holstein steers initially weighing 845, 947 and 927 kg and one Ayrshire steer weighing 776 kg were randomly allocated to four dietary treatments in a balanced Latin Square design. Each animal had been surgically prepared with rumen and duodenal cannulae for the taking of samples to be analyzed in relation to other objectives of the trial. The dietary treatments consisted of timothy-brome hay chopped to four different median particle lengths (5.0, 10.0, 15.0, and 20.0 mm) which were fed in a 60:40 forage to concentrate ratio at 9.5 kg per 100 kg of metabolic body weight per day. The rations were fed in four equal allotments during the day at 6 hour intervals, starting at 9:00 AM. Each experimental period was 21 days in length with 14 days for diet adaptation followed by 7 days of sample collection during which chewing behavior was monitored. The steers were housed in stanchions in the research area described above for the duration of the experiment with the exception of the first 10 days of adaptation in the first two periods during which the steers were housed unrestrained in individual pens. Chewing monitoring commenced immediately prior to the 3:00 PM feeding on the morning of the second sampling day and ran continuously for 48 hours.

PREPARATION OF CHOPPED FORAGE

All the forage that was fed in the two experiments above was chopped with either a John Deere Model 35 or a Fox forage harvester. The forage was

obtained in standard two strand or three wire square bales which were randomly allocated into dietary treatments prior to chopping. Randomly selected test bales were chopped, using various machine settings, into an open fronted bin. Each test sample of chopped hay was then subsampled and separated on the Forage Particle Separator (see Chapter 1) to determine the median particle length. Appropriate machine settings were then selected to prepare chopped forage of the required median particle lengths for use as dietary treatments in the experiments.

MONITORING OF CHEWING BEHAVIOR

The development of a chewing monitor system was required to enable continuous monitoring of the chewing behavior of the animals on trial. This system was installed in a separate research facility in which the animals on trial were held in individual stanchions (Figure 14).

The system consisted of a pneumatic device (Figure 15) which was held in place under the jaw of the animal by a specially designed halter (Figure 16). The halters were adjustable in three places (over the nose, behind the pohl, and under the neck) to enable correct positioning of the pneumatic device. Pressure impulses generated by jaw movements were transmitted via a length of tygon tubing to a "silicon chip" electronic pressure transducer (Figure 17) mounted between the ears of the animal on the pohl strap of the halter (Figure 16). Equilibration of static pressure in the closed pneumatic system was achieved by activation of the air valve mounted on the right hand side of the pneumatic device.

The pressure transducer was connected via a quick coupler electrical connector and an expandable cord to an amplifier which was mounted on the

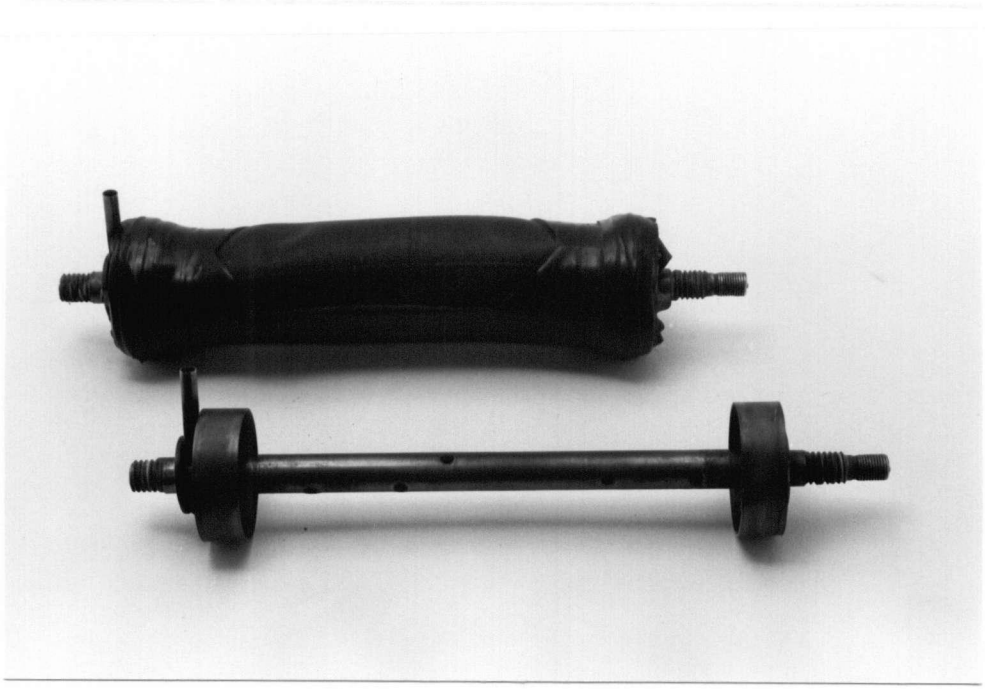

FIGURE 15: Pneumatic device of the chewing monitor for producing pressure impulses from jaw movement.

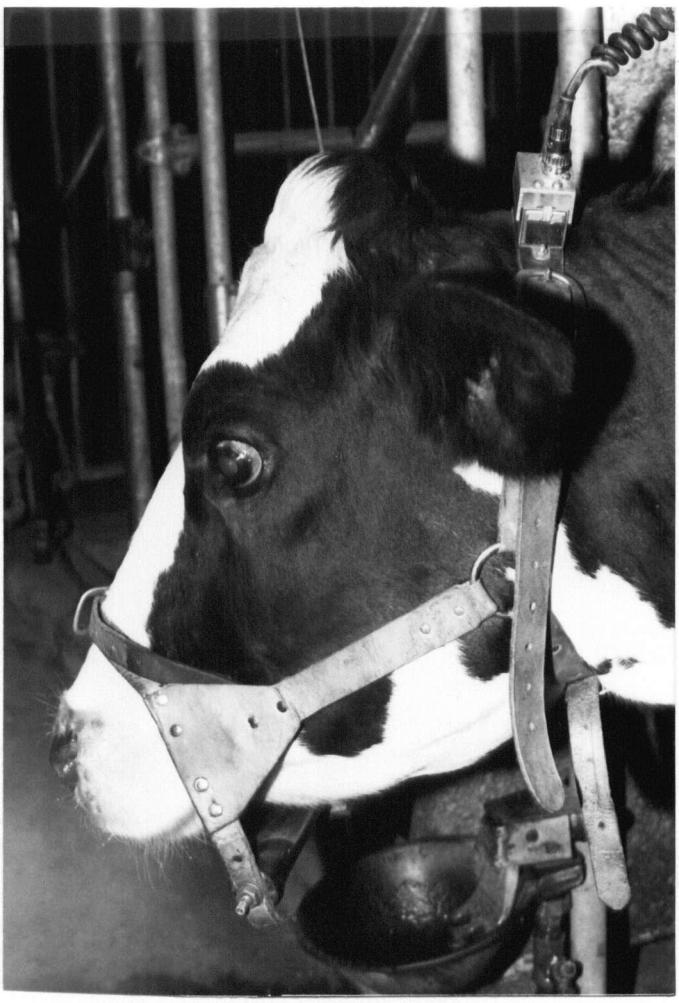

FIGURE 16: Chewing monitor halter with pneumatic device and pressure transducer mounted.

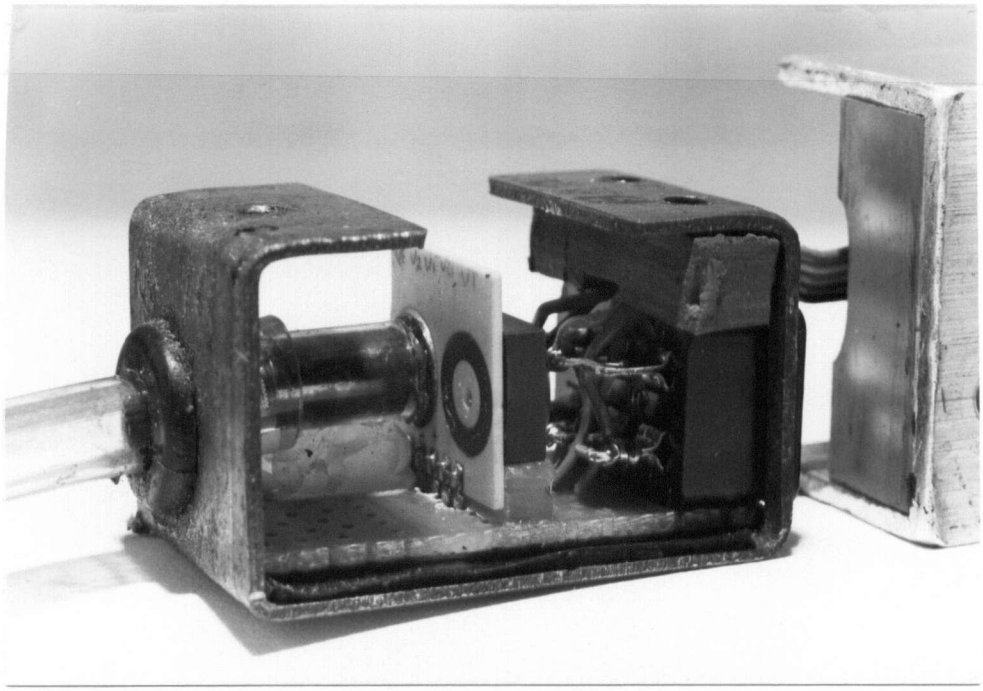

FIGURE 17: Chewing monitor "silicon chip" pressure transducer mounted in its steel housing.

stanchion support directly above the animal's head. This method of connection allowed unrestricted movement of the animal's head and easy disconnection to release the animals to go to the milking parlor. The amplifier was "hard-wired" to a special power supply and to a variable speed chart recorder on which output tracing were recorded. Both the amplifier and power supply were designed and constructed by Gilles Galzy, Senior Technician of the Department of Animal Science, University of British Columbia.

During the monitoring of chewing behavior, animal activity was also visually monitored using closed circuit video equipment. Tracings recorded on the chart recorder were simultaneously compared with the animal activity seen on the video monitors to ensure accurate recording of chewing behavior.

ANALYSIS OF CHEWING RESULTS

During each chewing monitoring period, each one hour segment of recorded data was collated into total times spent eating and ruminating. The remaining time was classified as idling, which included time spent drinking, bawling, and grooming, all of which were discernable from the tracings. The number of boluses that were regurgitated during periods of rumination were also calculated from the tracings. The chewing activities for each hour of recording were then totalled for the entire recording period and expressed as total time per 24 hours. These times were then divided by the dry matter intake for each animal to give the time spent chewing and idling per kilogram of intake as was suggested by Balch (1971) as an index of the fibrousness of feedstuffs. Time chewing per bolus regurgitated was calculated by dividing the total time spent ruminating by the number of

boluses regurgitated during a twenty four hour period.

STATISTICAL ANALYSIS

The effect of forage particle length and forage to concentrate ratio on parameters of chewing behavior was tested by General Linear Hypothesis using the BMD:10V packaged program of the University of British Columbia. Yield variables were expressed as chewing activity per kg of DM intake with metabolic body weight ($BW^{\cdot 75}$) included in the analysis as a covariable. Differences between means for the treatment combinations were tested by Duncan's Multiple Range Test ($\alpha = 0.05$).

The General Linear Hypothesis for the Dairy cow trial was as follows:

$$Y_{ijklm} = u + A_i + P_j + L_k + H_l + LH_{kl} + bBW_{ijklm} + E_{ijklm}$$

where: Y_{ijklm} = the dependent variable: chewing parameters.

u = the overall mean

A_i = the effect of the i'th animal.

P_j = the effect of the j'th period.

L_k = the effect of the k'th forage median particle length.

H_l = the effect of the l'th forage:concentrate ratio.

LH_{kl} = the effect of the interaction between the k'th forage median particle length and the l'th forage to concentrate ratio.

bBW_{ijklm} = the effect of the covariable metabolic body weight

E_{ijklm} = the unexplained residual error associated with each sample.

The General Linear Hypothesis for the Dairy Steer trial was as follows:

$$Y_{ijk} = u + A_i + P_j + L_k + bBW_{ijk} + E_{ijk}$$

where: Y_{ijk} = the dependent variable: chewing parameter.

u = the overall mean.

A_i = the effect of the i'th animal.

P_j = the effect of the j'th period.

L_k = the effect of the k'th forage median particle length.

bBW_{ijk} = the effect of the covariable metabolic body weight.

E_{ijk} = the unexplained residual error associated with each sample.

RESULTS

DAIRY COW TRIAL

The particle length distributions of the two median chop lengths of forage fed in this experiment are shown in Table XXI. The median particle length (MPL) of the short chopped forage was 7.32 mm which was significantly smaller ($P < 0.05$) than that of the long chopped forage which had a median particle length of 18.06 mm. The coefficient of spread (CS) of the short chop forage (1.284) was also significantly smaller than that for the long chop (1.488). The higher CS for the long chop indicated that it had a relatively narrower distribution of particle lengths which were also more normally distributed.

There was no significant difference ($P > 0.05$) in nutritional

TABLE XXI: Particle length distribution (% sample wt.) and distribuion parameters of the short and long chopped orchardgrass hay.

PARTICLE LENGTH		FORAGE SHORT	FORAGE LONG
<3.30 mm		23.6	9.5
3.30- 8.25 mm		29.9	9.0
8.25-16.50 mm		34.0	25.5
16.50-33.00 mm		11.7	38.8
33.00-66.00 mm		0.8	15.1
>66.00 mm		0.0	2.1
MEDIAN LENGTH:		7.3 mm[a]	18.1 mm[b]
COEFFICIENT OF SPREAD:		1.284[a]	1.488[b]
WEIBULL PARAMETERS:	B	0.136678	0.055357
	C	1.283979	1.487754

[a-b] Median lengths and coefficients of spread with different superscripts were significantly different ($P < 0.05$).

TABLE XXII: Nutrient content (%, DM basis) of the concentrate and short and long chopped orchardgrass hay used in the experiment.

	CONCENTRATE	HAY	
		SHORT	LONG
DM	86.5	88.1	86.7
CP	14.9	14.6	14.0
NDF	--	68.5	68.5
ADF	11.0[a]	38.9[b]	38.3[b]

[a-b] Means within rows with different superscripts were significantly different ($P < 0.05$).

composition between the two chop lengths of forage (Table XXII). There was, however, a significant difference ($P < 0.05$) in acid detergent fiber (ADF) content between the forage and concentrate, but no significant difference ($P > 0.05$) in dry matter and crude protein content. The two forage to concentrate ratio treatments therefore also had significantly different ADF contents ($P < 0.05$).

Throughout the statistical analysis of this experiment the effect of the covariable ($BW^{\cdot 75}$) was not significant ($P > 0.05$) indicating that the metabolic weight of the animals did not have a significant effect on chewing behavior in this experiment. There was also no significant ($P > 0.05$) animal effect, except on time spent chewing per bolus regurgitated during rumination. Subsequently, the covariable and, where appropriate, the animal effect were removed from the General Linear Hypothesis for the analysis of this trial. The partitioning of sums of squares by the reduced General Linear Hypothesis model for each yield variable is given in Appendix A.

Decreasing the MPL of the forage being fed did not significantly affect ($P > 0.05$) the intake or chewing time of the animals (Table XXIII). There was a consistent trend, however, towards increased idle time and decreased time spent eating and ruminating when the MPL of the forage was decreased.

TABLE XXIII: Effect of forage median particle length on intake and chewing characteristics.

	MEDIAN PARTICLE LENGTH (mm)		
	7.3	18.1	SEM
INTAKE (kg, DM):			
Hay	10.1	10.1	0.1
Conc.	10.2	10.3	0.1
Total	20.3	20.4	0.3
CHEWING TIME (min/kg intake):			
Idling	33.0	29.2	1.7
Eating	10.9	12.1	0.7
Rumination	17.9	19.4	0.8
Total Chewing	28.8	31.4	1.3
RUMINATION CHARACTERISTICS:			
# Boli / kg intake	17.6	19.7	1.0
Time chewing / Bolus (min)	1.00	0.97	0.01

TABLE XXIV: Effect of forage to concentrate ratio on intake and chewing characteristics.

	FORAGE:CONCENTRATE RATIO		
	40:60	60:40	SEM
INTAKE: (kg, DM)			
Hay	8.5^{a}	11.7^{b}	0.1
Conc.	12.7^{b}	7.8^{a}	0.1
Total	21.2^{b}	19.6^{a}	0.3
CHEWING TIME: (min/kg intake)			
Idling	32.4	29.7	1.7
Eating	9.7^{a}	13.2^{b}	0.7
Rumination	16.6^{a}	20.7^{b}	0.8
Total Chewing	26.3^{a}	33.9^{b}	1.3
RUMINATION CHARACTERISTICS:			
# Boli / kg intake	16.0^{a}	21.3^{b}	1.0
Time chewing / Bolus (min)	0.99	0.98	0.01

$^{a-b}$ Mean values within rows having different superscripts were significantly different ($P < 0.05$).

Increasing the proportion of forage and, therefore, the proportion of fibre in the diet significantly decreased ($P < 0.05$) voluntary intake and significantly increased ($P < 0.05$) the amount of time the animals spent eating and ruminating per kg of DM ingested (Table XXIV). There was therefore also a significant cumulative effect ($P < 0.05$) of time spent eating and ruminating on increasing the total time spent chewing per kg of feed ingested as the proportion of forage in the diet increased. Although increasing the proportion of hay ingested did not significantly affect ($P > 0.05$) the amount of time spent idle there was a trend towards reduced idle time.

During rumination, increasing the proportion of forage in the diet significantly increased ($P < 0.05$) the number of boli regurgitated per kg of feed ingested but did not significantly affect ($P > 0.05$) the time spent

TABLE XXV: Effect of forage to concentrate ratio and forage median particle length (mm) on intake and chewing characteristics.

	DIETARY TREATMENTS				
FORAGE:CONCENTRATE RATIO	40:60		60:40		
MEDIAN PARTICLE LENGTH	7.3	18.1	7.3	18.1	SEM
INTAKE (kg, DM):					
Hay	8.4	8.5	11.8	11.8	0.2
Conc.	12.6	12.8	7.8	7.8	0.2
Total	21.0	21.3	19.6	19.6	0.4
CHEWING TIME (min/kg intake):					
Idling	33.6	31.3	32.4	27.0	2.4
Eating	9.9	9.6	11.9	14.5	1.0
Rumination	15.2	18.0	20.6	20.8	1.2
Total Chewing	25.1	27.6	32.5	35.3	1.8
RUMINATION CHARACTERISTICS:					
# Boli / kg intake	14.3	17.7	20.8	21.7	1.5
Time chewing / Bolus (min)	1.02	0.95	0.98	0.98	0.02

chewing per bolus regurgitated (Table XXIV). Increasing the MPL of the forage being fed also increased the number of boli regurgitated during rumination but the effect was not significant ($P > 0.05$) (Table XXIII). Though also not significant ($P > 0.05$), there was a strong trend towards a reduced time spent chewing per bolus regurgitated when the MPL of the forage increased.

There was no significant interaction ($P > 0.05$) between MPL and the proportion of forage in the diet on the chewing characteristics of the animals in this trial (Table XXV).

DAIRY STEER TRIAL

The particle length distributions of the four treatments of chopped forage fed in this experiment are given in Table XXVI. There was a significant difference ($P < 0.05$) between the MPL of the four chop lengths

TABLE XXVI: Particle length distributions (% sample wt.) and distribution parameters of the chopped timothy-brome hay.

PARTICLE LENGTH	CHOPPED FORAGE TREATMENTS A	B	C	D
<3.30 mm	36.8	23.0	20.6	13.9
3.30- 8.25 mm	28.4	20.3	10.2	8.0
8.25-16.50 mm	23.5	33.3	24.7	18.1
16.50-33.00 mm	8.9	17.3	33.0	35.8
33.00-66.00 mm	2.5	5.5	9.9	20.8
>66.00 mm	0.0	0.6	1.7	3.6
MEDIAN LENGTH (mm):	5.2^a	9.0^b	13.3^c	20.0^d
COEFFICIENT OF SPREAD:	0.955	1.109	1.098	1.219
WEIBULL PARAMETERS B:	0.192308	0.110988	0.075482	0.050100
C:	0.955450	1.109449	1.097834	1.218846

$^{a-d}$ Median lengths and coefficients of spread with different superscripts were significantly different ($P < 0.05$).

of forage but no significant difference ($P > 0.05$) between the CS. The shortest length of forage, however, had the smallest CS and the longest chop length had the largest. The CS for the middle chop lengths were intermediate.

There was also no significant difference ($P > 0.05$) in nutritional composition between the four forage particle length treatments (Table XXVII). The concentrate that was fed with the hay had a significantly higher crude protein ($P < 0.05$) and significantly lower ADF content ($P < 0.05$) than did the forage; the two feedstuffs did not significantly differ ($P > 0.05$) in moisture content. However, since the forage to concentrate ratio remained constant throughout the experiment, there was no significant difference ($P > 0.05$) in nutritional composition between the dietary treatments (Table XXVIII). Therefore, as was the objective, this experiment was only testing the effect of median particle length on chewing behavior.

The feeding level during the experiment was fixed at 9.5 percent of metabolic body weight on an as fed basis. All animals except the Ayrshire consumed their total feed allotment throughout the experiment. The Ayrshire's intake, on the basis of metabolic body weight, was lower than

TABLE XXVII: Nutrient content (%, DM basis) of the concentrate and the four lengths (mm) of chopped timothy-brome hay used in the experiment.

	CONCENTRATE	FORAGE MEDIAN PARTICLE LENGTH (mm)			
		5.2	9.0	13.3	20.0
D.M.	88.3	88.3	88.0	87.9	89.2
C.P.	16.0^{b}	12.1^{a}	11.6^{a}	11.4^{a}	11.5^{a}
NDF	--	53.7	55.2	54.2	56.3
ADF	10.1^{a}	36.8^{b}	39.2^{b}	37.0^{b}	38.0^{b}

$^{a-b}$ Means within rows with different superscripts were significantly different ($P < 0.05$).

TABLE XXVIII: Nutrient content (%, DM basis) of the dietary treatments (40% concentrate with 60% timothy-brome hay chopped at four median particle lengths).

	FORAGE MEDIAN PARTICLE LENGTH (mm)			
	5.2	9.0	13.3	20.0
D.M.	88.3	88.1	88.1	88.8
C.P.	13.7	13.4	13.2	13.3
ADF	26.1	27.6	26.2	26.8

that for the other steers and was not constant over the four treatment periods of the experiment. This may have been caused by a chronic frothy bloat suffered by the Ayrshire throughout the experiment. It was not clear whether the length of hay (5.2 mm) fed to the Ayrshire in the first period had any effect on the incidence of bloat in this animal.

The covariable, metabolic body weight, had a significant effect ($P < 0.05$) on time spent idle, time spent ruminating and total time spent chewing per kg of intake, and on the time spent chewing per bolus regurgitated during rumination. Metabolic body weight, however, did not have a significant effect ($P > 0.05$) on the time spent eating, nor on on the number of boli regurgitated during rumination per kg of feed consumed. Where appropriate, the following results were therefore adjusted for the effect of metabolic body weight on chewing behavior. The partitioning of the sums of squares by the full General Linear Hypothesis model for each yield variable is given in Appendix B.

The results of the effect of decreasing the MPL of the forage on the chewing activity of the steers is shown in Table XXIX. There was a consistent trend towards decreased time spent eating per kg of feed ingested as the MPL of the forage decreased, but this effect was not significant ($P > 0.05$). The same trend was seen in the time spent ruminating which

TABLE XXIX: Effect of forage median particle length (mm) on intake and chewing characteristics.

	FORAGE MEDIAN PARTICLE LENGTH (mm)					
	5.2	9.0	13.3	20.0	SEM	COV[#]
INTAKE (kg, DM):	12.4^{a}	12.8^{ab}	12.7^{ab}	13.0^{b}	0.1	NS
CHEWING TIME (min/kg intake):						
Idling	94.4^{b}	86.1^{ab}	83.5^{a}	77.3^{a}	2.5	*
Eating	8.4	9.6	9.7	10.3	0.5	NS
Rumination	16.9^{a}	20.9^{b}	22.6^{bc}	24.6^{c}	0.8	*
Total Chewing	25.3^{a}	30.5^{b}	32.3^{bc}	34.9^{c}	1.0	*
RUMINATION CHARACTERISTICS:						
# Boli / kg intake	18.9^{a}	23.8^{ab}	28.2^{bc}	31.1^{c}	1.3	NS
Time chewing / Bolus (min)	0.856^{b}	0.859^{b}	0.794^{ab}	0.786^{a}	0.018	*

[#] Covarible effect of $BW^{0.75}$: NS = not significant, * = significant ($P < 0.05$).

[a-c] Mean values within rows having different superscripts were significantly different ($P < 0.05$).

significantly decreased ($P < 0.05$) as the MPL of the forage decreased. The cumulative effect of decreasing the MPL of the forage on time spent eating and ruminating resulted in a significant decrease ($P < 0.05$) in total time spent chewing per kg of feed ingested as the MPL of the forage decreased. Subsequently, there was a concomitant significant increase ($P < 0.05$) in the amount of time the animals were idle per kg of feed ingested.

During rumination, there was a significant decrease ($P < 0.05$) in the number of boli regurgitated per kg of feed ingested (DM basis) as the MPL of the forage decreased. The time spent chewing per bolus regurgitated was also significantly affected ($P < 0.05$) by the MPL of the forage. There was a reduced amount of time spent chewing per bolus when the animals were fed the 20.0 mm length of forage as compared with the 5.2 and the 9.0 mm lengths. The time spent chewing per bolus on the 13.3 mm forage was intermediate but not significantly different ($P > 0.05$) from the other lengths of forage.

Curvilinear regression was performed on the responses of the yield variables discussed above to the changes in forage MPL. In general,

TABLE XXX: Regression ($Y = a + b\log X$) and $BW^{0.75}$ covariable coefficients for the effect of forage median particle length on chewing and rumination characteristics.

	REGRESSION			$BW^{0.75}$
	a	b	R^2	
CHEWING TIME (min/kg intake):				
Idling	114.233	-28.238	0.98	1.388*
Eating	6.380	3.074	0.93	-0.226
Ruminating	7.924	12.998	0.99	-0.439*
Total chewing	14.259	16.108	0.98	-0.667*
RUMINATION CHARACTERISTICS:				
#Boli / kg intake	3.720	21.285	0.99	-0.289
min chewing / bolus	--	--	--	-0.009*

* Covariable was significant ($P < 0.05$).

regressing chewing activity on the logarithm of the MPL of the forage gave a better fit to the data than did simple linear regression. The observed values are shown with the predicted regression lines in Figures 18 and 19 and the regression coefficients and the coefficients of determination for each regression line are given in Table XXX, along with the covariable coefficients for the effect of metabolic body weight on chewing activity. Animals with higher metabolic body weights spent significantly ($P < 0.05$) more time idle and less time eating and ruminating per kg of feed ingested than did lighter animals. Larger animals also ruminated for significantly less time ($P < 0.05$) on each bolus regurgitated during rumination. They also tended to regurgitate a smaller number of boli per kg of feed ingested but this effect was not statistically significant ($P > 0.05$).

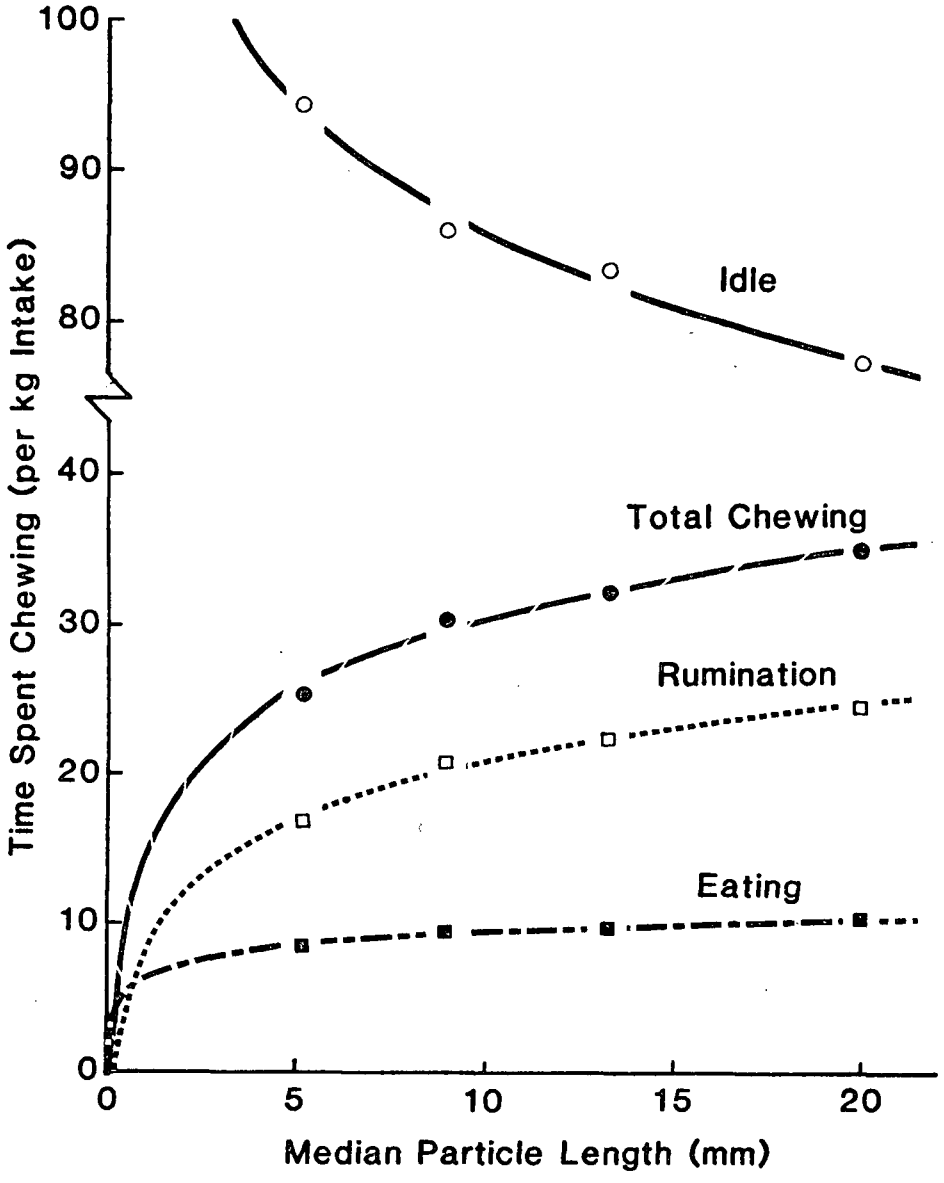

FIGURE 18: Plot of observed values and predicted regression lines (Y = a + blogX) for the relationship between the times animals spent idle and chewing per kg intake (Y) and the median particle length of a timothy-bromegrass hay chopped to 4 median particle lengths (X) when the hay was fed in a 60% forage, 40% concentrate ration.

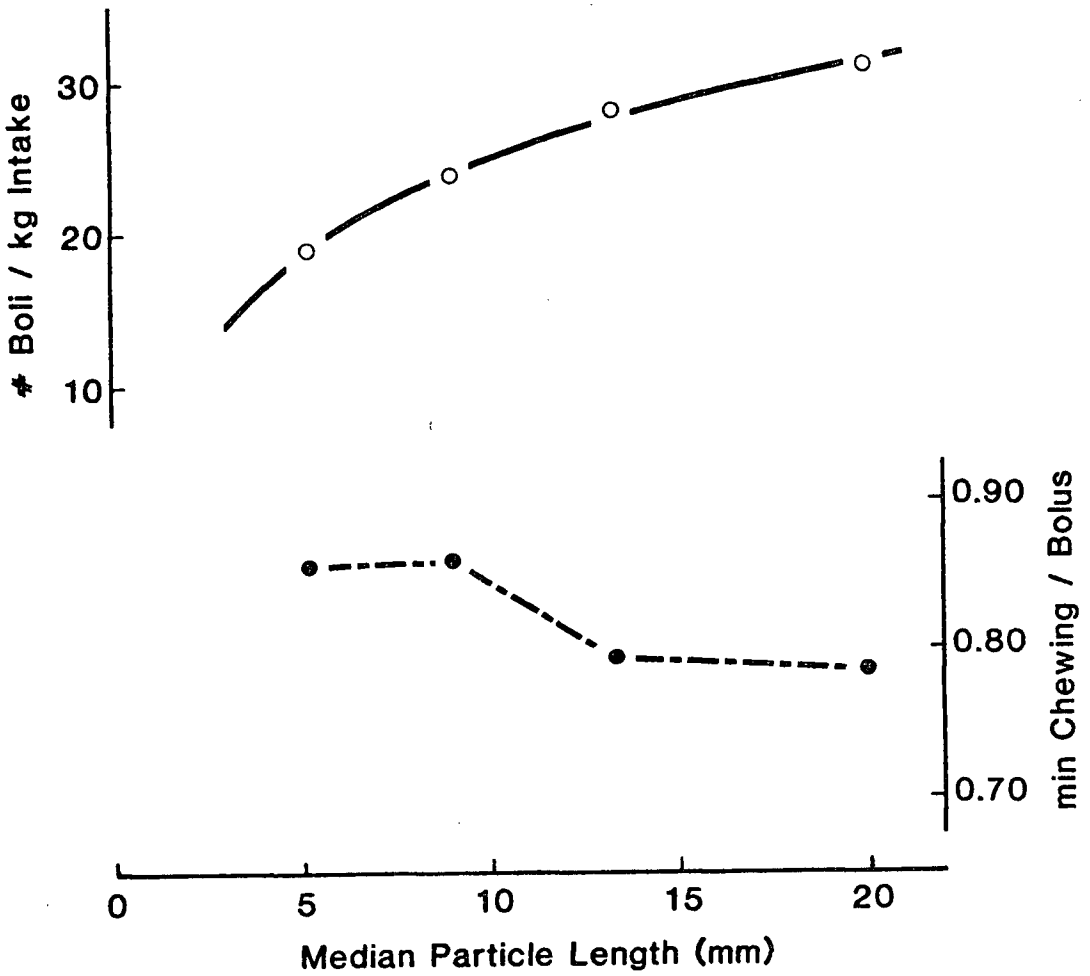

FIGURE 19: Plot of observed values and predicted regression line (Y = a + blogX) for the relationship between the number of boli regurgitated during rumination per kg of intake (Y) and median forage particle length (X), and the effect of median particle length on time spent chewing per bolus regurgitated when timothy-bromegrass hay was chopped to 4 median particle lengths and fed in a 60% forage, 40% concentrate ration.

DISCUSSION

As demonstrated by other research, and in the present study, the reduction of particle size in forages fed to ruminants does not always affect the chewing behavior of cattle. In both of the present studies reducing the MPL of the forage did not significantly change ($P > 0.05$) the rate of intake of the diets that were fed. However, there was a consistent trend towards a reduced amount of time spent eating per kg of feed ingested as the MPL of the forage decreased. One must therefore conclude that the difference between the lengths of forage in the amount of comminution required by the animals to swallow the rations was minimal and did not significantly inhibit the rate of intake. On the other hand, increasing the proportion of the forage in the ration fed to the dairy cows significantly increased the amount of time required for chewing each kg of feed prior to swallowing. The greater rate of intake for concentrates as compared with that for forages has been reported before (Balch, 1958). The faster rate of intake for concentrates may be due to a smaller particle size and/or less resistance to comminution by chewing. Therefore, as the proportion of forage in a ration increases, one would expect a longer time chewing per kg of intake to be required prior to swallowing.

Research has shown that decreasing the particle size of forages fed to ruminants can increase voluntary feed intake and decrease the time spent ruminating. The cause of these effects is believed to be a greater rate of passage of particles from the rumen; the increased rate of passage being caused by a decreased requirement for particles to be reduced in size by rumination to enable passage through the reticulo-omasal orifice. Such a decrease in time spent ruminating was observed in the dairy steer trial.

Decreasing the MPL of the timothy-brome hay from 20.0 to 9.0 mm, 13.3 to 5.2 mm, or 9.0 to 5.2 mm significantly decreased the amount of time the animals spent ruminating per kg of intake. One would therefore conclude that the decreases in time spent ruminating would be associated with a greater rate of passage of unruminated particles from the rumen and that the potential for higher intakes would be increased.

In the dairy cow trial, however, decreasing the MPL of the orchardgrass hay from 18.1 to 7.3 mm did not significantly alter the intake of the ration or the time the cows spent ruminating per kg of intake. Why, therefore, did a change of 10.8 mm in MPL not significantly affect the time spent ruminating by the dairy cows when smaller changes had a significant effect when the dairy steers were fed chopped timothy-brome hay? In the steer trial, the effect of reducing forage particle length on decreasing the amount of time the animals spent ruminating increased as the MPL of the forage decreased. There was a direct relatioship between the time spent ruminating and the logarithm of the median particle length of the forage that was fed (R^2 = 0.99). This relationship was similar to that described by Poppi et al. (1980) for the effect of particle size on resistance to passage from the rumen. On the basis of their findings, Poppi et al. (1980) suggested that there existed a critical particle size above which passage may be possible, but the probability of such passage was very low. Therefore, related to the resistance of particle size passage from the rumen, there appears to be a "threshold length" below which the reduction of forage particle length may have a significant effect on decreasing the time spent ruminating and, therefore, increasing voluntary feed intake. It is possible that the median particle lengths of the orchardgrass hay fed in the dairy cow trial were above the "threshold" required to elicit a significant

response in the time spent ruminating by these animals.

It has been reported that the effect of decreasing forage particle length on increasing intake and decreasing the time spent ruminating becomes more pronounced as the fiber content of the forage increases (Welch and Smith, 1969a). Although different forages were fed in the present two trials, the ADF content of the two forages was similar (38.6% ADF for the orchardgrass hay in the dairy cow trial and 37.8% ADF for the timothy-brome hay in the steer trial). The timothy-brome hay, on the other hand, had a lower CP content (11.7 vs 14.3%) and produced a much coarser and stiffer particle when processed than did the orchardgrass hay. Pearce (1965) suggested that increased protein intake could decrease rumination time, and the coarseness of the timothy-brome hay may indicate a greater resistance to comminution. Therefore, the reduction in particle length of the lower protein content and stiffer timothy-brome hay particles may have elicited a greater response in chewing behavior than that which was elicited by the orchardgrass hay.

The experimental design of the dairy cow trial may also have influenced the detection of significant differences between the effects of the dietary treatments on chewing behavior. There is extreme variation in the chewing behavior of ruminants which, if uncontrolled, can introduce significant experimental error into the results of experiments. The design used for the steer trial was a balanced Latin Square whereas that used for the cow trial was a two period changeover design with four treatments. In the steer trial each animal received each treatment while in the dairy cow trial each cow only received two of the four treatments. The unbalanced nature of the cow trial therefore may not have fully controlled the animal to animal variation to the point that the differences in chewing behavior between particle

length treatments were not statistically significant.

There was, however, a significant increase in the amount of time spent ruminating per kg of intake as the proportion of forage in the ration fed to the dairy cows was increased. The increase in the proportion of forage was also associated with an increase in the fiber content of the ration which has been shown to increase the time spent ruminating. Bae et al. (1981) demonstrated that, regardless of level of intake, ingested roughage required a constant amount of comminution per kg of cell wall content for passage from the rumen. Therefore, one would expect animals to spend a greater amount of time ruminating per kg of intake as the proportion of forage in the diet increases. The detection of a significant effect of forage to concentrate ratio, but not of particle length, on rumination time in the dairy cow trial supports the suggestion that the composition of the diet has the greatest effect on the process of digestion in the ruminant (Mertens and Ely, 1982).

Both increasing the forage to concentrate ratio in the dairy cow trial and increasing the MPL in the steer trial significantly increased the number of boli regurgitated during rumination. Except when the particle length of the hay fed to the steers was increased to 20.0 mm, there was no significant change in the time spent chewing per bolus regurgitated in each trial. Therefore, there was no change in the efficiency of mastication during rumination when the proportion of forage in the diet or the MPL of the forage was altered. The increase in the efficiency of mastication during rumination of the longest hay fed to the steers is difficult to explain. Duckworth and Shirlaw (1955) found that chopping of long hay increased the duration of rumination cycles as compared with that when the long hay was fed. It is possible that the longer length of particles in the rumen cause

the formation of a lighter bolus during rumination. Such a bolus would require less comminution than a bolus of the same volume made up of a greater weight of shorter particles. Unfortunately no research has been done to investigate the effect of diet particle size on the particle size and weight of boli regurgitated during rumination.

The chewing results in the dairy steer trial support the results of Bae et al. (1983) who showed that larger animals were more efficient chewers than were smaller animals. In the steer trial, higher metabolic body weight was associated with a significant decrease in time spent eating and ruminating per kg of feed ingested, and a decrease in the time spent chewing per bolus regurgitated during rumination. Although the trends were similar to those found in the steer trial, metabolic body weight did not have a significant effect on the chewing behavior in the dairy cow trial. The lack of detection of a significant effect of body weight may have been due to the experimental design that was used and its inability to completely account for all the effects of animal variation in the experiment.

The effects of higher metabolic body weight on chewing behavior are likely due to an increased size of the mouth, teeth surface area, esophagus and reticulo-omasal orifice in larger animals. Greater prehension potential, more grinding surface on the teeth, and a larger esophagus would allow a greater rate of intake with a reduced time requirement for comminution prior to swallowing. During rumination, due to a larger esophagus, larger animals could regurgitate larger boli which could be more efficiently reduced in size by the larger surface area of the teeth. Finally, a larger reticulo-omasal orifice could pass larger particles than those passed in a smaller animal. This would increase the rate of passage of digesta and decrease the requirement for time spent ruminating per kg of intake in

larger animals. Bae et al (1983), however, found that fecal particle size did not significantly differ for different body sizes in their experiments.

SUMMARY

The present study investigated the effect of forage median particle length and forage to concentrate ratio on the chewing behavior in dairy cattle. In the first experiment, lactating dairy cattle were fed orchardgrass hay chopped to two MPLs (7.3 and 18.1 mm) in two forage to concentrate ratios (40:60 and 60:40) ad libitum. In the second experiment, dairy steers were fed timothy-brome hay chopped to four MPLs (5.2, 9.0, 13.3 and 20.0 mm) in a 60:40 forage concentrate ratio at 9.5 percent of metabolic body weight.

In the dairy cow trial, decreasing the particle length of the forage did not significantly affect the chewing behavior of the cattle. Increasing the proportion of forage in the diet, however, significantly increased voluntary feed intake, increased the time spent ruminating and total time chewing per kg of intake, and increased the number of boli regurgitated per kg of intake during rumination. Eating time was not significantly affected by the proportion of forage in the ration. There was also no significant interaction between the effects of MPL and the proportion of forage in the ration on the chewing behavior of the cattle.

Decreasing the MPL of the timothy-brome hay fed to the steers significantly decreased the time the animals spent ruminating and total time chewing per kg of intake and increased the number of boli regurgitated during rumination. There was also evidence that the efficiency of mastication during rumination increased as the MPL of the forage increased. The MPL of the forage did not significantly affect the time spent eating per kg of intake. There was a direct relationship between the logarithm of MPL and the chewing behavior of the steers. This relationship suggested that

there existed a "threshold length" below which the effect of MPL on chewing behavior becomes significant. Differences in the metabolic body weight of the steers during the experiment also had a significant effect on chewing behavior.

GENERAL SUMMARY AND CONCLUSIONS

The particle size of forages in ruminant diets affects the rate of passage of undigested feed particles from the rumen, the ruminal digestibility of the ration, and, therefore, the chewing behavior of the animal. However, until recently, only qualitative or semi-quantitative methods have been used to characterize the particle size distribution in processed forage. A method for the quantitation of the particle length distribution in processed forage was therefore developed, tested, and used to investigate the effect of processing method and forage type on the particle length distribution in processed forage. The same method was also used to investigate the effect of forage particle length on voluntary feed intake and chewing behavior in dairy cattle.

A simple vibrating tray forage particle separator (FPS) was constructed to separate forage particles into six theoretical length fractions (<4, 4-10, 10-20, 20-40, 40-80 and >80 mm). The method of application of forage particles to the FPS during separation significantly affected ($P < 0.05$) the measurement of the particle length distribution. The separation results, however, were repeatable within a given method of application. When orchardgrass hay, chopped at three theoretical lengths of cut (TLC: 3.18, 6.35 and 9.53 mm), was separated, only 56.6% of all particles separated (by weight) were correctly classified into the above theoretical particle length frations; 32.4% were oversized (classified as being longer than they actually were) and 11.0% were undersized (classified as being shorter than they actually were). Based on this degree of over and undersizing, the theoretical particle length fractions classified by the FPS were calibrated to be <3.3, 3.3-8.25, 8.25-16.5, 16.5-33.0, 33.0-66.0 and >66.0 mm. Because

the FPS separated particles on the basis of a specific size parameter, the measurement of forage particle size by this method is more appropriate than is the measurement of an unidentified particle size parameter using sieving.

Separation data for the chopped orchardgrass hay, expressed as percent cumulative weight undersize, was fitted by regression to a linear equation, two exponential equations, a lognormal distribution, and a modified Weibull function. Only the Weibull function adequately fit the separation data. The coefficients of determination for the Weibull function were all greater than 0.99 and the residuals were randomly distributed around the predicted regression line. The median particle length (MPL) could be predicted by the inverse of the B parameter in the modified Weibull function while the use of the C parameter (named the coefficient of spread [CS]) as a measure of the spread of particle lengths around a given median was discussed.

Alfalfa and low and high quality orchardgrass hays were hammermilled through a 12.7 mm screen and chopped at 3 TLC (3.18, 6.35 and 9.53 mm) and separated on the FPS to determine the dry matter (DM), crude protein (CP) and acid detergent fiber (ADF) MPL and CS of each processed forage. The MPL were based on the weight of each nutrient collected in each particle length fraction on the FPS. There was a significant interaction ($P < 0.05$) between the effect of processing method and forage type on the DM, CP and ADF MPL and CS produced in the processed forage. Furthermore, the differences in DM MPL and CS between forages were significantly different ($P < 0.05$) from those for CP and ADF. There were also significant differences ($P < 0.05$) between the DM and CP MPL, and the DM and ADF MPL, within each forage type. Therefore, different forages processed by the same method do not always result in the production of similar DM, CP and ADF MPL or CS within or between forage types. Lack of quantification of particle size in research

using processed forage may therefore introduce uncontrolled variation into dietary treatments.

Twelve lactating Holstein cows were fed orchardgrass hay chopped to two different MPL (7.3 and 18.1 mm) at two forage to concentrate ratios (40:60 and 60:40) in a two by two factorial arrangement in a two period changeover design. The particle length of the forage did not significantly affect ($P > 0.05$) voluntary feed intake (VFI) or chewing behavior. Increasing the forage to concentrate ratio in the diet significantly ($P < 0.05$) decreased VFI, increased the time spent chewing per kg of feed intake during eating and rumination and increased the number of boli regurgitated per kg of feed intake during rumination. Time spent idle per kg of feed intake and the time chewing per bolus regurgitated during rumination were not significantly affected ($P > 0.05$) by the forage to concentrate ratio of the diet. There was no significant interaction ($P > 0.05$) between the effects of forage MPL and forage to concentrate ratio on VFI and chewing behavior.

When dairy steers were fed timothy-brome hay chopped to 4 MPL (5.2, 9.0, 13.3 and 20.0 mm) at a 60:40 forage to concentrate ratio in a 4 x 4 Latin Square design, increasing the MPL of the forage in the diet significantly ($P < 0.05$) decreased the time spent idle, increased the time spent ruminating and the total time spent chewing (eating plus rumination), and increased the number of boli regurgitated per kg of feed intake. These effects of forage MPL on chewing behavior were shown to be directly related to the logarithm of the forage MPL. Increasing the MPL of the forage from 5.2 or 9.0 mm to 20.0 mm also significantly decreased ($P < 0.05$) the time spent chewing per bolus regurgitated during rumination. The MPL of the forage, however, did not have a significant effect on the time spent chewing per kg of feed intake during eating.

Body size, included as a covariable in both dairy cattle trials, had a significant effect ($P < 0.05$) on chewing behavior in the steer trial, but not in the dairy cow trial. As body size increased, time spent idle increased and the time spent chewing per kg of feed intake, during both eating and rumination, decreased. Larger animals also spent less time chewing each bolus that was regurgitated during rumination.

The differences in the effect of forage particle length, and body size, on chewing behavior between the two trials indicated that there may exist a maximum particle length, possibly related to body size, below which the effect of dietary particle length on the digestion process in ruminants becomes significant.

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APPENDICES

APPENDIX A:

PARTITIONING OF THE SUMS OF SQUARES FOR THE ANALYSIS OF INTAKE AND CHEWING BEHAVIOR IN THE DAIRY COW TRIAL (Reduced General Linear Hypothesis Models)

(a) Total feed intake:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	1	8.062	8.062	9.43	0.015
Length	1	0.036	0.036	0.04	0.842
% Hay	1	11.056	11.056	12.93	0.007
Leng x Hay	1	0.003	0.003	0.00	0.954
Error	19	46.280	2.436		
Total	34	104.876			

(b) Time spent idle:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	1	596.106	596.106	17.78	0.001
Length	1	87.440	87.440	2.61	0.123
% Hay	1	44.038	44.038	1.31	0.266
Leng x Hay	1	14.680	14.680	0.44	0.516
Error	19	636.984	33.525		
Total	23	1379.248			

(c) Time spent eating:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	1	29.260	29.260	4.78	0.042
Length	1	8.592	8.592	1.40	0.251
% Hay	1	72.107	72.107	11.77	0.003
Leng x Hay	1	12.586	12.586	2.05	0.168
Error	19	116.395	6.126		
Total	23	238.940			

(d) Total time spent ruminating:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	1	0.113	0.113	0.01	0.907
Length	1	13.365	13.365	1.64	0.215
% Hay	1	100.901	100.901	12.41	0.002
Leng x Hay	1	10.283	10.283	1.26	0.275
Error	19	154.512	8.132		
Total	23	279.175			

(e) Total time spent chewing (eating plus ruminating):

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	1	33.654	33.654	1.70	0.208
Length	1	42.560	42.560	2.15	0.159
% Hay	1	341.562	341.562	17.28	0.001
Leng x Hay	1	0.086	0.086	0.00	0.948
Error	19	375.565	19.767		
Total	23	793.427			

(f) Number of boli regurgitated:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	1	1.042	1.042	0.08	0.777
Length	1	26.042	26.042	2.06	0.167
% Hay	1	165.375	165.375	13.10	0.002
Leng x Hay	1	9.375	9.375	0.74	0.400
Error	19	239.792	12.621		
Total	23	441.625			

(g) Time chewing per bolus regurgitated:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	1	0.008	0.008	4.16	0.078
Animal	11	0.225	0.020	10.21	0.002
Length	1	0.005	0.005	2.72	0.134
% Hay	1	0.000	0.000	0.06	0.809
Leng x Hay	1	0.006	0.006	2.96	0.124
Error	8	0.016	0.002		
Total	23	0.260			

APPENDIX B

PARTITIONING OF THE SUMS OF SQUARES FOR THE ANALYSIS OF INTAKE AND CHEWING BEHAVIOR IN THE STEER TRIAL (Full General Linear Hypothesis Models)

(a) Total feed intake:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	3	0.093	0.031	0.65	0.614
Animal	3	54.287	18.096	383.73	0.000
Length	3	0.933	0.311	6.59	0.035
$BW^{0.75}$	1	0.186	0.186	3.95	0.104
Error	5	0.236	0.047		
Total	15	55.734			

(b) Time spent idle:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	3	115.967	38.656	1.58	0.305
Animal	3	3632.728	1210.910	49.50	0.000
Length	3	638.998	213.000	8.71	0.020
$BW^{0.75}$	1	190.768	124.460	7.80	0.038
Error	5	122.302			
Total	15	4700.762			

(c) Time spent eating:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	3	9.323	3.110	3.06	0.130
Animal	3	341.094	113.698	112.92	0.000
Length	3	9.118	3.039	2.99	0.134
$BW^{0.75}$	1	5.064	5.064	4.98	0.076
Error	5	5.079	1.016		
Total	15	369.679			

(d) Total time spent ruminating:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	3	42.399	14.133	5.55	0.048
Animal	3	73.195	24.398	9.57	0.016
Length	3	131.102	43.700	17.15	0.005
$BW^{0.75}$	1	19.095	19.095	7.49	0.041
Error	5	12.744	2.549		
Total	15	278.535			

(e) Total time spent chewing (eating plus ruminating):

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	3	67.718	22.572	5.43	0.050
Animal	3	418.917	139.639	33.58	0.001
Length	3	207.679	69.226	16.65	0.005
$BW^{0.75}$	1	44.058	44.058	10.59	0.023
Error	5	20.793	4.159		
Total	15	759.165			

(f) Number of boli regurgitated:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	3	63.500	21.167	2.92	0.134
Animal	3	45.500	15.167	2.09	0.220
Length	3	334.500	111.500	15.39	0.006
$BW^{0.75}$	1	8.285	8.285	1.14	0.334
Error	5	36.214	7.243		
Total	15	488.000			

(g) Time chewing per bolus regurgitated:

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F Value	Pr > F
Period	3	0.005	0.002	1.22	0.395
Animal	3	0.058	0.019	14.88	0.006
Length	3	0.025	0.008	6.47	0.036
$BW^{0.75}$	1	0.009	0.009	6.80	0.048
Error	5	0.006	0.001		
Total	15	0.103			