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Dit proefschrift met stellingen van Ynze van der Honing, landbouwkundig ingenieur, geboren te Donkerbroek (Fr.) op 20 maart 1941, is goedgekeurd door de promotor, dr.ir. A.J.H. van Es, buitengewoon lector in de energiehuishouding der dieren.

De Rector Magnificus van de Landbouwhogeschool,
J.P.H. van der Want

Wageningen, 30 januari 1975

Y. van der Honing

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Proefschrift
ter verkrijging van de graad van
doctor in de landbouwwetenschappen,
op gezag van de rector magnificus,
prof.dr.ir. J.P.H. van der Want, hoogleraar in de virologie,
in het openbaar te verdedigen
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Abstract

Honing, Y. van der (1975) Intake and utilization of energy of rations with pelleted forages by dairy cows. Agric. Res. Rep. (Versl. landbouwk. Onderz.) 836, ISBN 90 220 0565 8, 156 p., 20 tbs, 5 figs, 213 refs, Eng. and Dutch summaries, 2 appendices.
Also Doctoral thesis, Wageningen.

A survey of the literature showed that forage processing, that is grinding and pelleting, increased feed intake of ruminants. This increase, due to reduction in particle size distribution of the forage, depends mainly on forage quality, proportion of concentrates in the diet and nutrient requirement of the cow. Pellets could replace part of the concentrates; complete substitution for long forage caused digestive disorders and reduced fat content of the milk. Eating rate, microbial breakdown and production of volatile fatty acids often increased too. Processed forages offered to sheep and beef cattle depressed digestibility, which was compensated by slightly lower losses of methane and less heat production.

Data from energy balance trials at Wageningen from 1967 to 1973, mostly with 4-6 lactating Dutch Friesian cows per trial, were examined by multiple factor analysis for effects of processing. Rations in which processed forages replaced part of the long forages or the concentrates were tested in 130 trials. Processing decreased digestibility of energy in the forage by about 9 percentage units, 15%, and its metabolizability by 7 percentage units, 13%. Utilization of metabolizable energy increased, roughly compensating the decrease in metabolizability. Regressions were calculated for the prediction of digestibility and net energy of processed forage in a feed evaluation system for dairy cows, to be introduced in the Netherlands in 1977.

This thesis will also be published as Agricultural Research Reports 836.

Stellingen

1. In verband met de wereldvoedselsituatie zou het gebruik van ruwvoerbrokjes in de rundveevoeding als vervanging van voor éénmagigen geschikt krachtvoer gestimuleerd moeten worden.

Dit proefschrift.

2. De bijdrage van de dikke darm in de energievoorziening lijkt bij melkkoeien minder belangrijk dan bij schapen.

Dit proefschrift.

3. De waarde van voederproeven die als doel hebben om het gehalte aan netto energie van voedermiddelen voor melkvee te meten wordt vaak overschat.

Y. van der Honing & Y.S. Rijpkema, 1974. Vergelijking van kunstmatig gedroogd gras met hooi in rantsoenen voor melkvee door middel van een voederproef en energiebalansproeven. Versl. landbouwk. Onderz. 820.

4. Het gebruik van een lagere ruwecelstofaftrek voor kuilvoer dan voor hooi in de berekening van de zetmeelwaarde voor melkvee leidt ten onrechte tot een overwaardering van kuilvoer vergeleken met hooi.

Handleiding voor de berekening van de voederwaarde van ruwvoedermiddelen. Centraal Veevoederbureau, 1965.

5. De overeenkomst tussen de mens en het varken ten aanzien van de invloed van de voeding na de geboorte op de vermeerdering van de vetcellen, zoals door Hermans verondersteld, is aanvechtbaar.

P.G.C. Hermans, 1973. The development of adipose tissue in swine foetuses. Tijdschr. Diergeneesk. 98:662.

6. Om fysiologische redenen is te verwachten, dat graskarpers de door hen opgenomen hoeveelheid organische stof slechts zeer onvolledig omzetten in koolzuur en warmte, hetgeen in vergelijking tot mechanische reiniging van sloten en plassen een nadeel kan zijn.

7. Bij een juist gebruik van een veldhakselaar bij de winning van voordroogkuil mag het drogestofgehalte belangrijk lager zijn dan 50%, zonder dat dit veevoedkundige of inkuiltechnische bezwaren oplevert.

8. Het verschil tussen de gevonden produktie van melkvee in de weide en die welke volgens berekeningen met de normen van het Centraal Veevoederbureau en van Geith verwacht wordt, moet eerder gezocht worden in een onjuiste schatting voor de grasopname door het melkvee en de samenstelling van het gras dan in de aangenomen behoefte van de koeien.

J.M. Bergsma, 1973. Voedernormen en grasopname bij melkvee (Literatuurstudie) Intern Rapport Proefstn Rundveehouderij 33.

9. De leesbaarheid van publikaties kan worden bevorderd door het gebruik van uniforme symbolen voor begrippen in de energiehuishouding en de veevoeding, bij voorkeur afgestemd op symbolen die in de basiswetenschappen gehanteerd worden. Meer overleg tussen verschillende internationale commissies, die zich met uniformering bezig houden, is echter gewenst.

10. Het lijkt gewenst dat bij selectie naar hogere melkproduktie meer aandacht wordt geschonken aan een zo groot mogelijke ruwvoeropname door melkvee.

Y. van der Honing
Intake and utilization of energy of rations with pelleted forages by dairy cows

Voorwoord

Het onderzoek van dit proefschrift werd uitgevoerd bij de Afdeling Fysiologie der Dieren van de Landbouwhogeschool. De beheerder, prof. dr. A.M. Frens, ben ik zeer erkentelijk voor de outillage en mankracht welke ik voor dit onderzoek mocht gebruiken. De gastvrijheid en de medewerking bij de Afdeling Fysiologie der Dieren heb ik steeds gewaardeerd.

Mijn promotor, dr. ir. A.J.H. van Es, dank ik in het bijzonder voor de stimulerende begeleiding bij het energiebalansonderzoek. Voor de vrijheid bij de voorbereiding van dit verslag, de discussies omtrent opzet van proeven en de interpretaties van de resultaten alsmede de waardevolle critiek en suggesties bij het samenstellen van het manuscript ben ik hem zeer erkentelijk. Van de door hem welwillend ter beschikking gestelde resultaten van het energiebalansonderzoek tot 1970, waaronder enige met ruwvoerbrokjes, werd dankbaar gebruik gemaakt.

Ir. F. de Boer, directeur van het Instituut voor Veevoedingsonderzoek 'Hoorn', ben ik erkentelijk voor de mij geboden gelegenheid in Wageningen aan dit proefschrift te werken binnen het kader van een onderzoekproject van het instituut.

De hierna genoemde personen en instellingen en allen die verder hebben meegewerkt aan het tot stand komen van dit proefschrift dank ik hartelijk.

Energiebalansonderzoek met grote landbouwhuisdieren is slechts mogelijk in teamverband. Voor een goede uitvoering en uitwerking van deze proeven zorgden de heren J.E. Vogt en zijn medewerkers G.A. Bangma, W. Hofs, W. van der Laan, M.J.N. Los, R. Terluin en D. Vink. De chemische analyses onder leiding van de heer H.J. Nijkamp werden uitgevoerd door de heer A.D. Bode, mej. H.W. Brouwer, mej. D.J. Honders, de heer J.W. Molenveld, mej. G. Posthuma, mej. M. Smit en mej. J.E. Wassenaar.

Het voer en de proefdieren waren afkomstig van de proefboerderij van de Afdeling Fysiologie der Dieren. De bedrijfsleider, de heer H. van Dijk en zijn personeel verzorgden ook tijdens de proeven het melken van de proefdieren.

Proefvoer werd verkregen door medewerking van de Fa. E.H. Koetsier & Zn te Woerden, de Coöp. Groenvoederdrogerij te Workum en Middenmeer, de proefboerderij 'De Vijf Roeden' te Duiven (ILR) en de proefboerderij 'Zegveld' (PR). De medewerking en bemiddeling door de heren Q.P.M. van Bijsterveldt, M.H. Huisman, ir. H.J. Leutscher en ir. P.J.J. Philipsen (IBVL), ir. G.A. Benders (ILR) en Tj. Boxem en ir. A.B. Meyer (PR) hierbij werd op prijs gesteld.

Het verteerbaarheidsonderzoek in vitro werd verzorgd door de heer C.J. van der Koelen (IVVO).

Adviezen betreffende de statistische verwerking van een deel der proeven werden verstrekt door de heren A. Heyting en ir. A.A.M. Jansen (IWIS-TNO te Wageningen).

Het typewerk voor het definitieve manuscript werd in korte tijd op uitstekende wijze verzorgd door mej. S. Vink.

De heer C. van Eden wist van mijn schetsjes toch duidelijke figuren te maken.

De publikatie van dit verslag werd verzorgd door de heer R.J.P. Aalpol (Pudoc). De Engelse tekst werd nauwkeurig gecorrigeerd door de heer J.C. Rigg (Pudoc).

Veel dank ben ik verschuldigd aan mijn ouders, die mij tot verdere studie stimuleerden en deze ook mogelijk maakten.

Niet in de laatste plaats bewonder ik mijn vrouw en kinderen, die het zovele uren als het ware zonder man en vader moesten stellen. Voor de morele en daadwerkelijke steun van mijn vrouw en de vele uren die zij besteedde aan het typen van het concept-manuscript ben ik haar erg dankbaar.

Curriculum vitae

Ynze van der Honing begon na het behalen van het HBS-B diploma aan de 2e Christelijke HBS te Groningen in 1959 zijn studie aan de Landbouwhogeschool te Wageningen. In 1966 slaagde hij voor het ingenieursexamen, studierichting Veeteelt. Van 1 mei 1965 tot 31 augustus 1970 was hij verbonden aan het Instituut voor Bewaring en Verwerking van Landbouwprodukten te Wageningen waar hij onderzoek deed over de opname door rundvee van geconserveerde ruwvoeders. Tijdens deze periode werd gedurende 19 maanden de militaire dienstplicht vervuld bij de Koninklijke Luchtmacht. Sinds 1 september 1970 is hij werkzaam bij het Instituut voor Veevoedingsonderzoek 'Hoorn', gedetacheerd bij de Vakgroep Fysiologie der Dieren van de Landbouwhogeschool te Wageningen met als opdracht het onderzoek naar de energiehuishouding van landbouwhuisdieren.

Contents

List of symbols

Subscripts

Capital letters indicate chemical or nutrient components.
Lower case (small) letters indicate parts of a total quantity utilized in particular ways.

B	= indication of a constituent, e.g. C, N, O, T, XP, XL
C	= (1) carbon, e.g. R_C mass of carbon retained; carbon retention (2) concentrates, only in the symbol P_C proportion of concentrates
E	= combustible energy; enthalpy of combustion; 'energy'
f	= growing and fattening, e.g. $M_{E,f}$ metabolizable energy for fattening
G	= combustible gas
l	= milk, e.g. $M_{E,l}$ metabolizable energy for milk production
L	= long forage
m	= maintenance, e.g. $M_{E,m}$ metabolizable energy for maintenance
N	= nitrogen, e.g. R_N retention of (combined) nitrogen
NE	= net energy, e.g. e_{NE} efficiency of utilization of energy
O	= organic matter, e.g. I_O intake of organic matter
P	= pelleted forage
T	= dry matter, e.g. I_T intake of dry matter
XF	= crude fibre
XL	= crude lipid, usually extract with light petroleum or diethyl ether
XP	= crude protein, usually 6.25N
XX	= nitrogen-free extract

Superscript

* function of metabolic body size ($W^{\frac{3}{4}}$), e.g. $R_E^* = R_E/W^{\frac{3}{4}}$

Principal symbols for quantities

Symbols that can be used with any subscript to represent a component are indicated by the subscript B.
Quantities referring to amount entering of leaving the body (I, D, F, G, U, R, M, L, H) refer to totals for a day and have the units of, for instance, kg/day, being 'mean fluxes' or 'mean flow rates'.
As a simplification, the dimension of time has been ignored.
The first term is that used usually in the text and then after a colon the complete strict term, followed by units of quantities in brackets.

a, b	= regression coefficients. In the text, d and e are called 'coefficient d' or 'coefficient e' to distinguish them from digestibility and efficiency of utilization
CV	= coefficient of variation
d_B	= digestibility of a component: apparent digestibility coefficient, (I - F)/I (%)
D_B	= digestible component: mass of apparently digested component, I - F (kg)
D_E	= digestible energy: combustible energy apparently digested (kcal)
e_{NE}	= (efficiency of) utilization of energy for all purposes or, with a further subscript, for maintenance, m, milk production, l, and growth or fattening, f (%)
F_B	= faecal component; faecal losses: mass of component in faeces (kg)
F_E	= faecal energy; energy loss in faeces: combustible energy of faeces (kcal)
FCM	= fat-corrected milk: mass of milk corrected to a mass fraction of 4% fat (kg)
G_E	= gas losses; gas energy: combustible energy of methane produced by the animal (kcal)
H	= heat production: mean heat flux, usually as calculated from respiration (kcal/day)
I_B	= intake of component; component consumed; ration: mass of component in consumed ration (kg)
I_E	= gross energy; intake of energy: combustible energy of consumed ration (kcal)

k = (efficiency of) utilization of metabolizable energy for all purposes or, with a subscript, for maintenance, m, milk production, l, or growth and fattening, f (%)

L_B = component in milk: mass of component in milk (g)

L_E = net energy for milk production: combustible energy of milk (kcal)

M_E = metabolizable energy for all purposes or, with a subscript, for maintenance, m, milk production, l, or growth and fattening, f: $D_E - G_E - U_E$ (kcal)

MF = modulus of fineness (unity)

MU = modulus of uniformity (unity)

P = (1) probability (unity)
(2) contribution to total intake, with subscript for ingredient, C for concentrates, and L and P for long and pelleted forages; proportion of concentrates, long forage or pelleted forage: mass fraction in consumed ration on the basis of dry matter or organic matter (%)

q = metabolizability: quotient of metabolizable to gross energy, M_E/I_E (%)

r = (1) correlation coefficient (unity)
(2) relative substance concentration, used of $r(C_2/C_3)$, that of acetate to propionate

R_B = retention of component: mass of component calculated to retained in body tissue (g)

R_E = net energy for growth and fattening: (calculated) combustible energy retained in or lost from body tissue (kcal)

R^2 = part of sum of squares attributable to regression (unity)

RSD = residual standard deviation (units as for quantity referred to)

SD = standard deviation (units as for quantity referred to)

SE = starch equivalent (kg)

TDN = total digestible nutrients (kg)

U_B = urinary component; loss of component in urine: mass of component in urine (kg)

U_E = urinary energy; energy loss in urine: combustible energy of urine (kcal)

$\dot{V}$ = mean volume rate, corrected to a temperature of 0 °C and a pressure of 760 mmHg, negative for 'consumed' and positive for 'produced', with subscripts O_2, CO_2 and G for oxygen, carbon dioxide and methane (litre/day)

VFA = volatile fatty acids, usually substance concentration of titratable acid (mmol/litre)

W = liveweight: mass of live animal (kg)

$W^{\frac{3}{4}}$ = metabolic body size ($kg^{\frac{3}{4}}$)

Miscellaneous conventions

The term content normally indicates a quantity in which an amount of component has been divided by the mass of the system. For energy as a function of mass of feed, it is used here in the following ways either on a dry matter (I_T) or organic matter (I_O) basis.

I_E/I_T = (gross) energy content: specific combustible energy (kcal/kg)

D_E/I_T = content of digestible energy; digestible energy content: specific apparently digested combustible energy (kcal/kg)

M_E/I_T = content of metabolizable energy; metabolizable energy content: specific metabolizable combustible energy (kcal/kg)

$(R_E + L_E + x)/I_T$ = content of net energy, using for x (net energy of maintenance) a constant per unit metabolic body size; net energy content: specific utilized combustible energy (kcal/kg)

1 Introduction

1.1 SCOPE

In dairy farming, the number of cows and the area of grassland per man has increased because of the higher costs of labour and the lower income per cow during recent decennia. These trends have induced investment in machinery and in automation on dairy farms.

In dairy farming, the feeding of roughages requires much labour. Mostly because of the bulkiness of roughages like hay and silage, mechanical handling, transport and provendering is difficult. Grinding and pelleting of roughages considerably reduces their volume. Storage and conveyance of pelleted roughages are simpler than of long roughages. As the grinding and pelleting process was rather expensive, this kind of processing was considered attractive only for high-quality forages like early-cut grasses or legumes conserved in a good way, e.g. by drying. The forages were dried artificially and processed to produce pellets of grasses or legumes used mainly as a source of carotene and protein in the feeds for pigs and poultry.

More recently, pelleted forages have also been used for cattle. The aim was not a better supply of carotene and protein but replacement of part of the concentrates or of normal long forages. Forage pellets were often eaten in greater amounts than long forages. The value of pelleted forages depends on the amount eaten under different circumstances, the content of nutrients and of net energy in these pellets relative to concentrates and long roughages, and properties during storage, transport and handling.

The purpose of this study was to investigate factors that control the intake of pelleted forages and to estimate their net energy content for dairy cattle.

1.2 TERMINOLOGY OF PROCESSED FORAGES

Several methods of processing and packaging have been used to overcome the disadvantages of storage, transport and handling of bulky loose forages, but the literature provides no uniform terminology, especially for different kinds of compressed forages. The following concepts were used in this investigation.

Long: long forage unprocessed apart from drying and ensiling, and forage chopped to a length of not less than 3 cm, if it contained a substantial fraction of pieces longer than 3 cm, if not, it should be called 'coarsely ground forage'.

Pellets: hammermilled material extruded through the die of a rotary press.

Wafers: forage formed by extruding the long material through a reciprocating press.

Cobs: forage produced by the extrusion of chopped material through the die of a rotary press.

The production of wafers and cobs was developed mainly to overcome the disadvantages of ground and pelleted roughages in cattle rations. Cattle fed on ground and pelleted forages with little or no long roughage often showed digestive disturbances (off-feed, bloat), ruminal parakeratosis and depression of the fat content of milk (Minson, 1963; Moore, 1964; Beardsley, 1964). As these side-effects were largely suppressed by supplying sufficient long forage, it was tried to maintain the average length of the forage as much as possible during compression. First cobs were made with rotary die presses but the cobs contained too much fines, so later reciprocating presses were used to make wafers.

The pellets are generally smaller than cobs and wafers (Marchant & Shepperson, 1973; Wilkins, 1973). Wafers normally have a diameter of 5-10 cm, which is at least twice their length. The diameter and length of cobs is mainly 2-4 cm. Pellets are mostly less than 1½-2 cm diameter and up to 3 or 4 cm long.

2 Literature on intake of ground and pelleted forages

The production of milk or body tissue by cattle depends largely on the amount of feed consumed and the digestibility of the nutrients in that ration.

As processing influences both intake and digestibility of roughages, this chapter reviews only effects of processing on voluntary intake and factors on which they depend. It sketches regulation of intake, the effect of different kinds of processing, how the physical properties of the feed are correlated with the effect of processing, and physiological changes in the gut so far as they seem related to feed intake.

2.1 REGULATION OF FEED INTAKE: A SKETCH

Mechanisms regulating feed intake in ruminants are poorly understood, as appears from recent reviews on regulation of feed intake by Campling (1970), Baumgardt (1970), Baile & Maier (1970), Forbes (1971) and Baile & Forbes (1974). One reason may be the great variety of factors involved in the complicated regulation of feed intake.

It is generally accepted that ruminants and monogastric animals alike try to adjust voluntary feed intake to their energy requirement. So over longer periods, the adult animal can keep net energy intake almost in balance with energy output, if the amount of feed consumed and its net energy content is not a limiting factor and if the rations are balanced for contents of protein, minerals, vitamins and trace elements (Baumgardt, 1970; Forbes, 1971).

Baumgardt (1970) gathered evidence for regulation of feed intake by metabolic factors, when ruminants received rations with high levels of concentrates. He concluded from several reports that factors like low pH or high concentrations of volatile fatty acids in the rumen could inhibit feed intake for several hours in a day. It is not known whether the reduced intake of energy with rations very low in roughage is caused by a feedback signal in response to pH or concentration and proportions of volatile fatty acids in rumen fluid or to lack of tactile stimuli so that the motility of the forestomachs, normal fermentation and passage rate are inhibited.

The rather bulky and fibrous feeds often given to ruminants, however, fill the rumen to capacity before nutrient requirements for maintenance and production have been met. According to Campling (1970), limitation of feed intake by physical properties of diets consisting mainly of roughages depends on the capacity of the reticulorumen and on the rate of disappearance of digesta from these organs. Rumen capacity is related to the size of the animal and depends on the size of the abdominal cavity and on its distendability. According to Forbes (1970), foetal enlargment late in pregnancy and extensive deposition of fat apparently occur at the expense of rumen capacity and reduce feed intake. The animal, however, seems able to increase the rate of passage of digesta (Graham & Williams, 1962), thus recompensing any reduction due to compression of the rumen late in pregnancy.

Hypertrophy of the gut, allowing an increased feed intake and meeting the high demand for nutrients in cows with high milk yields was suggested by Leaver et al. (1969). Tulloh (1966) showed that seasonal changes occurred in the capacity of the rumen, which appeared to be associated with similar trends in voluntary intake.

Rumen capacity is obviously not constant but depends on physiological state, for instance stage of pregnancy, lactation and fatness.

Balch & Campling (1969) considered the rate of disappearance of digesta from the reticulorumen to be a function of rate of breakdown by combined action of microbial fermentation and mechanical activity of the gut, including chewing during eating and rumination, and muscular contractions of the gut. The soluble products of digestion are absorbed or, if gaseous, removed by eructation, and the undigested residues are transferred through the reticulo-omasal orifice to the abomasum and intestine. The rate of enzymic digestion by rumen microbes is closely related to the chemical composition of the feed. When inferior roughage was supplied, addition of nitrogen to the rumen increased microbial activity, rate of breakdown and voluntary intake, as was shown by Campling et al. (1962).

The relationships between feed intake and rate of disappearance of digesta is reflected in the well-known relationship between voluntary intake and digestibility of various roughages. Conrad et al. (1964) showed this direct relation between intake and digestibility for diets predominantly of long roughage with digestibility 52-67%; above 67% intake decreased with increasing digestibility of the diet. With highly digestible diets, the amount of material in the rumen is less than with diets mainly consisting of long roughage (Bines, 1971). When the digestible energy content of the feed increases above a certain value, which depends on the physiological state or the energy requirement of the animal, dry matter intake decreases so that digestible energy intake remains constant (Baumgardt, 1970). The energy content at which this occurs will be the point at which regulation of feed intake moves from physical to metabolic factors. It is still not known whether intake of digestible, metabolizable or net energy (definitions in List of Symbols) is kept constant when the animal is trying to keep energy intake equal to energy expenditure for maintenance and production.

Campling (1970) concludes in his review that the limits within which physical regulation occurs are not yet clearly defined. But physical factors alone are not solely responsible for regulating intake of feed in ruminants. Although it is convenient to separate physical from metabolic factors regulating intake, these are not necessarily independent and it is unlikely that any one factor or group of factors will be universally responsible for regulating intake.

In conclusion, it is difficult to explain or predict the feed intake of a certain animal, because voluntary intake seems to depend, for instance, on the animal's size and physiological state as well as on the diet's composition and components. The quantitative relationships between the various factors are known only superficially.

2.2 FACTORS IN THE INTAKE OF PROCESSED FORAGES

Particle size distribution in the pellets or wafers, bulk density and dimensions of the pellets or wafers differ from the original long material. A reduction in particle size is caused by grinding as well as by pelleting of the forage. The compacting of unground forages also reduces particle size. Besides the factors already mentioned, shape and hardness of pellets may play a role in voluntary feed intake too. To study the effect of processing of roughages on voluntary feed intake, one must also consider the interaction between the processed forages and the other components of the diet.

2.2.1 Particle size

Measurement of particle size Fineness is usually described by the size of the screen used in the hammermill for the grinding process. This description, however, cannot be accurate for particle size distribution, because several factors affect fineness: the speed of the grinder, the forage species, the stage of maturity and the content of dry matter.

To describe the particle size distribution, several authors used the percentage of the material retained by different standard sieves (Rodrigue & Allen, 1960; Stone et al., 1966; Demarquilly & Journet, 1967; Wilkins, 1973). The modulus of fineness (MF), a method of the American Society of Agricultural Engineers (1967), is commonly used as a single figure to indicate the particle size distribution, usually combined with the modulus of uniformity (MU), indicating to what extent the particles, by mass, are distributed over three classes.

Sieving, however, cannot give a precise estimate of the particle size distribution if the particles deviate far from a cubic or a spherical form, as in coarsely ground roughages. Elongate threadlike particles incident end--on can pass small sieves but have less chance of doing so than cubic or spherical particles (Troelsen & Campbell, 1968).

Both grinding and pelleting reduce the particle size of roughages. To estimate the particle size spectrum of pelleted roughages is still more difficult than of meal, because it is necessary to break the pellets up before sieving, usually by soaking in water and sieving wet (Troelsen & Campbell, 1968; Thomas et al., 1968) or after drying over a set of standard sieves (Stone et al., 1966; Wilkins, 1973; Jarrige et al., 1973a). With the wet-sieving procedure some of the very fine particles and the soluble fraction can be lost with the water. Before dry-sieving, the adhered particles in the dried material should be separated without altering the size of the particles. None of these procedures is ideal for measuring the particle size distribution precisely and all are rather laborious. No perfect method of determining particle size distribution is yet available, but these procedures can be used to get a rough estimate.

Obstruction of digesta by the reticulo-omasal orifice The reticulo-omasal orifice is generally accepted to be the major obstruction for the passage of coarse roughage through the digestive tract of ruminants. The size, shape and mass density of forage particles seem to play a role in the passage rate of digesta from the reticulo-rumen (Balch & Campling, 1965; Troelsen & Campbell, 1968; Jarrige et al., 1973a). The limits of particle size of forages leaving the rumen are not well defined as shown in Section 2.3.5. A reduction below such limits would not increase feed intake when the outflow of digesta from the rumen is controlled by the fill of omasum, abomasum or intestine.

Reduction of particle size The extent to which the particle size is reduced by grinding, pelleting, or compression to wafers or cobs seems to depend on many factors, such as the kind of roughage, the stage of maturity, the type of press, the drying method and the content of dry matter (Stone et al., 1966; Jarrige et al., 1973a). According to Jarrige et al. (1973a) the mean particle size after processing grasses was less than for lucerne, and that of artificially dried forages less than of hays. The difference was mainly due to the drier state of artificially dried forages when processed. With a roller die press the reduction in particle size due to compression was greater than with a piston-type press.

Evidently the size of the apertures of the screen used for grinding can only indicate the maximum particle size that may be found for spherical particles and not the mean particle size nor the particle size distribution. Sieving the meal before pelleting gives only a poor estimate of the particle size distribution of pelleted forages, because the compression of meal into pellets itself involves a reduction in particle size (Jarrige et al., 1973a).

Particle size reduction of roughages for ruminants can increase passage rate of digesta and improve the rate of bacterial fermentation, although some of the processed material, staying for a shorter time in the rumen than the original long roughage, escapes microbial breakdown. So with grinding and pelleting, an increased voluntary intake may be expected, when physical factors control feed intake. The next part of this chapter will deal first with results of trials on the effect of grinding on forage consumption by cattle and secondly with those in which pelleted forages were used. Finally some experiments are described with cattle given unground forages compressed to wafers or cobs, to investigate the effect on feed consumption. A considerable amount of information has been obtained from trials with sheep rather than cattle and, where appropriate, we will also refer to these data.

Effect of grinding without pelleting Keith et al. (1961) reported that voluntary feed intake of dairy cows increased by 6.2 kg/day or 40% with grinding of hay, using a 1.2-mm screen (Table 1). Cullison (1961) fed weanling beef calves on coastal Bermuda grass hay (*Cynodon dactylon*), supplemented with 0.9 kg cottonseed oilmeal, and noted a higher forage intake of 30% with grinding. Campling & Freer (1966) gave ground oat straw to dry

Table 1. Effect of grinding of forages on voluntary intake by cattle.

Trial No	Sex and physiol. state of cattle	Type of ground forage	Daily intake of ration: with long forage, forage (kg)	with long forage, other (kg)	with ground forage, forage (kg)	with ground forage, other (kg)	increase with grinding, forage (kg)	increase with grinding, relative to long forage (%)	Ref.[5]
1	lact. cow	lucerne	6.0	1.3	6.3	2.1	0.3	6	1
2	lact. cow	lucerne/cocksfoot	15.4		21.6		6.2	40	2
3a[1]	lact. cow	lucerne e.c.[4]	14.5	7.8	12.9	7.8	-1.6	-11	3
3b[1]	lact. cow	lucerne l.c.[4]	12.8	7.8	11.3	7.8	-1.5	-11	3
4	lact. cow	lucerne	15.6	7.1	17.5	6.9	1.9	12	4
5	dry cow	grass hay	9.2		9.3		0.1	1	5
6	heifer	grass hay	1.7[3]		1.6[3]		-0.1[3]	- 5	6
7	beef calf	grass hay	4.7	1.0	6.1	1.0	1.4	30	7
8a[1]	dry cow	dried grass	10.9		10.7		0.2	2	8
8b[1]	dry cow	oat straw	5.7		7.2		1.5	25	8
9a[1]	heifer	lucerne e.c.[4]	8.2		9.4		1.2	15	3
9b[1]	heifer	lucerne l.c.[4]	7.0		9.2		2.2	31	3
10a[1]	heifer	lucerne e.c.[4]	8.4		9.3		0.9	11	3
10b[1]	heifer	lucerne l.c.[4]	7.3		8.4		1.1	14	3
10c[1]	steer	lucerne e.c.[4]	9.4		10.6		1.2	12	3
10d[1]	steer	lucerne l.c.[4]	8.8		8.5		-0.3	- 4	3
11a[1]	steer	dried grass[2]	2.8[3]		2.9[3]		0.1[3]	3	9
11b[1]	steer	dried grass[2]	2.4[3]		2.7[3]		0.3[3]	13	9

1. More than one roughage used in the same experiment indicated by 6a, 6b, etc.
2. Both the chopped and ground dried grass were wafered.
3. Intake of dry matter divided by bodyweight (kg/100 kg).
4. Early cut, e.c.; late cut, l.c.
5. 1. Porter et al., 1953; 2. Keith et al., 1961; 3. Stone et al., 1966; 4. O'Dell et al., 1968; 5. Campling et al., 1963; 6. O'Dell et al., 1963; 7. Cullison, 1961; 8. Campling & Freer, 1966; 9. Lonsdale & Tayler, 1971

non-pregnant rumen-fistulated cows. The feed intake increased by 1.5 kg or 26% over that with long straw, but they could not detect any effect of grinding artificially dried grass. The effect of grinding early and late cut hay that Stone et al. (1966) found with heifers ranged from 11.4% to 31.0% in favour of ground hay. With steers, the effect was positive for early cut hay (+12.2%) and negative for late cut hay (-4.0%). Dairy cows showed a reduced feed intake of 11.3% with grinding for both types of hay, but their ration included 7.8 kg grain mixture on average. O'Dell et al. (1963) reported a small reduction of 4.7% in feed consumption of yearling heifers, fed on ground hay. More recently, O'Dell et al. (1968) found that cows consumed 12.2% more ground lucerne than long. Porter et al. (1953), using ground lucerne as the sole forage for dairy cattle, noticed an increase in forage consumption of 5.6% over baled lucerne. In their experiment, much rain fell during field-drying of the lucerne and afterwards some molasses were added to the ground material, which may have increased the palatability of the lucerne meal. The feed intake of spring and autumn artificially dried grass by steers increased by 3.2 and 14.9% with grinding, respectively (Lonsdale & Tayler, 1971). However their chopped and ground forages were wafered.

Grinding various hays increased the voluntary intake of sheep. The intake increased between 16.2 and 25.4 $g/kg^{\frac{3}{4}}$ (i.e. intake divided by metabolic body size, $W^{\frac{3}{4}}$) or 23-44% (Demarquilly & Journet, 1967). Similar results were found by Greenhalgh & Reid (1973).

Table 1 shows that grinding does not always increase voluntary intake. On average, the difference in feed consumption between ground and long forages is positive and generally seems to be somewhat greater for sheep than for cattle and also greater for growing and fattening cattle than for lactating cows. Especially for lactating cows, the composition of the ration, for instance the type and the amount of concentrates, could interact with the effect of grinding on voluntary intake. Some authors (O'Dell et al., 1963; Stone et al., 1966) suggested that finding a negative or only a small positive effect may have been caused by the dustiness of the ground forage, making it less palatable than the long forage. Meyer et al. (1959) found evidence for this. Adding water to ground forage before feeding increased the feed intake of sheep by 50% to a level near the intake of pellets. The intake of dry meal (0.92 kg) and of pellets (1.63 kg) changed when water was added to the meal or to the reground pellets to 1.44 and 1.42 kg, respectively. So pelleting put a fine dusty feed into a more palatable form.

The effect of fineness of grinding is described later because of lack of experimental data on ground non-pelleted forage.

Effect of grinding and pelleting Experiments, in which the differences in intake between ground and pelleted forages were studied, are described and the intake of pelleted forage is compared with the intake of long or chopped forage (Table 2).

For lucerne hay, pelleting increased voluntary intake of steers, weighing about 290 kg, by 1.41 kg or 16.1% over ground forage (Weir et al., 1959). Beef calves consumed 0.44 kg or 7.3% more feed from pelleted than from ground coastal Bermuda grass hay, supplemented with 0.95 kg cottonseed oilmeal (Cullison, 1961). Feed consumption of yearling heifers increased by 46% with pelleting of ground hay (O'Dell et al., 1963). Stone et al. (1966), giving early or late cut hay in ground or pelleted form to heifers, found an increase with pelleting of 1.0% and 8.9% in the first year and 8.3% and 13.5% in the second year, respectively. With steers and lactating cows on early cut hay, they found no significant effect of pelleting (+1.0% and -1.4%, respectively), but, for late cut hay, voluntary intake increased by 28.6% and 25.3% for steers and cows. O'Dell et al. (1968) reported a small increase with pelleting of 3.4% in feed intake of ground coastal Bermuda grass by dairy cows. They observed, however, a negative effect of 42.6% for lucerne pellets and, in another trial with coastal Bermuda grass, a negative effect on feed consumption of 7% with pelleting of ground hay. They mentioned the very compact condition of the lucerne pellets in the last experiment, which could have helped to reduce feed intake. Keith et al. (1961) found an insignificant difference of +1.2% in feed intake between pelleted and ground hay of lucerne and cocksfoot by dairy cows. This result agreed well with the insignificant negative effect of -1.0% which Porter et al. (1953) found by pelleting ground lucerne hay as the sole feed for dairy cattle.

The effect of pelleting ground forage on feed intake is thus generally positive, unless the ground or the pelleted material is much less palatable than the original material.

In the comparison of the pelleted with long forages, the effect of grinding and pelleting is combined. Table 2 presents the results of experiments, in which the long and the pelleted forage was of the same material. However, not all the experiments were performed in the same way and also several circumstances were different between experiments. Sometimes a small part of the forage was pelleted, whereas in other trials much or all the forage was pelleted. Also in few experiments, the diet included two or more roughages. The feeding method varied considerably. Feeding ad libitum can be restricted by time (e.g. 5 hours a day as done by Campling et al., 1963) or by amount supplied (e.g. residues restricted to 15, 10, 5% or even less of the daily roughage supply). Especially when there is some selective eating of long forage, i.e. preferential uptake of some parts of the ration, the effect of pelleting can be affected by the feeding method, because the extent of selection is reduced by decreasing the allowable residue. The great effect of pelleting artificially dried grass on intake by dairy cows found by Veevoederbureau Friesland (1968) may partly be due to the restricted feeding method (van der Honing & van Es, 1971). Another factor which may affect the difference between pelleted and long forages is the amount of concentrates in the diet. This effect will be discussed later (Section 2.2.6).

With pelleted forages for growing and fattening cattle voluntary feed intake increased by 13-51% of the amount of forage consumed compared with long forage. Because the amount of forage eaten increases with liveweight, the improvement with pelleting should be considered as a quotient to liveweight (kg/kg or %) rather than as kg/day. This is not possible because of lack of information about liveweight by some of the authors and therefore the difference is calculated as a percentage of the amount of forage eaten in the unpelleted diet.

In rations for lactating cows, the effect on forage intake of pelleting ranges between -32 and +62% compared with long forage. Calculated as a percentage of the total amount of air-dry feed consumed, the effect of pelleting on voluntary feed intake ranged from -25 to +30%. This wide range may partly be caused by factors other than particle size distribution, such as feeding method or amount of concentrates in the diet. Porter et al. (1953) believed the negative effect of pelleting in the second experiment (Table 2) to be due to the extreme hardness of the lucerne pellets. Stone et al. (1966) could not explain the negative effect of pelleting, which was found on a diet with hay cut early supplemented with 7.8 kg concentrates, whereas with a late cut hay and the same amount of concentrates a positive effect was found.

The effect of pelleting forage against long or chopped forage on voluntary intake by sheep was positive, as reported by Meyer et al. (1959), Weir et al. (1959), Haenlein et al. (1962), Demarquilly & Journet (1967), Minson (1967), Heany et al. (1968), Raymond (1969) and Blaxter (1973), and

Table 2. Effect of pelleting on forages on voluntary feed intake by cattle.

Trial No	Sex and physiol. state of cattle	Type of pelleted forage	Daily intake of ration: with long forage, forage (kg)	with long forage, other (kg)	with pelleted forage, forage (kg)	with pelleted forage, other (kg)	increase with pelleting, forage (kg)	increase with pelleting, relative to long forage (%)	Ref.[5]
1	lact. cow	lucerne	5.9	2.4	6.2	2.2	0.3	5	1
2	lact. cow	lucerne	6.7	1.9	4.5	1.9	-2.1	-32	2
3a[1]	lact. cow	lucerne hay	12.0		15.1		3.1	26	3
3b[1]	lact. cow	lucerne	12.4	1.7	14.1	2.0	1.7	14	3
4	lact. cow	grass hay	15.4		21.8		6.4	42	4
5a[1]	lact. cow	lucerne e.c.[4]	6.5		6.8		0.3	5	5
5b[1]	lact. cow	cocksfoot	4.6		6.1		1.5	32	5
6	lact. cow	lucerne	1.6[3]		2.3[3]		0.7[3]	44	6
7a[1]	lact. cow	grass hay e.c.	3.3[3]		3.2[3]		-0.1[3]	- 3	7
7b[1]	lact. cow	grass hay l.c.	2.7[3]		2.9[3]		0.2[3]	8	7
8a[1]	lact. cow	lucerne e.c.[4]	14.5	7.8	12.7	7.8	-1.8	-12	5
8b[1]	lact. cow	lucerne l.c.[4]	12.8	7.8	14.2	7.8	1.4	11	5
9	lact. cow	lucerne hay	12.8	3.7	16.4	2.7	3.6	28	18
10	lact. cow	lucerne hay	10.4	4.5	16.4	2.4	6.0	58	18
11	lact. cow	lucerne hay	10.5	3.6	17.1	1.3	6.6	62	18
12	lact. cow	lucerne	15.6	7.1	13.4	6.8	-2.2	-14	8
13	lact. cow	dried grass	10.2	3.8	15.0	1.1	4.8	47	9
14	lact. cow	dried grass	11.1	2.7	13.1	2.7	2.0	18	10
15a[1]	lact. cow	dried grass	10.9	3.5	12.2	3.5	1.3	12	11
15b[1]	lact. cow	dried grass	14.4	0.7	16.9	0.9	2.5	17	11
16a[1]	lact. cow	dried grass	9.5	7.2	11.5	6.4	2.0	20	12
16b[1]	lact. cow	dried grass	10.1	5.8	12.4	5.2	2.3	22	12
17	steer calf	timothy/lucerne	4.3		6.5		2.2	51	13
18	steer	lucerne hay	7.2	0.8	8.5	0.8	1.3	18	14
19	beef calf	coastal Bermuda grass hay	4.7	0.9	6.5	0.9	1.8	39	15
20	heifer	grass hay	1.7[3]		2.4[3]		0.7[3]	39	16
21a[1]	heifer	grass hay e.c.[4]	2.1[3]		2.6[3]		0.5[3]	27	7
21b[1]	heifer	grass hay l.c.[4]	1.8[3]		2.4[3]		0.6[3]	34	7
22a[1]	heifer	lucerne e.c.[4]	8.2		9.5		1.3	16	5
22b[1]	heifer	lucerne l.c.[4]	7.0		10.0		3.0	42	5
23a[1]	heifer	lucerne e.c.[4]	8.4		10.1		1.7	21	5
23b[1]	heifer	lucerne l.c.[4]	7.3		9.5		2.2	30	5
23c[1]	steer	lucerne e.c.[4]	9.4		10.7		1.3	13	5
23d[1]	steer	lucerne l.c.[4]	8.8		10.8		2.0	23	5

24a[1]	bull	grass hay (ground, 4 mm)	4.4	3.2	5.2	3.2	0.8	19	17
24b[1]	bull	grass hay (ground, 2 mm)	4.4	3.2	5.8	3.3	1.4	31	17

1. More than one roughage used in the same experiment indicated by 6a, 6b, etc.
3. Intake of dry matter divided by bodyweight (kg/100 kg).
4. Early cut, e.c.; late cut, l.c.
5. 1. Porter et al., 1953
   2. Porter et al., 1953
   3. Ronning et al., 1959
   4. Keith et al., 1961
   5. Stone et al., 1966
   6. Haenlein et al., 1962
   7. Buchman & Hemken, 1964
   8. O'Dell et al., 1968
   9. Veevoederbureau Friesland, 1968
   10. v.d. Honing et al., 1969
   11. v.d. Honing et al., 1971
   12. v.d. Honing & Schlepers, 1971
   13. Webb et al., 1957
   14. Weir et al., 1959
   15. Cullison, 1961
   16. O'Dell et al., 1963
   17. Cottyn et al., 1971
   18. Journet & Jarrige, 1967

ranged from 7.5 to 104.5%. Thomson (1969) found no significant increase in feed intake by lambs with pelleting of artificially dried grass. In general, the effect of pelleting on voluntary intake of sheep was obviously greater than of cattle.

On average, the effect of pelleting on voluntary intake of the total diet is less for lactating than for growing and fattening cattle, perhaps because of the higher energy requirement, intake and concentrates in the diet of dairy cows than of growing or fattening cattle. The effect of concentrates will be discussed later in Section 2.2.6.

Although it is difficult to measure the reduction in particle size due to pelleting, one can try to find out the influence of increasing fineness by considering the results of experiments in which forage was ground through screens with decreasing size of the apertures and pelleted. It is possible that during the pelleting process, the particle size of the coarsely ground forages is reduced (Dobie, 1959) to almost the same size as the finely ground. According to Dobie (1959) the die holes should be 3-6 mm larger than the apertures of the screen used for grinding, if considerable reduction in particle size during pelleting is not desired.

Dobie (1959) reported a small increase in feed intake when increasing the fineness of grinding of the hay before pelleting. Feed consumption of pellets of hay ground through screens 1.6, 4.8, 7.9 and 12.7 mm in aperture by sheep was 2.09, 1.96, 1.99 and 2.01 kg/day, respectively. Grinding lucerne hay through a screen 5, 3 or 1.5 mm in aperture before pelleting resulted in an insignificant difference in voluntary feed intake by sheep (Demarquilly & Journet, 1967): the intake was 105, 101 and 108 $g/kg^{3/4}$, respectively. With hay from permanent pasture, treated in the same way, they found a small increase in feed consumption by sheep and for the forage ground through a screen of 5, 3 and 1.5 mm in the pelleted form the feed intake was 85, 87 and 93 $g/kg^{3/4}$, respectively. It is not known if the particle size distribution of the pellets from the various meals were different because only the ground hay was analysed before pelleting. Jarrige et al. (1973a) reported that forage intake by wethers increased with a reduction in mean particle size of the forage to a limit of 0.40 mm for tall fescue, or 0.55 mm for ryegrass and 0.75 mm for lucerne. In these experiments, a forage ground with screens of 10 or 20 mm was already reduced to this fineness. As this rather fine material was compared to a dehydrated grass or lucerne ground through a 3-mm screen, both as pellets, finer grinding than through a 10-mm screen did not improve feed consumption by sheep. O'Dell et al. (1968), using dairy cows, did not find any significant effect of fineness on voluntary intake. Intakes by dairy cows of dehydrated coastal Bermuda grass, ground through a screen of 6.4, 3.2 or 1.6 mm and compressed into 6.4-mm pellets was 15.7, 14.7 and 16.1 kg/day when supplemented by 6.1, 6.0 and 6.2 kg concentrates, respectively.

From these results it seems that a reduction of particle size distribution of forages below the level obtained with a 10-mm screen generally has little or no influence on voluntary intake of these forages in the pelleted form by cattle and sheep.

Effect of wafering Processing the long forages to cobs or wafers also reduces the mean particle size of forages, although less than by grinding and pelleting (Wilkins, 1973; Jarrige et al., 1973a). Table 3 presents data from experiments in which the difference in feed intake by cattle of wafers over long forage was calculated. This difference, calculated as a percentage of the consumed long forage, ranges from -13 to +27%. This effect tends to be much smaller than that of pelleting, perhaps because of a greater proportion of coarse particles in the wafers or palatability. Palatability could be less for wafers than for pellets, inter alia, because of a higher proportion of fines in a loose form in batches of wafers, many of which fall apart.

Chopping of hay sometimes resulted in a higher consumption (Keith et al., 1961) but sometimes in only minor improvement (Slack et al., 1960; Voskuil & Metz, 1973). If the reduction in particle size of wafered forage and of chopped material is similar, only a small improvement in feed intake would be expected. Several other factors are involved in the control of feed consumption. The great improvement with wafering of lucerne hay reported by Ronning & Dobie (1962) may be caused by the feeding method. Feed was available twice a day for two hours. As the eating rate of the less bulky wafers might have been higher than of long or chopped hay, a contribution of this influence to the difference in feed intake could not be excluded.

Table 3 shows that wafering of lucerne can improve feed intake by cattle, though less than pelleting. Wafering of dehydrated grass slightly improved feed consumption in one experiment but no general conclusion can be drawn.

Feed intake by sheep of dehydrated lucerne and tall fescue was increased with wafering compared with chopping by 10 and 9.5%, respectively

Table 3. Effect of wafering of forages on voluntary feed intake by cattle.

Trial No	Sex and physiol. state of cattle	Type of wafered forage	Daily intake of ration						Ref.[5]
			with long forage		with wafered forage		increase with wafering		
			forage (kg)	other (kg)	forage (kg)	other (kg)	forage (kg)	relative to long forage (%)	
1	lact. cow	lucerne hay	10.0		12.6		2.6	26	1
2a[1]	lact. cow	lucerne (diam.3.8 cm)	11.1	6.4	13.7	6.4	2.6	23	2
2b[1]	lact. cow	lucerne (diam.1.6 cm)	11.1	6.4	13.3	6.4	2.2	20	2
3a[1]	lact. cow	lucerne hay (good)	11.6		11.6		0.0	0	3
3b[1]	lact. cow	lucerne hay (med.)	10.7		10.0		-0.7	- 7	3
3c[1]	lact. cow	lucerne hay (low quality)	10.2		8.9		-1.3	-13	3
4	lact. cow	lucerne hay	12.9	6.0	14.5	6.0	1.6	13	4
5a[1]	lact. cow	lucerne, prebloom	2.1[3]		2.3[3]		0.2	9	5
5b[1]	lact. cow	lucerne, 1/10 bloom	1.8[3]		2.2[3]		0.4	24	5
5c[1]	lact. cow	lucerne, full bloom	1.7[3]		2.2[3]		0.5	27	5
6	lact. cow	grass hay	13.3	7.8	17.6	8.6	4.3	32	6
7	beef calf	lucerne	4.5		4.6		0.1	2	7
8a[1]	beef cattle	lucerne	8.7		9.0		0.3	3	8
8b[1]	beef cattle	lucerne	10.6		12.5		1.9	18	8
9	heifer	lucerne hay	7.7		8.1		0.4	5	3
10	beef steer	grass hay	6.1		7.2		1.1	18	9
11a[1]	heifer	lucerne, prebloom	1.8[3]		2.1[3]		0.3	17	5
11b[1]	heifer	lucerne, 1/10 bloom	1.9[3]		1.8[3]		-0.1	- 7	5
11c[1]	heifer	lucerne, full bloom	1.7[3]		1.7[3]		0.0	1	5

1. More than one roughage used in the same experiment indicated by 6a, 6b, etc.
3. Intake of dry matter divided by bodyweight (kg/100 kg).
5. 1. Ross et al., 1959; 2. Ronning & Dobie, 1962; 3. Veltman et al., 1962; 4. Hutton et al., 1964; 5. Waldern & Baird, 1967; 6. Ronning & Dobie, 1967; 7. Wallace et al., 1961; 8. Meyer & Jones, 1962; 9. Hodge & Tietze, 1964.

(Jarrige et al., 1973a). Intake of cobs of these forages was 25.0 and 22.3% more and of pellets (ground by a 3-mm screen) 29.5 and 28.5% more than chopped forage. The mean particle size they measured for lucerne in chopped, wafered, cobbed and pelleted form was 2.15, 1.10, 1.05 and 0.40 mm and for tall fescue 1.75, 0.93, 0.78 and 0.25 mm, respectively. In these experiments with sheep, the increase in feed intake was closely correlated with the reduction in particle size of the forages.

The maximum increase in voluntary intake by reducing the particle size of forages seems to be reached at a certain degree of fineness. Below that, one can expect no effect or even a negative one. If the particle size of wafers or cobs has been reduced, but not below that specific range, a difference between pellets and wafers or cobs may be expected unless the palatability of the different forms of processed forage is not similar. Raymond (1969) showed a positive difference in feed intake of 5% between wafers and pellets of late cut perennial ryegrass, but for the early and medium cut the consumption of wafers only tended to be higher than of pellets when fed to cattle 3-6 months old. Minor differences were also found in feed intake of wafers and pellets of artificially dried grass by dairy cows (Bines & Connell, 1971). Journet & Hoden (1973) compared pellets, cobs and wafers from artificially dried lucerne or grasses as cobs and pellets as feed for dairy cows and found no significant differences in feed consumption between the different forms of processing, although the intake of lucerne cobs tended to be higher than of wafers. This could be due to a reduction in particle size by compressing these forages to cobs and wafers almost to that with grinding and pelleting. Of pellets slightly less dry matter was consumed than of cobs. Burgstaller & Averdunk (1972) reported the same intake of dry matter by lactating cows fed with cobs or wafers from artificially dried grass. Salewski et al. (1973) obtained similar results. However the consumption of forages using cobs or wafers was considerably more than with traditional diets in which hay and silage was used (Burgstaller & Averdunk, 1972).

In summary, the effect of chopping and wafering, if not accompanied by a great reduction in particle size, is much smaller than that of grinding and pelleting. The effect of particle size reduction on feed consumption may vary considerably with the many factors involved in regulation of feed intake. Differences in methods of feeding used while studying this effect increase the variation between experiments. A few of the factors interacting with pelleting and wafering are discussed in the following sections.

2.2.2 Density and hardness

Mass density of a pellet or wafer is the mass (commonly called 'weight') of a pellet or wafer divided by its volume. A distinct measure is bulk (mass) density, mass of a sample of pellets or wafers divided by volume, of pellets or wafers including interpellet space. Such space contains air or dust, and has a much lower density than the pellet itself. The difference between the two measures of density depends also on the diameter of the pellets or wafers and the proportion of fines or dust.

Hardness, mostly defined as the power required to crack the pellet (under standard conditions), is correlated with density. For a given type of forage, hardness increases with mass density.

Baile & Pfander (1967) reported a depression of feed intake on metabolic body size basis by sheep of 18 $g/kg^{\frac{3}{4}}$ or 19% when the bulk density of pellets of a given type increased from 517 to 583 kg/m^3. O'Dell et al. (1968) suggested that the lower intake of lucerne pellets by dairy cattle than of long material (Table 2) was due to the high bulk density, 835 kg/m^3. This was not found with Bermuda grass pellets of lower bulk density, 589 kg/m^3. The bulk densities reported by O'Dell et al. (1968) were 83.5 and 58.9 kg/m^3, but presumably these figures need to be multiplied by a factor 10, through a wrong conversion from lb/ft^3 to kg/m^3. Porter et al. (1953) suggested the 32% lower consumption of lucerne pellets than the long form by lactating cattle was due to the extreme hardness of the pellets. Tayler (1970) stated that if pellets are too hard (indicated by a mass density of a pellet exceeding 1100 kg/m^3) young cattle may eat even less than of the same material in the chopped form; but also if the pellet is too easily broken and is dusty, the potential intake may not be reached. Similar tendencies were reported by Wilkins (1973) for sheep fed on pellets and wafers. He concluded from experiments on feeding into the rumen through a fistula that the hardness or mass density of pellets did not limit feed intake by an oro-pharyngeal mechanism because total dry matter intake (by mouth + by fistula) was not affected by feeding method, though further evidence from different situations is required before this conclusion can be taken as general.

These results indicate that for maximum of feed intake with ground and pelleted or wafered feeds there are optimum ranges of hardness and density. These ranges are not yet well defined. For mass density, it seems to include 800-1000 kg/m^3.

2.2.3 Size of pellets or wafers

The size of pellet or wafer can affect feed intake directly and indirectly. The direct influence of size was demonstrated when diameter and length of wafers was too great. Wafers 6 cm in diameter and up to 6 cm in length reduced eating rate and occasionally choked cattle or obstructed the oesophagus (Wilkins, 1973). Wafers of diameters more than 6 cm are normally broken by the animals before they are swallowed. This generally increases the proportion of fines, which may reduce voluntary feed intake, as found with sheep, fed either on wafers 5 cm in diameter or on the same material cut directly after extrusion into half or quarter wafers of the same length as the whole wafers (Tetlow & Wilkins, 1972). Cobs, 2.4 cm in diameter and 1-4 cm long were reported by Milne et al. (1972) to be eaten much slower than pellets, 1.2 cm in diameter and 1.6-4.0 cm long. The lower intake of wafers than of long artificially dried grass found by Burgstaller (1972) was ascribed to too long and too hard wafers.

To increase feed intake, the size of processed forages should be less than 5-6 cm in diameter and length to prevent choking and obstruction of the oesophagus of mature cattle. Also crumbling to fines and dust, with transport and handling or by the animal, should be reduced by using a smaller size.

2.2.4 Composition of the forage

The effect of processing forage on voluntary intake depends partly on the quality of the ration. This quality is related, for instance, to digestibility, stage of maturity, species of forage, and amount and type of any concentrates mixed with or added to the forage. Also the amount of long forage and proportion of processed forage in total intake may be a factor interacting with the effect of processing.

Forage quality is related to stage of maturity. With increasing maturity, the digestibility of a forage generally decreases and its content of crude fibre increases. Heany et al. (1963), Buchman & Hemken (1964), Stone et al. (1966) and Lonsdale & Tayler (reported by Raymond, 1969) studied the effect of pelleting of forages on feed intake in relation to maturity of the processed forages. Heany et al. (1963) used sheep and compared the effect of pelleting of early, medium and late cut lucerne, cocksfoot and timothy. For all forages, a greater inprovement of voluntary intake by pelleting was found for the mature than for the immature forage. The improvement with processing was expressed relative to the amount consumed of the unprocessed forage. A similar but smaller improvement was observed by Buchman & Hemken (1964) with sheep, calves, yearling cattle and cows fed with early and late cut lucerne. Stone et al. (1966) found similar intakes for heifers, steers and dairy cows to those found by Buchman & Hemken, for long or pelleted early and late cut grass hay (Table 2). The effect of pelleting of early cut lucerne on intake by dairy cows, however, tended to be negative but of late cut hay was positive. This difference may be due to the amount of concentrates in the ration (Section 2.2.6). Similar results again were found by Waldern & Baird (1967). They used lucerne cut before flowering, at one-tenth bloom and at full bloom. For lactating cows, wafering had more effect when the lucerne was more mature. For heifers, however, wafering had most effect with lucerne cut before flowering. Journet & Jarrige (1967) also concluded that the improvement in feed intake by cows was greater for poor than for good lucerne hay. Jarrige et al. (1973a) reported that the increase in voluntary intake by wethers with pelleting was small (10-20%) for early cut and larger (up to 60%) for late cuts of lucerne and grass. In the work of Lonsdale & Tayler (reported by Raymond, 1969) with calves fed on early, medium and late cut long and pelleted dehydrated perennial ryegrass, consumption increased with pelleting more for late and medium cut than for early cut, but there was no significant difference between medium and late cut forage.

With increasing maturity, digestibility of forages decreases. To illustrate the interaction of forage quality and pelleting, the increase in feed intake with grinding and pelleting, relative to intake of long forage, has been plotted in Figure 1 against the digestibility of dry matter or organic matter of the long or chopped forage. With decreasing digestibility, grinding and pelleting increased voluntary feed intake more. The increase was generally greater for sheep than for cattle and tended to be smaller for lactating cows than for growing and fattening cattle.

2.2.5 Type of forage

The influence of the type of forage on the increase in feed intake due to pelleting is difficult to determine, as within each type there is a great range in which factors, like stage of maturity, digestibility, cell-wall constituents and lignification are variable. Differences found, when various

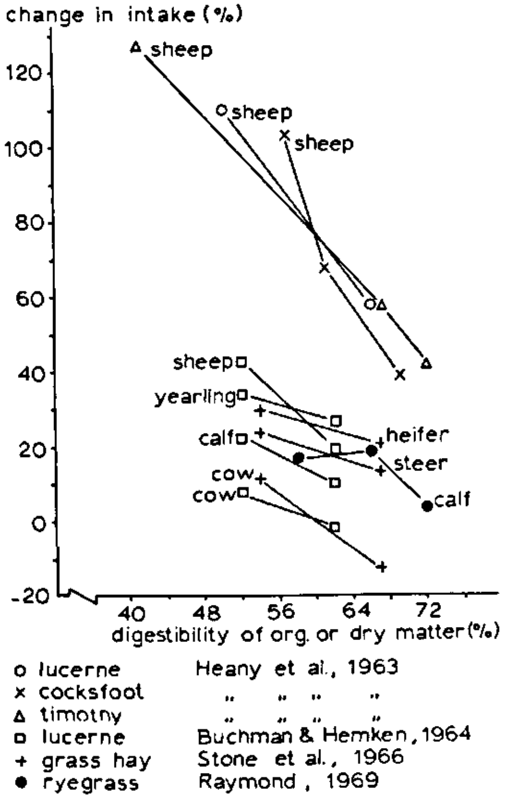


Fig. 1. Increase in voluntary feed intake with grinding and pelleting as a function of digestibility of dry or organic matter from the forages.

types of forages are used, probably can be explained by other factors than the type of forage. So far as could be traced, the literature contained no studies on the influence of type of forage on the increase in feed intake due to pelleting. However, it is possible to consider the results of several experiments and to see whether the increase in intake with pelleting is different for various types of forages.

When Campling & Freer (1966) fed dry cows on chopped and ground artificially dried grass and oat straw, they found a large increase in intake with grinding of straw but not of the dried grass.

Heany et al. (1963) used lucerne, cocksfoot and timothy and showed for early cut an increase in dry matter intake by sheep of 8, 27 and 32%, for medium cut of 37, 39 and 37% and for late cut of 54, 45 and 54%, respectively. These three types of forage behaved similarly. Demarquilly & Journet (1967) showed that the effect of pelleting on feed intake of sheep tended to be higher for grasses than for lucerne. The intake of unpelleted grasses was lower than of lucerne hay. For three stages of maturity of lucerne, an increase of 36, 62 and 75% was calculated, whereas for meadow fescue 67%, for ryegrass 70% and for hay from permanent pasture 80%.

Beardsley (1964) presented the literature about the effect of pelleting hay on intake by steers. Relative to long hay, the increase was on average 25%, but ranged from 8% (timothy) to 51% (mixture of timothy and lucerne). Prairie hay, with an increase of 21%, and coastal Bermuda grass hay, with 25% and 32%, were intermediate. Table 2 shows increases in feed intake by cows due to pelleting ranging from -33 to +62% for lucerne and from -3 to +42% for grasses. Experiments with steers or heifers showed an increase of 18 to 42% for lucerne and 27 to 39% for grasses.

There may be an influence of type of forage on the effect of pelleting on voluntary intake, but the size of this influence cannot be derived from these data, because of the overriding influence of other factors. A great deal of the variation may have been due to differences in digestibility but digestibility was only measured in a few experiments (Figure 1).

2.2.6 Amount and proportion of concentrates

For productive dairy cattle, a diet with only roughage is generally insufficient for nutrient and energy requirements. Because of the limited capacity for feed intake, the ration of these animals has to be enriched with concentrate mixtures, which generally have a much higher net energy content than forages like hay and silage. Even with much concentrates, it is often difficult to achieve a sufficient net energy supply for productive dairy cows (Miller & O'Dell, 1969; Baile & Forbes, 1974).

This section will consider the competition between forages and concentrates in voluntary feed intake. It is important to know whether the substitutive value of forage against concentrates differs between long and pelleted forages and what factors are involved. This information will be necessary in considering the value and the uses of pelleted forages for dairy cows.

Forages in the long form The addition of concentrates to a diet sometimes increased intake of dry matter from roughage (Blaxter & Wilson, 1963), when sheep were fed on a diet with roughage containing less than 8.5% crude protein. In other experiments, forage consumption by cattle was not significantly affected (Campling & Murdoch, 1966; Kirchgessner et al., 1968) or was reduced (Mather et al., 1960; Campling & Murdoch, 1966; Curran et al., 1970; Jarrige et al., 1973b). Total intake of dry matter increases as long as intake of dry matter from forage is not reduced by 1 kg or more per kg dry matter from concentrates added to a ration.

According to the literature, several factors influence the effect of an addition of concentrates on feed intake by ruminants, for instance energy requirement and physiological state of the animals, feeding frequency and composition of the diet. In the diet, relevant factors may be type, stage of maturity, digestibility, physical form and method of conservation of the forage, and type, physical form and amount of concentrates.

The reduction in feed intake found in late pregnancy of cattle and sheep, even on rations rich in concentrates (Forbes, 1970) suggests an effect of the physiological state, as does the high consumption of dry matter mostly found in productive animals, where it may be attributable to their high nutrients and energy requirements.

Blaxter & Wilson (1963) showed with sheep that the effect of concentrates on intake of dry matter depends on the maturity and digestibility of roughage in the diet. For poor, medium and good hay, 435 g added dry matter from concentrates reduced intake of dry matter from hay by 207, 345 and 462 g or 0.47, 0.79 and 1.06 g per g concentrates added. Campling & Murdoch (1966) found similar results, when concentrates were added to a ration of hay or straw for dry cows. According to Osbourn (1967), the decline in intake of dry matter from forage relative to the amount of concentrates added seemed higher for hay than for silage.

Heating, cooking, flaking or grinding, and pelleting of grain in a high-concentrates diet made feed intake irregular or reduced it (Putnam et al., 1966; Bakker, 1968; Miller & O'Dell, 1969). They attributed the effects to more rapid fermentation in the reticulo-rumen than of unground, rolled or cracked grain. Miller & O'Dell found considerable differences with type of concentrates.

Another important factor that influences the effect of concentrates on feed intake is the proportion of concentrates in the diet. Low proportions of concentrates generally cause little or no decline in forage intake but progressive increase in concentrates often inhibited forage consumption (e.g. Weir et al., 1959; Kesler et al., 1964; Campling & Murdoch, 1966; Kirchgessner et al., 1968). Ward & Kelley (1969), using different ratios of hay to concentrates (on a dry matter basis) between 1 and 0.5 found a nearly linear substitution of hay by concentrates of 0.44 kg hay per kg concentrates. In general, however, there was a considerable variation in the decline of dry matter from forage relative to the concentrates added for lactating cows. Although more extreme values have been observed for cows producing 15-30 kg milk, substitutive values for normal hay or silage diets are commonly between 0.2 and 0.6 (Jarrige et al., 1973b; Rijpkema, 1974). For fresh herbage cut at a young, leafy stage and maize silage high in dry matter, Jarrige et al. (1973b) mentioned a figure of 0.8. Taparia & Davey (1970) reported for fresh grass a somewhat lower value of 0.65.

Data on feeding more than twice a day suggest that a decline in forage intake with high amounts of concentrates in the diet may be sometimes reduced by frequent alternate feeding of roughage and concentrates (Miller & O'Dell, 1969; Kaufmann, 1973).

The decline in intake of long forage with added concentrates is greater for forages of high than of low digestibility and increases with the intake of concentrates. Total intake of dry matter, however, seems unaffected as long as the proportion of concentrates in the diet is below 60-65% of dry matter.

Processed forages Supplementation of a diet of ground and pelleted forages with concentrates and its effect on feed consumption has been more studied for sheep and beef cattle than for dairy cattle. Some trends for sheep or beef cattle may be valid for dairy cows too.

A significant decline in feed intake by lambs, changing from all-forage diets to rations with 50-60% concentrates, ranging from 0.5 to 19%, average 9.5%, was reported by Garrett et al. (1961). Beardsley (1964) reviewed data on change in performance of lambs with pelleting of a chopped ration. Pelleting increased feed intake of all-lucerne diets by 25.7%, but this effect was reduced to 6.1% for lucerne diets containing 30-50% concentrates.

Data from several United States agricultural experiment stations, presented by Tillman (1961), show that the change in feed intake by beef cattle with pelleting of the diet is positive for diets containing 60-100% roughage, but increasingly negative if the proportion of concentrates is higher (Table 4).

The effect of pelleting of a ground ration of roughage and concentrates on feed intake of steers was slightly positive in the range 85-100% and 40-60% roughage, but negative (-14.9%) in the range 20-30% roughage (Beardsley, 1964).

Dairy cows fed on rations with 1.8 kg concentrates consumed 14% more dry matter from pelleted lucerne hay than from long hay, but with no con-

Table 4. Effect of pelleting of rations on feed intake of beef cattle (data from Tillman, 1961).

Roughage		Daily feed intake			Place	Year
fraction of ration (% by mass)	type[1]	chopped (kg)	pelleted (kg)	difference pell.-ch. rel.to ch. (%)		
80-100						
100	lucerne hay	8.8	10.2	15.1	Calif.	1957
100	lucerne hay	5.0	7.1	42.7	Illinois	1955
100	lucerne hay	6.1	7.5	22.8	Nebraska	1959
100	meadow hay	4.3	6.4	50.0	Oregon	1959
87	Bermuda gr.	5.6	7.4	33.3	Georgia	1959
Average		5.9	7.7	29.8		
60-80						
80	lucerne + c.s.h.	8.9	10.2	14.2	Oklahoma	1961
74	lucerne + c.s.h.	11.9	14.3	20.6	Oklahoma	1961
70	maize cobs	10.2	11.6	13.8	Indiana	1958
70	lucerne hay	9.1	9.3	3.0	Calif.	1957
60	Bermuda gr.	11.8	11.8	0	Georgia	1959
Average		10.4	11.5	5.7		
40-60						
52	lucerne + c.s.h.	15.2	15.2	0.6	Texas	1958
45	Bermuda gr.	12.4	11.0	-11.0	Georgia	1959
45	maize cobs	11.0	11.7	6.2	Indiana	1959
40	lucerne hay	9.1	7.4	-18.5	Calif.	1957
Average		11.8	11.3	- 4.6		
20-40						
30	Bermuda gr.	11.9	10.0	-16.0	Georgia	1959
30	lucerne hay	10.9	8.9	-18.7	Kansas	1955
20	lucerne + c.s.h.	8.5	7.3	-13.4	Oklahoma	1961
20	lucerne + c.s.h.	11.5	10.7	- 7.1	Oklahoma	1961
20	maize cobs	10.2	9.8	- 3.5	Indiana	1958
Average		10.6	9.3	-10.7		

1. c.s.h. = Cottonseed hulls.

centrates this effect of pelleting was 26% (Ronning et al., 1959). Journet (1970) offered lactating cows lucerne hay with 0, 30 or 60% concentrates as a complete diet and observed a reduction in total intake of dry matter of 4-6% with 60% concentrates. In another experiment with lucerne and grass pellets, he found for an increase in the proportion of concentrates from 30 to 50% of dry matter a reduction in total feed intake of 5.8 and 6.7%, respectively. Journet & Jarrige (1967) fed dairy cows on long or pelleted hay, with silage, fodder beet and concentrates. As milk yield declined, they decreased the supply of concentrates by 2-3 kg and of fodder beet by 1.5 kg on a dry matter basis between the first and the last three weeks of the 10-week trial. They calculated the effect on dry matter from forage (i.e. hay + silage) (y_1) and total dry matter consumed (y_2) of the amount of dry matter from concentrates and fodder beet consumed (x) by linear regression as follows.

For long hay

$$y_1 = -0.302\ x + 10.050 \qquad (r = -0.83)$$
$$y_2 = 0.698\ x + 10.057 \qquad (r = 0.96)$$

For pelleted hay

$$y_1 = -1.171\ x + 19.444 \qquad (r = -0.99)$$
$$y_2 = -0.172\ x + 19.458 \qquad (r = -0.73)$$

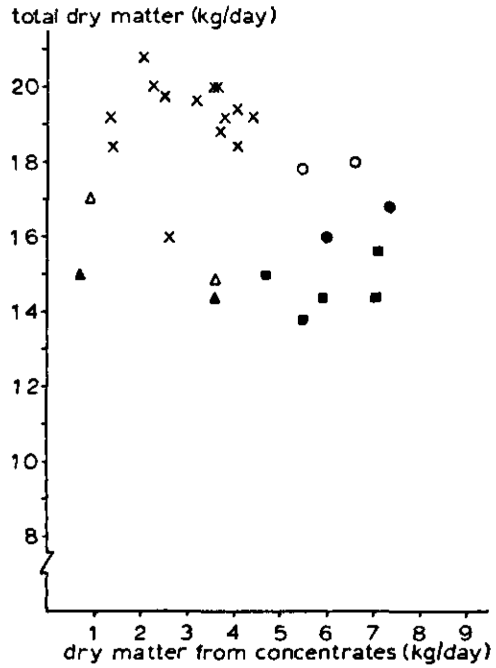
So in diets with pelleted forage, the substitutive value of forage against concentrates is much higher than in diets with long hay. Increasing the amount of concentrates in a ration with pelleted hay even reduced total dry matter consumed. From experiments with artificially dried grass for dairy cows, Jarrige et al. (1973b) reported that on average one should expect a substitutive value of 0.8 to 1.0 with forage in wafered or ground and pelleted form. These figures agree well with the results of similar experiments by Rijpkema (1974), from which a value of 0.9 was calculated for the substitutive value of grass pellets against concentrates.

Studying the value of complete feeds, Ronning & Laben (1966) found a higher intake by dairy cattle of diets of coarsely ground lucerne hay with 10-40% concentrates than of those with 70% or a 100% concentrates. Milk production was highest for the ration with 40% concentrates. For dairy cows on completely pelleted diets of coastal Bermuda grass and concentrates, Nelson et al. (1968) found no significant difference in intake of dry matter divided by liveweight between diets with 25, 50, 75 and 100% concentrates, whereas the intake of 100% forage was less. In trials with complete diets, containing straw and concentrates in different proportions, Thomson (1970) reported the highest intake by dairy cows with 30% straw. Respective intakes of diets with 20, 40 and 50% straw was 8, 5 and 19% less. Owen et al. (1971) compared feed intake and performance of dairy cows on a diet of rolled barley and 20, 35 or 50% chopped barley straw in loose form or as cubes and found the highest intakes with 20% loose straw and the 35% cubed diet. The authors attributed this difference to a lower mean particle size in the cubed diet. Jarrige et al. (1973a) observed maximum voluntary intake by dairy cows with 70% hay and 30% concentrates, if the hay was pelleted. Dobie et al. (1974) found highest intake by cows with 50% pelleted lucerne and 50% concentrates, and almost the same with 60 and 40%. With 40 and 60%, intake was about 10% less.

In our own experiments on intake of pelleted forages, the amount of concentrates was not planned as an experimental variable (van der Honing et al., 1971; van der Honing & Schlepers, 1971). Rations consisted of at least 4-5 kg long hay or long artificially dried grass with forage pellets fed ad libitum and a concentrates supplement to supply enough energy to meet requirements for maintenance and milk production. The amount of concentrates supplement supplied depended on the difference in amount of starch equivalent required by the dairy cow, according to Dutch feeding standards (CVB, 1970b), and the estimated amount of starch equivalent provided by the forage. As milk production declined during lactation, the amount of concentrates could be reduced. Because of this and the various kinds of forage used, which were not all consumed in equal amounts and had different starch equivalents, the average amount of concentrates in the daily ration of groups of 6-10 cows varied between 0.7 and 7.4 kg dry matter per cow. Each type of pelleted forage was supplied for 14 days at least and the average intake of dry matter during the last 5-7 days of this period was used to study the influence of amount of concentrates on consumption of forage pellets.

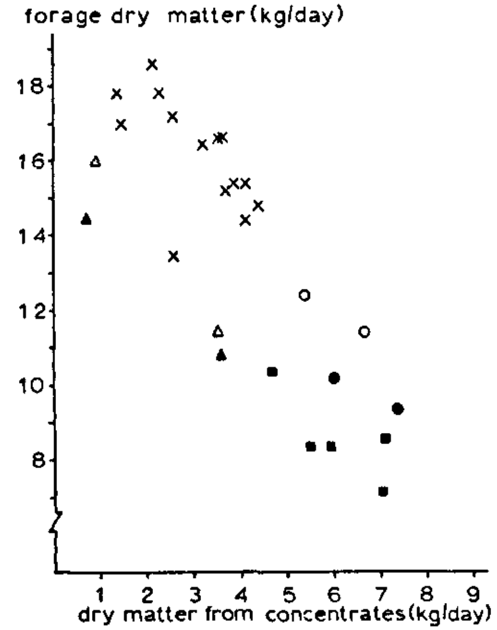
Figure 2 shows the result of this study. Intake of dry matter from forage and of total dry matter were plotted against the average amount of dry matter from concentrates, for groups of 6 to 10 cows. The more concentrates included in the ration, the lower the intake of dry matter from forage. Especially when a lot of forage pellets were supplied, the substitutive value of pellets against concentrates was close to 1 on a dry matter basis. The total intake of dry matter from rations with forage pellets and concentrates seems to reach a certain level, which is higher than for the rations with long hay ad libitum and concentrates according to Dutch feeding standards. The intake of total dry matter from diets with different sorts of long hay tended to increase slightly when the amount of concentrates increased. These tendencies agree well with results from the literature.

In summary, increasing amounts of concentrates generally cause a decline in intake of forage dry matter by dairy cows. This decline is usually



△,○,× = diet with pelleted forages
▲,●,■ = diet with long forages
△,▲,○,● = diet with long or pelleted artificially dried grass

Fig. 2a. Total intake of dry matter as a function of the intake of dry matter from concentrates.



△,○,× = diet with pelleted forages
▲,●,■ = diet with long forages
△,▲,○,● = diet with long or pelleted artificially dried grass

Fig. 2b. Intake of dry matter from forage as related to the intake of dry matter from concentrates.

much higher for pelleted than for long forages. Small amounts of concentrates can increase total intake of dry matter but when more than 50-60% concentrates are included in the diet, the total intake of dry matter declines too. Total intake of dry matter also seems to decrease for complete feeds at a higher ratio of roughage to concentrates for ground and pelleted diets than for those with unground roughages. The effect of pelleting roughages on intake of dry matter is generally positive at high ratios of roughage to concentrates but can become negative when more than 50-60% of the diet is concentrates. In normal rations, the substitutive value of forage pellets against concentrates is usually between 0.8 and 1.0 on a dry matter basis.

2.3 EFFECT OF PROCESSING ON CHANGES IN THE GUT ASSOCIATED WITH REGULATION OF INTAKE

In Section 2.2, the effect was described only of processing on voluntary intake. This section will describe the factors and mechanisms which may cause this effect. Because the regulatory mechanism of feed intake is only poorly understood (Baile & Forbes, 1974), all factors will be considered that could affect

- microbial breakdown of the feed in the reticulo-rumen
- amount and type of fermentation products
- rate of passage through the reticulo-omasal orifice, gut fill and sites of digestion.

2.3.1 Eating rate

Processing of roughages, for instance chopping, grinding and pelleting usually reduced the time required to consume one kg feed by sheep and cattle (Moore, 1964; Campling & Freer, 1966; Jarrige et al., 1973a). Kick et al. (1937) reported that steers required 153, 130, 90 and 78 min to eat equal amounts of hay, not chopped at all, chopped to a length of 5 and 0.6 cm or ground, respectively. Campling & Freer (1966) found that ground and pelleted dried grass and straw were consumed by cows about twice as fast as the long material. Piatkovski & Koriath (1970) reported similar results for pelleted or chopped dried grass with dairy cows. Increasing the fineness of forage particles reduced the time spent eating per kg dry matter for sheep and cattle (Kick et al., 1937; Demarquilly & Journet, 1967; Journet & Hoden, 1973).

2.3.2 Rumination

Rumination was reduced when particle size of forages was reduced. The steers of Kick et al. (1937) spent 402, 437, 414 and 277 min ruminating for equal amounts of hay in long form, cut to 5 or 0.6 cm, or ground, respectively. Campling & Freer (1966) found no rumination in cows on a diet of ground and pelleted artificially dried grass or straw. O'Dell et al. (1968) reported that rumination ceased in most dairy cows and was spasmodic in others when lucerne pellets were the only roughage. Rumination was observed more frequently in groups receiving ground hay than those receiving pellets, which O'Dell et al. thought to be due to the further reduction of particle size by pelleting. As shown by Demarquilly & Journet (1967) with sheep, reduction in particle size by grinding lucerne through a screen of 5 or 3 mm progressively decreased rumination; grinding through a screen of 1.5 mm did not cause further decrease. The same tendency was observed by Ruckebush & Marquet (1963) and Journet & Hoden (1973), using cattle. Normal rumination pattern of cows was found when the mean particle size was above 0.8 mm for grasses and 1.0 mm for lucerne in wafers or cobs. The times required for eating and ruminating were normal and there were no significant differences between grass cobs and grass pellets when the cows were allowed to consume long straw, of which 0.7 and 1.3 kg was eaten per day (Journet & Hoden, 1973). Several authors reported that the time spent eating was highly correlated with that spent ruminating. Welch & Smith (1971) found that in a steer fed on pellets of lucerne meal with concentrates rumination pattern recovered to normal when 1500 g poly(propylene) ribbon 5 cm long was supplied. It is unlikely that fatigue of jaw muscles might limit voluntary feed intake of forages, since Campling & Balch (1961) removed boli from the rumen and found a higher feed consumption. So there seems to be no evidence that the higher feed intake of ground and pelleted forages is caused by the lower time spent eating and ruminating.

Generally the time spent eating and ruminating declines with grinding and pelleting through reduction in the bulkiness of forages in the diet. This decline, related to mean particle size, can result in abnormal ruminating patterns or no rumination at all. Small amounts of straw, even from bedding or poly(propylene) fibres, can reestablish regurgitation and rumination.

2.3.3 Salivation

Lower salivation, with ground and pelleted roughages, was suggested by Moore (1964). Evidence for less salivary secretion was found by Putnam et al. (1966) with oesophageally fistulated steers receiving a finely ground and pelleted diet of 89% hay with concentrates, which was compared with a coarsely ground mixture. Saliva could be sampled only during periods without eating and ruminating. Oltjen et al. (1965) observed no significantly different amounts of saliva secreted by steers on pelleted or unpelleted conventional or purified rations.

A better measurement of salivary secretion, even during eating and ruminating, can be made with a permanent parotic fistula. Kaufmann & Orth (1966), using this technique, observed a 7-8% lower secretion of saliva, with ground and pelleted hay than with chopped hay. On concentrate-rich diets also 10% less saliva was produced than on diets rich in crude fibre. Poutianen (1968) reported lower saliva flux of cows when the amount of long hay was reduced to less than half the ration. Kaufmann & Orth (1966) found that during rumination, salivary flux increased over that during ingestion of feed. They estimated total flux of saliva produced by a cow at 75-90 litre/day and Balch (1958) at 90-190 litre/day. Reduced salivation will lower buffer capacity and ruminal pH, as found by Cullison (1961) and others on pelleted feeds. Baile & Forbes (1974) reviewed the evidence and concluded against a role of rumen pH in the normal range as a physiological regulator of intake, although under abnormal conditions it may be a principal cause of hypophagia. It is therefore unlikely that a reduction in saliva flux, as found by Kaufmann & Orth (1966) is an important factor in control of feed intake, especially since salivation did not increase as rumen pH decreased. However, feed intake seemed depressed when the pH of rumen fluid fell below 5.5 because of the rumen stasis that resulted (Baile & Forbes, 1974). An effect of pH in productive dairy cows receiving a lot of concentrates cannot be excluded.

2.3.4 Rumen function and microbial activity

The rate of passage of digesta from the reticulo-rumen depends on the motility of the stomachs. Pressure in the reticulum, reticulo-ruminal fold, rumen, omasum and abomasum can stimulate motility; however gross distention there and in the duodenum can inhibit contractions (Baile & Forbes, 1974). Orth & Kaufmann (1964) reported a 50% lower motoric pressure in the rumen when ground pelleted hay was fed instead of long hay, although the contractile rate was no different. However, reticular contractile rate in dairy cows measured by Freer & Campling (1966) on a diet of long or ground artificially dried grass ad libitum was 1372 and 1049 per day and for straw 1812 and 1648 per day, respectively. A decrease in rumen motility on an all-pelleted diet relative to a ration of silage with pellets of forage and concentrates, fed to dairy cattle, was reported by Jentsch et al. (1970).

The liquid in the rumen and its suspended microbes and small particles were mixed more rapidly and completely than rumen contents with long hay (Hungate, 1966). In sheep, however, this mixing may be more difficult, when rumen contents with forage pellets formed a "thick purie", as reported by Blaxter & Graham (1956), whereas with long material there was a marked separation of a liquid portion. Also because a higher content of dry matter in rumen digesta was found (Thomson, 1972), it seems reasonable to suppose that the fermentative process was not identical for diets with pelleted or long forages under these circumstances. It is not clear whether the same effects are found in cattle since the dry matter content of rumen digesta in cattle is generally lower than in sheep. So the effect is uncertain of a lower contractile rate on rumen fermentation in cattle on a diet of pelleted forages. The effect of motility on rate of passage of digesta in relation to regulation of feed intake is discussed later.

Changes in the microbial population of the rumen and in fermentation products might affect voluntary feed intake. In the literature, however, variable changes in the microbial flora with grinding and pelleting of the forage have been reported. This may be partly due to difficulties in sampling of rumen contents at the right time and place and in the culture of the rumen micro-organisms. Warner (1965) reported that populations could be quite different between ruminant individuals. Even the same animal, kept under constant conditions, could have entirely different rumen populations from time to time. He concluded that it would be difficult to establish any relation between the nature of the diet and the microbial flora without taking many samples, preferably from different parts of the rumen and from several animals.

Alterations in the diet are often accompanied by changes in the microbial populations. Diets richer in readily fermentable nutrients support greater numbers of microbes. On diets of ground pelleted dried grass, about twice as many viable bacteria were counted than on diets with long forages. This was mainly thought to be caused by the increased availability of carbohydrates by processing the forage. Cereal diets also usually increased the total numbers of microbes, although the extent of the change depended on the nature of cereal, its level relative to roughage and the total dry matter intake of the ruminant. Too rapidly fermentable carbohydrates, as from flaked maize, and great amounts of concentrates reduced cellulolytic activity and often resulted in high populations of lactogenic bacteria (Porter et al., 1972). On ground forage, high populations of cellulolytic bacteria were found but the decreased digestion of cotton fibre in the rumen suggested lower cellulolytic activity (Porter et al., 1972), reported also by Bines & Davey (1970) and Jarrige et al. (1973a).

A distinct difference was found in distribution of types of bacteria isolated for cattle fed on ground pelleted forages from cattle on long dry forage. In particular the numbers of butyrivibrios, which are sensitive to dietary changes, were greatly reduced, whereas higher counts of selenomonads (propionate-producing) and lactobacilli and bifidobacteria (lactate-producing) were found (Porter et al., 1972).

Changes in rumen microbial population are unlikely to affect regulation of feed intake directly but more likely indirectly through fermentation products, like volatile fatty acids (VFA), which are considered to play a role in the regulation of meal size in ruminants (Baile & Forbes, 1974). They concluded that there may be receptors on the luminal side of the rumen sensitive to acetate and probably propionate; moreover receptors for propionate may exist on the blood side of the ruminal epithelium (perhaps in the walls of ruminal vein). High concentrations of VFA seem to influence blood flow from the rumen and possibly act through regulation of rumen motility. Although in the long term, VFA introduced into the rumen did not much affect feed intake, the changes in VFA concentration may play a role in regulation of meal size.

Increased counts of microbes in rumen contents on a diet with ground pelleted roughages were associated with a lower pH of rumen contents, according to Cullison (1961), Orth & Kaufmann (1964), Montgomery & Baumgardt (1965), Oltjen et al. (1965) and Cottijn & Boucqué (1971) with cattle or sheep. They were also associated with increased concentration of VFA, according to Alexander et al. (1961), Orth & Kaufmann (1964), Cottijn & Boucqué (1971) and Journet & Hoden (1973). Alexander et al. (1961) measured a higher pH of 6.7, in the rumen contents when ground coastal Bermuda grass was offered instead of the long material. No reason for this result could be found but the higher VFA concentration with the diet of ground hay corresponded with the expected effect of grinding. No significant differences in VFA concentration were found with cobs or pellets from ryegrass (Journet & Hoden, 1973) or with early and late cut clover as cobs or chopped (Piatkovski & Koriath, 1970). Oltjen et al. (1965) found a tendency for higher VFA concentrations when conventional or purified rations were offered in loose ground form instead of pelleted. Eriksson et al. (1968) found higher VFA concentrations with pelleted forage than with wafers or cobs for dairy cows. Orth & Kaufmann (1964) and Putnam et al. (1966) found an increase in VFA concentration with pelleting of a ground ration. Hinders & Owen (1968) reported a lower ruminal concentration of VFA on a diet of lucerne pellets than of long material and found incomplete digestion of carbohydrates from pellets. From these results, no uniform effect of grinding and pelleting on changes in VFA concentration in the rumen could be deduced, although the reduction in particle size usually increases VFA production. Warner (1965) indicated that several factors could influence the concentration of VFA in rumen contents, for instance time of sampling, frequency of feeding, total feed intake, fineness of the feed, and ingredients and proximate composition of the ration. Since ground forage produced a higher peak of VFA immediately after feeding but was lower at other times of the day, it is difficult to draw a conclusion from samples taken at a single moment after feeding. Nevertheless, the change in VFA concentrations seemed to depend mainly on the availability of carbohydrate for microbial fermentation. Grinding and pelleting of forage may increase this availability, presumably mainly by the greater surface exposed to enzymic attack (Hungate, 1966). Probably the latter effect may explain why Eriksson et al. (1968) and Journet & Hoden (1973) found a high VFA concentration, when pellets were offered to dairy cows instead of wafers or cobs from grass hay or lucerne, but then no increase in VFA will be found when particle size is small enough or when processing does not further reduce particle size, as indicated by the results of Journet & Hoden (1973) for italian ryegrass. The result of the experiment of Hinders & Owen (1968) may indicate that if finer particles can escape microbial breakdown in the rumen there would be no increase in VFA concentration.

The greater availability of readily fermentable carbohydrates in diets with ground and pelleted forages not only influenced VFA concentration in the rumen but also altered the proportion of acetate, propionate and butyrate in total VFA produced. The pH could fall as a result of lower amounts of saliva entering the rumen, the lesser buffering capacity, and an increase in VFA production. At a lower pH the cellulolytic activity of the rumen microbial flora decreases and more propionate and butyrate is produced relative to acetate. Most reports, according to Moore (1964), mentioned a decrease in the molar percentage of acetate and an increase of propionate or butyrate and a higher relative concentration of acetate to propionate, $r(C_2/C_3)$, although several changes were not statistically different. A significantly lower proportion of acetate was observed by Montgomery & Baumgardt (1965) on a pelleted diet with equal amounts of hay and maize, by Hinders & Owen (1968) and by Cottijn & Boucqué (1971) for grass hay pellets, and by Thomas et al. (1968) for a ground pelleted mixture of hay and grain (2.3/1). A higher proportion of propionate was found by Thomas et al. (1968) and Journet & Hoden (1973) on pelleted diets and a lower $r(C_2/C_3)$ was reported by Koriath & Piatkovski (1971) for lucerne cobs, by Cottijn & Boucqué (1971) for grass hay pellets, and Journet & Hoden (1973) for ryegrass pellets. Cottijn & Boucqué (1971) found no significant difference for propionate but a higher proportion of butyrate in the rumen of wethers fed on grass hay pellets compared with the long form.

Addition of concentrates to the diet resulted also in higher concentrations of VFA in ruminal fluid (Montgomery & Baumgardt, 1965; Cottijn et al., 1970; Koriath & Piatkovski, 1971) and an increase in the proportion of propionate and sometimes butyrate and a decrease of acetate. According to Hungate (1966), increasing amounts of starch stimulated microbial activity and caused higher concentrations of VFA and proportions of propionate. Because of the lower cellulolytic activity in rumen contents (Bines & Davey, 1970; Porter et al., 1972; Jarrige et al., 1973a; Journet & Hoden, 1973) acetate production decreased markedly and much lower $r(C_2/C_3)$ was found. The effect of grinding and pelleting of forages on VFA production was usually similar to an addition of concentrates to the ration. This may explain why in the respective experiments of Montgomery & Baumgardt (1965) and Koriath & Piatkovski (1971), supplements of maize and barley changed VFA production of the ration more with long forage than with processed forage.

It is difficult to test whether regulation of feed intake from diets with ground and pelleted forages is markedly affected by differences in concentrations and types of VFA produced in the rumen. Experimental addition of VFA salts, particularly acetate and propionate, added to the feed or to drinking water resulted in a feeding response of ruminants, which varied from marked decreases to some increases (Baile & Forbes, 1974). However, introduction of VFA into the rumen for some weeks had little or no influence on feed intake, presumably because of adaptation of either the receptors or the control centres. Baile & Forbes (1974) suggested that during feeding, even of spontaneous meals, increased fermentation, stratification of digesta, and slow mixing in the rumen could increase the concentration in rumen fluid around the papilli substantially more than the average in whole digesta. VFA action on receptors, either at the surface or after absorption, would then be enhanced. This effect could be greater in the rumen of sheep, where the concentration of dry matter is usually higher than in cattle. However if this should happen with ground pelleted feeds too, the higher VFA concentration usually found would have resulted in lower feed intake, whereas it was higher with grinding and pelleting of forages in several experiments. So the effect on feed intake is unlikely to be due to changes in VFA in the rumen. More evidence for an influence of VFA and pH in rumen contents seems available for ground and pelleted diets with much concentrates, though lactic acid may also be involved. With a gross excess of rapid available carbohydrates, especially on high-cereal diets, rapid fermentation could decrease the pH in the rumen below 5.5 or 6 and would upset the balance of the microflora and change the fermentation pattern. Lactic acid would then accumulate (Porter et al., 1972; Baile & Forbes, 1974). An increase in concentration of lactic acid in the rumen with pelleting was reported by Ghorban et al. (1966). On a diet with long lucerne hay and before supplying lucerne pellets, concentration of lactic acid was less than 50 mg/litre but 50 minutes after feeding lucerne pellets, it reached a peak of 250 mg/litre. Still higher values were found on diets with a large proportion of concentrates (Ghorban et al., 1966). The bacterial flora seemed able to convert lactic acid to VFA (Walker, 1968) and probably could reduce the absorption of VFA (Ghorban et al., 1966). This could perhaps partly explain the small positive or even negative effects found with grinding and pelleting of forages in diets with large proportions of concentrates.

For energy balance too, Baile & Forbes (1974) concluded that it was unlikely that VFA play a major direct role in regulation. On concentrate--rich diets, other metabolic factors associated with VFA concentration in rumen contents could play a role in regulation of energy balance.

Although it cannot be excluded that VFA play some role in feed intake of pelleted diets, no conclusion can be drawn about any quantitative effect in the regulation of voluntary feed intake.

2.3.5 Rate of passage of digesta

The voluntary intake of diets consisting mainly of roughages was considered to be limited by physical factors, like the capacity of the reticulo-rumen and the rate of disappearance of digesta from these organs (Section 2.1).

Information about the critical particle size necessary to pass the reticulo-omasal orifice is rather limited.

Welch (1965) placed indigestible poly(propylene) fibres 7 cm long in the rumen of sheep and recovered them in the faeces in a finely ground condition. Longer fibres 30 cm long remained unchanged in the rumen even after 28 days. Troelsen & Campbell (1968) showed that 71-97% by mass of the particles of lucerne and grasses in the abomasum of sheep could pass a 0.5-mm screen, whereas 95-99% was smaller than 1.0 mm. Pearce (1967) concluded that particles less than 0.7 mm passed the orifice, because such particles were frequent in the faeces.

Becker et al. (1963) reported that 93% of the dry matter in the omasum of young cattle could pass a 2-mm screen, and 67% a 1-mm screen; 35% and 70% of the material in the rumen of these calves was smaller than 1 and 2 mm, respectively, whereas 12% was greater than 3 mm. Dry matter in omasum included less than 1% of the category 3 mm or more. Grenet (1970) studied particle size of omasal contents and faeces of cattle fed on different rations and slaughtered 8-24 hours after the last feeding: 18% of omasal contents and 12% of the faeces did not pass a 1-mm screen and average length of omasal contents varied between 0.26 and 0.70 mm for different rations. Not only rumination but also bacterial breakdown would help to reduce particle size. Poly(propylene) ribbon 5 cm long (1500 g) was introduced into the rumen of a fistulated steer and 713 g was recovered after 14 days. No fibres were evident in the original form because of rumination. The reduction in particle size, however, was slow (Welch & Smith, 1971).

This information suggests that particles less than 1 and 2 mm diameter are small enough to pass the reticulo-omasal orifice of sheep and cattle, respectively. Troelsen & Campbell (1968) thought that the threshold value for particle size of digesta that can pass the orifice could not be measured in absolute terms, because of the element of randomness in the passage of digesta. They suggested that particle shape could have a greater specific importance for the rate of passage of digesta than "relative particle size" (i.e. the percentage of digesta passing a 0.25-mm screen).

Clearly any further reduction in particle size below the range, where the reticulo-omasal orifice is the main obstruction for passage of coarse roughage, has little or no effect on passage rate and voluntary intake of processed forages. Only when the breakdown of roughage is improved by increasing fineness, without exceeding the metabolic limits of regulation of feed intake may an effect on voluntary intake be expected.

Methods or processes that directly stimulate ruminal outflow of digesta or that increase the rate of fermentation and enhance the reduction in particle size enough to pass the reticulo-omasal orifice may affect the rate of disappearance of digesta. So an increase in the rate of passage of ground pelleted feeds may be expected as this processing reduces particle size.

As Sutton (1971) discussed, the rate of liquid outflow from the fore-stomachs or the abomasum can easily be measured, but the difficulties of marking and sampling solid particles in digesta have led to the use of indirect procedures for measuring mean retention times of indigestible feed residues. A common technique has been to measure the rate of excretion of stained feeds in the faeces, but also chromium oxide and lignin have been used as exogenous and endogenous markers, respectively. The reciprocal of the rate of decline in a marker, the average time spent in the rumen by the marker, is often called mean retention time. It is a common expression of differences in passage rate of digesta.

The excretion of the first 5% by mass of a sample of stained feed particles, given orally, was suggested by Balch (1950) as indicative of the time needed by feed residues to pass through the omasum, abomasum and intestine, whereas the difference in time needed by the next 75% of the stained particles (called the "80-5 percent excretion time") was thought indicative for the time the feed residues remained in the reticulo-rumen. However from later evidence, Balch & Campling (1965) concluded that the "80-5 percent excretion time" may not be a reliable index of the time digesta are retained in the reticulo-rumen, when there is a marked increase in the time digesta are retained in the lower gut.

The rate of passage depended on various factors: e.g. amount of food consumed; meal frequency; reduction in particle size by physical or microbial degradation; shape and mass density of feed particles (Balch & Campling, 1965).

Increase in the amount of feed ingested usually decreased the mean retention time of solids and liquids in the rumen (Sutton, 1971). Also lower retention times were associated with higher rates of reticular contraction. Increased rumen motility during eating was accompanied by a higher outflow of digesta from the rumen. The highest intake was found in those cows that had the smallest amount of dry matter in the reticulo-rumen and the lowest retention time (Balch & Campling, 1965).

The effect of grinding and pelleting on retention time in the digestive tract varied. Finely ground hay, included in a ration of long hay, passed through the tract more rapidly than the long hay (Balch, 1950). According to reports, either increases or decreases in mean retention time occur if all the hay is ground. Such inconsistencies are probably due to variations in fineness and the amount of feed consumed (Sutton, 1971). Campling & Freer

(1966) observed a lower mean retention time for ground pelleted dried grass and straw than for the original long forage, when given in restricted amounts, but no significant difference, when freely available for 5 h daily. When freely available for 5 h, a faster initial excretion of forage particles and a more prolonged later excretion resulted in little change in mean retention time. However Rodrigue & Allen (1960) showed that grinding of hay in a dairy ration of 2 parts hay and 1 part concentrates produced an earlier initial excretion of hay residues but also a lower "80-5 percent excretion time": the finer the hay, the faster the excretion. This difference from Campling & Freer (1966) could be caused by differences in feeding method or fineness of grinding. Keith et al. (1961) used chromium oxide and noticed the highest chromium concentration in faeces of dairy cows 22, 20, 32 and 28 h after dosage for ground, pelleted, chopped and long mixture of lucerne and cocksfoot, respectively. O'Dell et al. (1963) concluded from coloured particles in the contents of the digestive tract of dairy heifers a more rapid passage of ground pelleted coastal Bermuda grass hay.

These results agreed well with several experiments on sheep. Demarquilly & Journet (1967) showed that the amount of feed consumed by wethers interfered much with the effect of fine grinding and pelleting on the rate of passage of hay. Pelleted hays freely available twice a day remained in the digestive tract shorter than the corresponding chopped hays. With pelleted hays in restricted amounts, only retention time in the intestine ("5 percent excretion time") decreased. Stielen (1967) offered two levels of coarse, medium and finely ground lucerne hay to wethers and found no significant differences in rate of passage between the three degrees of fineness. A similar result with wethers was reported by Cottijn & Boucqué (1971) with pellets of ground hay from a screen with apertures of 2 or 4 mm. Jarrige et al. (1973a) presented a close relationship between mean retention time in the digestive tract of wethers and the mean particle size of 23 forages. The reduction in retention time found with decrease in mean particle size (mainly below 2 mm) was only partly related to the increase in level of feeding.

The effect of grinding and pelleting on rate of passage of undigested feed residues may depend also on mass density of the feed particles. Balch & Campling (1965) suggested that particles of 1.1-1.2 relative mass density passed most rapidly through the gut, as the shortest retention time in the rumen and in the hind gut was found for particles with relative density 1.2 and 1.0, respectively. King et al. (1962) concluded that ground coastal

Bermuda grass hay stayed longer in the reticulo-rumen and omasum than baled hay, whereas pelleted hay seemed to pass twice as fast, perhaps because of differences in relative density.

From the literature, the intake of forages depends largely on the amount of digesta in the reticulo-rumen and their rate of disappearance from it. Campling et al. (1963) supposed that the rate of disappearance of digesta derived from long roughages was presumably limited by the rate of breakdown of feed particles in the reticulo-rumen, but with ground roughages by the rate of elimination of digesta from the hind gut, which directly or indirectly affected the rate of flow of digesta from the reticulo-rumen. A more rapid initial excretion of stained particles from ground roughages supported this view and a longer excretion time may be caused partly by a lower rate of breakdown of feed particles in the reticulo-rumen, as indicated by the decreased cellulolytic activity and lower degradation of cotton thread or the rate of disappearance of straw from nylon bags in the rumen (Balch & Campling, 1965; Alvash & Thomas, 1971; Campling et al., 1963; Campling & Freer, 1966; Journet & Hoden, 1973; Jarrige et al., 1973a). Decreased motility, lower salivation, presence of a different microbial population and little or no rumination could also result in a lower breakdown of ground or pelleted roughages, because mixing and buffering of rumen contents was suboptimum under these conditions. These findings agreed with the alteration with grinding and pelleting in the place where digestion occurs, as reported by Beever et al. (1972) for sheep. Dirksen et al. (1972) provided data, which shows that less organic matter was digested in the reticulo-rumen and more in the intestines, when the diet included forage pellets.

With high-concentrate rations, the effect of grinding and pelleting of forage was only slightly positive or even negative because metabolic or chemical factors and not gut fill mainly regulated feed intake (Balch & Campling, 1965; Baile & Forbes, 1974).

2.3.6 Synopsis

Section 2.3 discusses the influence of grinding and pelleting of forages on various factors possibly involved in regulation of feed intake. Grinding and pelleting usually altered eating and ruminating behaviour, which, however, probably did not much affect control of meal size. Lesser salivation accompanied by lesser mastication and rumination could limit the buffering capacity in the reticulo-rumen and inhibit microbial fermentation after some time and alter rumen microbial population. Fermentation in the rumen usually increased because of a greater surface of feed particles and a greater availability of carbohydrates with grinding and pelleting. Also the proportions of volatile fatty acids in the rumen changed. Usually proportion of acetate decreased and propionate or butyrate increased. However, it seems unlikely that these changes were responsible for a higher feed intake from ground pelleted forages. Only with complete diets with a higher proportion of concentrates, in which the effect of pelleting was slightly positive or even negative, could these factors have played a role in regulation of feed intake.

Several authors suggested that the increased feed intake of ground pelleted forage was perhaps due to more rapid passage of digesta through the reticulo-rumen. Much evidence supported this hypothesis, although Demarquilly & Journet (1967) concluded that the increased rate of passage was due to a greater amount of feed consumed. However gut fill distal to the reticulo-rumen seemed to inhibit the increase in rate of passage due to reduction in particle size of pelleted forages.

The effect of grinding and pelleting of forages seemed to depend on the amount of readily fermentable carbohydrate in the diet, which was greater in highly digestible forages and in concentrate-rich diets. With such diets, feed intake may be mainly regulated by chemical or metabolic factors, since these readily available carbohydrates ferment rapidly, resulting in a lower pH, a higher concentration of VFA in the rumen, and a lower $r(C_2/C_3)$.

2.4 CONCLUSION

Regulation of feed intake and of energy balance are closely related, although the mechanism is poorly understood. In ruminants, the main physical factors in limitation of feed intake from roughage-rich diets were rumen capacity and rate of disappearance of digesta from the digestive tract, whereas metabolic factors may play a more dominant role in regulation of intake of highly digestible forages and concentrate-rich diets. Animal factors, like size and physiological state, and dietary factors, like composition and ration quality, for instance types of ingredient and physical form seemed to influence the amount of feed consumed. The quantitative relationships between the various factors are poorly known.

Mean particle size of ground forages cannot be described by the size of the apertures of the screen used for grinding. Particle size distribution was only roughly indicated by sieving methods in terms of mean particle size, modulus of fineness or modulus of uniformity.

Pelleting of ground forages can further reduce particle size. The extent to which particle size of forages is reduced by grinding and pelleting depends on the type of forage, stage of maturity, drying method and dry matter content of the material, the type of mill and the speed at which it is run, the screen and the type of press.

The reticulo-omasal orifice seems to be the main obstruction for passage of coarse particles from the reticulo-rumen, although no precise size limit can be defined. Diameter of particles in the omasum of cattle is mostly less than 2 mm.

An important reason for higher voluntary intake of ground, pelleted or wafered forages than of the original long forage seems to be the reduction in particle size. However, a lesser increase or even a decrease in feed intake may accompany poor palatability of the processed forage through a lot of dust or fines, or because pellets or wafers are too hard and too compact. In general feed consumption increases as particle size decreases, although grinding through a screen with apertures less than 10 mm and pelleting caused little or no further increase in voluntary feed intake.

The effect of grinding and pelleting seems greater for sheep than for cattle and smaller for lactating than for growing and fattening cattle. The composition of the diet may be involved too. The effect of processing on intake seems greater in more mature forage and in less digestible forage. The type of forage may influence the size of this effect too. The amount of concentrates (mostly rather high for dairy cows) decreases the intake of dry matter from long forages by 0.2-0.6 kg per kg dry matter from concentrates and often decreases intake of dry matter from pelleted forages by 0.8-1.0 kg per kg dry matter from concentrates. The positive effect of pelleting forage on total intake of dry matter generally decreases with a higher proportion of concentrates, and even became negative when more than 50-60% of the total dry matter in the ration was from concentrates.

Grinding and pelleting of forage reduces the time spent eating and ruminating and might lower salivation. It sometimes lowers pH and increases concentration of VFA in the rumen fluid, alters the microbial population and lowers the proportion of acetate and raises that of propionate or butyrate. The increased rate of disappearance of digesta from the rumen caused by the small initial particle size could also be due to the greater surface area exposed to microbial breakdown. Rapid fermentation can thus cause both physical effects – lack of gut fill – and metabolic effects – increase in VFA. The metabolic effects seem important for pelleted concentrate-rich diets and for highly digestible roughages.

3 Literature on digestibility and utilization of energy from ground and pelleted forages

The nutritive value of feedstuffs mainly depends on their digestibility and the utilization of the digestible nutrients by the ruminant. After absorption from the gut, the nutrients can be used in intermediary metabolism for maintenance and production.

In the ruminant, a substantial part of the feed consumed can be fermented and utilized by microbes in the rumen. Much of the fermentation products formed, like VFA and ammonia, are absorbed through the rumen wall. After leaving the reticulo-rumen, these microbes can serve as feed for the host animal. The microbes thus enable ruminants to utilize cellulose-rich feeds, which are indigestible for monogastric animals. The microbes in the reticulo-rumen produce methane while utilizing part of the ingested feed and this methane and its energy (9.45 kcal/litre; 39.54 MJ/m^3) are lost by eructation.

The rate of fermentation will depend largely on the availability of the feed to microbial attack. Chemical or physical treatments that increase this availability may accelerate breakdown and increase the amounts of degradation products like VFA and ammonia formed shortly after feeding. The extent to which the microbes are able to ferment the cellulose-rich feeds depends not only on the availability of the feed to microbial attack but also on the time the feed particles stay in the rumen. A rapid rate of passage, for instance by high feeding level or small particle size, may decrease microbial breakdown of feed particles.

The potential nutritive value of a feed for dairy cattle can be derived from its chemical composition and from digestibility of its nutrients, determined either in vitro with rumen fluid or in digestibility trials with ruminants. The common basis of feed evaluation for ruminants is the digestibility of feed by sheep (wethers). The predictability of digestibility in the cow from a sheep trial depends on the difference in digestive capacity between cows and sheep and also in the feeding level, which markedly influences digestibility in ruminants. In most digestion trials, the wethers are fed at maintenance level or just above. The high feeding level of dairy cows producing 20-30 kg milk or even more cannot be reached by wethers. In such digestion trials, the requirement for proteins, vitamins, minerals and trace elements have to be met to avoid abnormal results.

To calculate metabolizable energy, which is the energy available to the dairy cow, it is necessary to know the faecal energy losses and those with methane and urine, either by estimation or by measurement.

The net result of consumed feeds for the dairy cow can be measured in a feeding trial. The milk produced and the body gain results from the consumed ration; body loss may occur at low feed intake. It is, however, difficult to measure the net energy content of a feed in this way, because it is not possible to measure the change in the animal's energy content. Only by roughly estimating this value from the change in liveweight is it possible to calculate the net energy content from a feeding trial (van der Honing & Rijpkema, 1974).

Energy balance trials can better measure the net energy of feeds. Moreover, the balance technique provides more information about the different steps in utilization of the feed's gross energy by the dairy cow and also shows the types of energy loss.

This chapter presents information from the literature about the effect of processing on digestibility, on the amount of methane and urinary energy lost and on the nutritive value or content of net energy for milk production of processed forages.

3.1 DIGESTIBILITY

The difference between the amounts of a component in the feed consumed and in the faeces excreted is said to have been 'apparently digested'. Digestible organic matter, nitrogen and energy, for instance, are indicated by D_O, D_N and D_E according to the proposal to European Association of Animal Production by Blaxter et al. (1973) and are calculated as

$$I_O - F_O = D_O$$
$$I_N - F_N = D_N$$
$$I_E - F_E = D_E$$

in which I_O, I_N and I_E is the amount of organic matter, nitrogen and energy consumed and F_O, F_N and F_E is the amount of organic matter, nitrogen and energy excreted in faeces, respectively. The unspecific term 'digestible' and the symbol D are used hereafter for 'apparently digestible'.

3.1.1 Digestive capacity of sheep and cattle

In various investigations, the digestibility of feeds by sheep and cattle have been compared (e.g. Cipolloni et al., 1951; Swift & Bratzler, 1959; Dijkstra et al., 1962; Blaxter & Wainman, 1964; Buchman & Hemken, 1964; Blaxter et al., 1966; Leaver et al., 1969; Schiemann et al., 1971; Greenhalgh & Reid, 1973; Schiemann et al., 1974).

Cipolloni et al. (1951) studied 1912 digestibility trials from 386 authors and found significant differences between sheep and cattle in the digestibility of organic matter (d_O), crude fibre (d_{XF}), N-free extract (d_{XX}) and ether extract (d_{XL}) for dry forages. For silages and concentrates, only d_{XL} was different, although some feeds appeared to be digested better by sheep and others by cattle. They concluded that to predict digestibility of feeds for cattle with a high precision trials with cattle were preferable over those with sheep.

Swift & Bratzler (1959) reported for 28 forages no significant difference in digestibility of sheep and cattle for dry matter, crude protein and energy from trials at different experiment stations. In the Netherlands, Dijkstra et al. (1962) observed no important differences in digestibility of hay and silage by wethers and dry cows. Both species were fed at the same level relative to maintenance. These findings were generally confirmed by Blaxter & Wainman (1964) and Schiemann et al. (1971), although, with cattle, the latter reported a 5 percentage unit lower digestibility for crude protein than with wethers.

Differences in digestibility of energy between sheep and steers were found by Blaxter et al. (1966) for oat straw, hay and artificially dried grass, when given ad libitum. The feeding level, expressed as a multiple of maintenance requirement or mass of a constituent or energy divided by metabolic body size, was different for sheep and steers. Leaver et al. (1969) used dry or lactating cows to compare their digestive capacity with that of sheep. All received artificially dried grass ad libitum and some sheep were also fed at maintenance level. Despite the higher feeding level, the dry and the lactating cows had a slightly higher digestibility of organic matter and crude fibre than the sheep fed ad libitum, but for sheep fed at maintenance, there was a good agreement. However, the digestibility of cows was determined using a marker (chromium oxide) technique but in sheep by total collection and this may have reduced the validity of the comparison.

Buchman & Hemken (1964) reported that dairy cows, heifers and sheep digested dry matter, crude protein and energy from their experimental hays equally well, although digestibility of pelleted hays was lower than of chopped hays. In these trials, the feeding level differed between the species (on average 142, 105 and 80 $g/kg^{\frac{3}{4}}$ for dairy cows, heifers and sheep, respectively) but not excessively.

Greenhalgh & Reid (1973) showed that respective digestibility of dry matter for steers and wethers was 69.9 and 67.2 for long and 56.9 and 58.6 for ground pelleted artificially dried grass. Intake of dry matter by cattle and sheep was 81.8 and 56.8 for long and 90.7 and 82.4 $g/kg^{\frac{3}{4}}$ for pellets, respectively. They concluded that on average cattle and sheep did not differ in their digestive capacity, although there was a tendency for cattle to digest long forages better than sheep, whereas sheep digested pellets better.

Schiemann et al. (1974) showed that the digestibility of energy from different rations offered to dairy cows at 2.9 to 4.3 times maintenance requirement for energy was a few percentage units lower than for sheep at feeding level between 1.2 and 1.4.

In general, digestibility of organic matter and energy from forages by sheep is useful in predicting digestibility by cattle. The discrepancies sometimes found are probably mainly due to a different level of feeding for cattle and sheep. The digestibility found at maintenance level of feeding of wethers is close to that for cows and this digestibility can be derived from the sheep data with reasonable precision. However for crude protein, there is some evidence for a lower digestibility by cattle than by sheep (Schiemann et al., 1971), although not from all trials (Swift & Bratzler, 1959; Dijkstra et al., 1972).

3.1.2 Effect of level of feeding on digestibility of forages

The literature on the effect of feeding level on digestibility by sheep and cattle has been surveyed recently by several authors (Wiktorsson, 1971; Schiemann et al., 1971; Dijkstra, 1972; Ekern, 1972).

The digestibility of dry long or chopped forages by sheep was only slightly reduced by increasing the feeding level. In general, digestibility was further depressed when ground and pelleted forages were used or with mixed rations of forages and concentrates (Blaxter & Graham, 1956; Leaver et al., 1969; Alvash & Thomas, 1971; Wainman et al., 1972; Dijkstra, 1972).

According to Blaxter & Graham (1956), the main reason digestibility is depressed at a higher feeding level seems to be a lower retention time in the digestive tract and especially in the reticulo-rumen. Because of the faster rate of passage, the microbes in the rumen have less time to degrade fibrous parts of the feeds and the digestibility of cell-wall constituents is depressed more than that of the cell contents. The amount of dry matter consumed is an important factor in digestibility as measured. Dijkstra (1972) suggested that in digestibility trials wethers should be given a restricted constant amount of dry matter rather than fed to the maintenance requirement for energy, because a much greater amount of dry matter from poor forage than from highly digestible concentrates is required to meet the maintenance requirement. Dijkstra (1972) envisaged that standard figures could be obtained in this way for predicting feeding value in tables, which would be comparable between different stations.

For cattle fed on long forage as sole feed the digestibility was generally not significantly different, when feed intake increased, although a few reports indicated a depression (Ekern, 1972). This will be at least partly due to the rather restricted increase in intake, which can be obtained with long forages. With mixed rations of forage and concentrates, the increase in level of feeding over maintenance requirement usually resulted in a substantial depression in digestibility. But some authors have reported an equal or even a higher digestibility (Ekern, 1972; Dijkstra, 1972; Wiktorsson, 1971). Moe et al. (1965) offered rations containing 50 to 67% concentrates to dairy cows at increasing levels of feeding up to five times maintenance requirement. They calculated a depression in digestibility of 4 percentage units per unit increase in feed intake relative to maintenance requirement for total digestible nutrients (TDN). Experiments with dairy cattle by Brown (1966) indicated a decline in digestibility of 3.8, 2.0 and 1.6 percentage units for rations with a grain-to-hay ratio of 4:1, 2:1 and 1:4, respectively, whereas Flatt et al. (1967) found a decrease of 6.6 percentage units with cows receiving purified diets. Schiemann et al. (1971) reported a decline of 3 percentage units and Ekern (1972) found in his own experiments a depression of 3.6 percentage units for digestibility of organic matter per unit increase in feeding level relative to maintenance. For different rations offered to dairy cows, Schiemann et al. (1974) calculated an average decrease in digestibility of energy of 2.7 percentage units per unit increase in relative feeding level, assuming that digestibility at maintenance level was the same for cows and wethers.

However Wiktorsson (1971) offered cows a ration of 7 kg hay and 1 kg beet pulp supplemented with increasing amounts of concentrates up to 15.7 kg, but found no decrease in digestibility of concentrates, if he assumed that the digestibility of hay and beet pulp remained constant. He suggested that the long preliminary period before the digestibility trial allowed the cows to become well adapted to the ration and might explain why these results did not agree with the general view of the literature. His assumption that the digestibility of hay and pulp remained constant is probably incorrect.

The decline in digestibility at higher levels of feeding is variable. Factors like forage quality, forage-to-concentrate ratio, content of crude fibre in the diet, processing of the forage, forage species and amount of structured material in the diet seems to be involved in the depression of digestibility, though the quantitative effect of these factors is poorly known (Schiemann et al., 1971; Dijkstra, 1972; Ekern, 1972; Journet & Hoden, 1973; Jarrige et al., 1973a).

The effect of feeding level on digestibility seldom differs between dry matter and organic matter, but there is some evidence for a greater effect on crude fibre and nitrogen (Blaxter & Graham, 1956; Ekern, 1972). Ekern observed a significant decline in d_O, d_N, d_{XL} and d_{XF} of 3.55, 5.78, 7.01 and 7.29 percentage units, respectively but an insignificant decline in d_{XX} by 1.28 percentage units, when the relative feeding level to maintenance of a ration of silage, roots and concentrates was raised by one unit without changing the composition of the diet.

In energy balance studies, increasing levels of feeding increased faecal losses of energy but decreased losses of energy in urine and methane. So the greater faecal losses were partly or fully compensated by lower methane and urinary losses and metabolizable energy content could not very well be predicted from digestibility of energy measured at higher feeding levels (Schiemann et al., 1971; Ekern, 1972) because at the higher level, metabolizable energy relative to digestible energy was higher than at maintenance level.

Most reports from the literature support the conclusion that at higher feed consumption of rations by cattle, the digestibility of organic matter and energy declines, although this decline is small for rations with only long forage. The decline is greater for mixed rations containing a substantial proportion of ground pelleted forages or concentrates. The depression in digestibility seems to increase with poorer forage and also with a higher proportion of concentrates. This depression at higher levels of feeding is thought to be caused mainly by an increased rate of passage of digesta and a lower retention time, reducing microbial breakdown of the fibrous part of the ration. The greater decline in digestibility of fibre and cellulose reported in the literature supports this view. The lower digestibility of fibre may also be partly caused by a lower cellulolytic activity of the rumen bacteria, with lower pH and the altered conditions in the rumen with diets containing a high proportion of concentrates (Porter et al., 1972).

3.1.3 Effect of grinding and pelleting of forages on digestibility

The effect of grinding and pelleting on digestibility and on factors involved have been the subject of many studies. Many used sheep but some also cattle. Table 5 surveys results with cattle of comparisons of ground or pelleted forages with similar data on the same forages in long or chopped form. As shown in Section 3.1.2, a comparison of chopped or long forage with the ground or pelleted material can only show the change in digestibility with processing when the feeding level of both rations is the same. Otherwise a combined effect of level of feeding and processing is measured.

Wilkins (1973) found a similar effect of processing forages on their digestibility by cattle and sheep. Greenhalgh & Reid (1973) reported only small differences between these species, so that the influences of the factors observed for sheep can in general be applied to cattle too.

Many authors reported a decline in digestibility of forages with processing, although some insignificant differences and a few increases were found (Minson, 1963; Koriath & Piatkovski, 1970; Greenhalgh & Wainman, 1973). The depression in digestibility was often greatest for crude fibre and cellulose (Table 5; Blaxter & Graham, 1956; Minson, 1963; Demarquilly & Journet, 1967; Wilkins, 1973). With grinding and pelleting of forage, the average depression of d_O, d_N and d_{XF} calculated from Table 5 was 5-6, 2-4 and about 15 percentage units or about 10, 5 and 25%, respectively, but the results varied considerably.

The depression in digestibility seemed to increase with higher feeding levels for sheep (Blaxter & Graham, 1956; Wainman et al., 1972) and for cattle (Campling et al., 1963; Campling & Freer, 1966).

Finer grinding generally resulted in a greater decline in digestibility (For sheep: Blaxter & Graham, 1956; Demarquilly & Journet, 1967. For cows: Rodrigue & Allen, 1960), although not always (Swanson & Herman, 1952; Cottijn & Boucqué, 1971). The reduction in particle size was the most important factor in the decline in digestibility (Jarrige et al., 1973a). Compressing ground forages into pellets may reduce the mean particle size and may further depress digestibility (King et al., 1963; Stone et al., 1966). However particle size distribution in many studies was not measured, or only before pelleting, and the discrepancies in results could possibly have been explained, if the differences in mean particle size or particle size distribution of the processed forages had been known. A supposed finer grinding may in some cases not have resulted in a substantial reduction in mean particle size. Pelleting of ground forages differing in mean particle size may further reduce the particles of the coarsely ground forage to a greater extent than of the finely ground. The lack of information on fineness in absolute terms makes it difficult to interpret the results.

Little or no differences in digestibility by sheep between meal, pellets and reground pellets were reported by Lindahl & Reynolds (1959) and between meal and pellets by Dijkstra & Frens (1963). Demarquilly & Journet (1967), however, observed a greater depression in digestibility of organic matter and crude fibre for pelleted than for ground hay compared with the chopped material. However, the chemical composition, especially crude fibre, of ground and pelleted forages of Demarquilly & Journet (1967) were quite different. So there is no reason to suggest a specific effect of pelleting on digestibility, except that due to a reduction in particle size.

Forage species may also influence the depression in digestibility (Demarquilly & Journet, 1967; Wainman & Blaxter, 1972 and Jarrige et al., 1973a). The depression due to processing in sheep seemed greater for grasses than for lucerne. However the decline was practically unaffected by grass species, stage of maturity and the preceding number of harvests in that season (Jarrige et al., 1973a). Heany et al. (1963), however, reported a greater depression in digestibility of processed forage by sheep with increasing maturity. The effect of maturity on the depression in digestibility was also variable in digestibility trials with cattle (Stone et al., 1966; Greenhalgh & Reid, 1973).

Hinders & Owen (1968) found a tendency for an adaptation to a ration of pelleted forages, because the depression of digestibility of organic matter was 7.2 percentage units during the first weeks, but fell to 5.0 after 5 weeks.

Alteration in the composition of the ration by adding concentrates to it resulted in greater (Balch, 1950; Montgomery & Baumgardt, 1965) or smaller (Greenhalgh, 1973; Greenhalgh & Reid, 1973) depressions in digestibility with grinding and pelleting than with forages as the sole feed.

For the different proximate components of the ration, a high correlation

Table 5. Effect of processing of forages on apparent digestibility (d) by cattle.

Sex and physiol. state of cattle	Feeding level or method[5]	Type of feed, unprocessed – processed
Steer	restr. (3.5- 7.5 kg)	lucerne hay – ground
Steer	ad lib. (9.4-10.6 kg)	e.c. grass hay – ground
Steer	ad lib. (9.4-10.7 kg)	e.c. grass hay – pelleted
Steer	ad lib. (8.8- 8.5 kg)	l.c. grass hay – ground
Steer	ad lib. (8.8-10.8 kg)	l.c. grass hay – pelleted
Steer	restr. (27 g/kg)	lucerne – pelleted
Steer	ad lib. (84-85 g/kg$^{3/4}$)	e.c. dried grass – pelleted
Steer	ad lib. (74-94 g/kg$^{3/4}$)	l.c. dried grass – pelleted
Steer	ad lib. (87-93 g/kg$^{3/4}$)	l.c. grass/conc. 60/40 – pelleted
Heifer	over 20 g/kg	chopped lucerne – coarse-ground
Heifer	over 20 g/kg	chopped lucerne – fine-ground
Heifer	near ad lib.	c. Bermuda grass hay – ground
Heifer	near ad lib.	c. Bermuda grass hay – pelleted
Heifer	ad lib. (82-99 g/kg$^{3/4}$)	grass hay (2nd cut) – pelleted
Heifer	ad lib. (87-86 g/kg$^{3/4}$)	grass hay/maize (50/50) – pelleted
Heifer	ad lib. (47-36 g/kg$^{3/4}$)	straw – ground
Heifer	ad lib. (74-83 g/kg$^{3/4}$)	straw/maize (50/50) – pelleted
Dry cow	restr. (9-11 kg)	grass hay – ground
Lact. cow	restr.	grass hay /conc. – ground
Lact. cow	restr. (25-30 g/kg)	grass hay/maize (2/1) – coarse-ground
Lact. cow	restr. (25-30 g/kg)	grass hay/maize (2/1) – medium ground
Lact. cow	restr. (25-30 g/kg)	grass hay/maize (2/1) – fine-ground
Dry cow	restr. (5 h/day)	grass hay – pelleted
Dry cow	ad lib. (5 h/day)	grass hay – pelleted
Dry cow	restr. (4½ kg)	art. dried grass – pelleted
Dry cow	ad lib. (10.9-10.7 kg)	art. dried grass – pelleted
Dry cow	restr. (4½ kg)	oat straw – pelleted
Dry cow	ad lib. (5.7-7.2 kg)	oat straw – pelleted
Lact. cow	ad lib.	wafered e.c. grass – pelleted
Lact. cow	ad lib.	wafered l.c. grass – pelleted

1. d_T = digestibility of dry matter.
2. digestibility of XF + XX.
3. digestibility of acid detergent fibre.
4. digestibility of cellulose.
5. Some rations are calculated per kg bodyweight or metabolic body size ($W^{3/4}$).
6. 1. Forbes et al., 1925
   2. Stone et al., 1966
   3. Hinders & Owen, 1968
   4. Greenhalgh & Reid, 1973
   5. Swanson & Herman, 1952
   6. King et al., 1963
   7. Montgomery & Baumgardt, 1965
   8. Balch, 1950
   9. Rodrigue & Allen, 1960
   10. Campling et al., 1963
   11. Campling & Freer, 1966
   12. Connell, 1973.

For subscripts, see List of Symbols.

d_0 or d_T[1] (long ration)	Increment with processing						
	d_0 or d_T[1]	d_N	d_{XL}	d_{XF}	d_{XX}	d_E	Ref.[6]
62.8	- 2.6	- 1.3	- 0.1	- 4.9	- 0.6	- 1.9	1
66.6[1]	- 4.4[1]	- 1.8	- 0.6	- 5.3[2]			2
66.6[1]	- 5.1[1]	+ 1.0	+ 4.0	- 6.9[2]			2
54.0[1]	-11.8[1]	- 4.7	- 6.7	- 8.5[2]			2
54.0[1]	- 5.2[1]	+ 1.4	+ 7.6	- 5.9[2]			2
64.4	- 7.2	-14.6	- 2.2	-17.0	+ 3.1	- 7.7	3
73.0	-16.7	-16.6		-24.8[3]		-17.5	4
69.0	-15.6	- 3.9		-28.1[3]		-12.2	4
71.3	- 8.3	- 2.8		-21.5		- 7.7	4
58.2	- 1.2	- 1.5	- 8.4	- 0.3	- 1.7		5
58.2	+ 0.2	+ 1.7	- 0.3	- 1.1	+ 0.9		5
54.0[1]	- 2.7[1]	- 3.1	-11.0	- 4.2	- 1.1		6
54.0[1]	- 8.7[1]	- 7.6	-11.1	-17.1	- 3.6		6
55.9[1]	+ 0.9[1]			-10.5[4]	+ 0.9		7
69.2[1]	- 1.7[1]			-18.3[4]	- 0.8		7
45.3[1]	- 3.9[1]			- 4.8[4]	- 0.3		7
59.7[1]	- 1.8[1]			- 9.3[4]	- 1.4		7
59.7[1]	+ 1.0[1]	+ 5.7	+ 1.9	- 4.2	+ 3.0		8
69.6[1]	-10.0[1]	- 8.4	-20.6	-20.2	- 7.0		8
62.8[1]	- 1.9[1]	+ 1.1	- 0.4	- 7.9	- 1.5		9
65.9[1]	- 4.5[1]	+ 0.0	- 3.7	-15.5	- 5.6		9
65.6[1]	- 9.3[1]	- 5.8	- 2.8	-22.2	- 0.6		9
61.8	-14.1	- 7.1	+ 9.2	-26.8	- 8.6		10
63.6	-20.7	- 1.2	+19.4	-34.6	-16.6		10
74.0	- 6.1	-10.9	+13.4	-17.7	- 3.1		11
72.2	-10.4	- 2.8	+19.7	-27.1	- 8.7		11
47.9	- 9.3	- 5.3	+ 0.3	-17.8	- 1.0		11
43.2	- 4.4	+16.0	+11.1	-11.7	+ 2.3		11
71.1[1]	- 8.9[1]						12
58.9[1]	- 0.0[1]						12

in digestibility coefficients was found mainly for dry matter, organic matter and energy. On average, the decline for nitrogen was smaller, but varied widely, whereas for ether extract increases or decreases were reported. The greatest depression was generally found for such cell-wall constituents as crude fibre, cellulose or acid-detergent fibre, whereas the decline for nitrogen-free extract was also variable, but on average less than of organic matter.

Many authors concluded that an increased rate of passage of ground and pelleted forages was the main reason for a decline in digestibility (Blaxter & Graham, 1956; Minson, 1963; Demarquilly & Journet, 1967; Jarrige et al., 1973a). As described in Section 2.3.4, the higher rate of passage gave cellulolytic bacteria less time to degrade the fibrous parts of the feed. However the greater surface area of finely ground forages may increase the rate of fermentation. The resulting change in conditions in the rumen, however, might have shifted the bacterial flora towards those with less cellulolytic activity (Porter et al., 1972; Jarrige et al., 1973a). Greenhalgh & Wainman (1973) suggested that the increased rate of fermentation partly compensates for the depression in digestibility caused by increased rate of passage of ground forages. The extent of this compensation would depend on type and number of microbes in the rumen, conditions of fermentation, rumen motility and absorption of fermentation products. This could be one reason for the great variation in results from different experiments. The inadequate quantitative knowledge of digestive processes in the rumen makes it difficult to predict the effect of processing for a given ration, also because a greater part of the feed could be digested in the lower gut (Section 3.1.4). Wilkins (1973) showed that 85% of the variation in depression of cell-wall digestibility could be accounted for by content of water-soluble carbohydrates, level of feeding, modulus of fineness and buffering capacity of the forage. He suggested that the association of depression in cell-wall digestibility with level of feeding and modulus of fineness was brought about by their effects on rate of passage, whereas the association with the water-soluble carbohydrates and buffering capacity probably arose through the suitability of conditions in the rumen for fibre digestion.

This section has shown that grinding and pelleting of forage generally depressed digestibility, more for crude fibre than for organic matter and energy. In Table 5, digestibility of organic matter, nitrogen and crude fibre were on average depressed by about 10, 5 and 25% or 5-6, 2-4 and about 15 percentage units, respectively, with grinding and pelleting, but the results vary considerably. The depression in digestibility seems to result from an increased rate of passage, especially at higher levels of feeding, and a reduced retention time in the reticulo-rumen. This and a lower cellulolytic activity of the bacterial flora caused a great reduction in the digestibility of fibre. The fermentation rate of readily available carbohydrates and of protein may have increased through the reduced particle size of the forage and the increased surface area for microbial attack. The lower retention time of digesta in the reticulo-rumen, however, may still depress digestibility of these nutrients. But incomplete digestion of feed in the rumen could be partly compensated by a shift of food digestion towards the small and large intestine, as described in the next section.

3.1.4 Sites of digestion of processed forages

To study whether greater amounts of digesta from diets with pelleted roughages were digested behind the reticulo-rumen, ruminants were used fistulated in the duodenum or ileum. This method of studying the digestion in the small intestine with fistulae is rather complicated and there are still technical problems, for instance, in the measurement of flow rate of digesta, the markers used and the sampling of digesta. These problems and the effect of this technique on the animal's behaviour hamper the interpretation of results that have been obtained in this way.

Experiments with sheep A considerable part of total digestible organic matter and digestible energy disappears from the gastro-intestinal tract behind the reticulo-rumen (Thomson et al., 1972). For long lucerne, 59, 29 and 12% of the digestible organic matter left the tract before, in and after the duodenum, respectively. Similar figures for pelleted lucerne were 51, 34 and 15%, respectively. For digestible energy, these percentages were for long forage 59, 33 and 8 and for pelleted forage 51, 36 and 13%, respectively. Beever et al. (1972) reported similar results for long or pelleted dried grass. Thomson et al. (1972) found lucerne cobs to be intermediate between long forage and pellets.

The changes in site of digestion of structural carbohydrates with pelleting of lucerne and dried grass were greater than for organic matter and energy. Cellulose and hemicellulose together formed between 30 and 40% of the dry matter in the feed. In sheep, 20-30% of the digestible cellulose and 15-40% of the digestible hemicellulose of pelleted forages were digested in caecum and colon (Thomson et al., 1972; Beever et al., 1972). Hogan & Weston (1967) found much lower values, supplying lucerne at 3-h intervals. Perhaps the type and drying method of the forage or the use of lignin as a marker by Hogan & Weston could be responsible for the discrepancy in results.

Pelleted forages resulted in a total flow of nitrogen through the duodenum as high as or higher than with long or wafered material (Thomson, 1972). Thomson (1972) argued that the increased flow of nitrogen through the duodenum could be attributed to food nitrogen rather than to microbial protein synthesized in the reticulo-rumen. The methods used to estimate synthesis of microbial protein in vivo, however, were not entirely satisfactory.

Macrae et al. (1969) showed that increasing the proportion of concentrates resulted also in a greater proportion of cellulose being digested in or behind the small intestine.

The increased rate of passage from the rumen with small particles and higher feed intake is suggested to be the major factor in an increased contribution of the small and large intestines to digestion of energy by sheep fed on pelleted diets (Blaxter & Graham, 1956; Thomson, 1972).

Experiments with cattle The literature on pelleted forages describes no investigations with cattle comparable in size with those for sheep. There were only a few experiments with cattle fed on long forages and concentrates. The proportion of structural carbohydrates digested in the large intestine, for various rations, was for cattle small (Gaillard & van 't Klooster, 1969; Watson et al., 1972) and for sheep greater (Thomson et al., 1972; Beever et al., 1972). So the effects on site of digestion found with cows may probably be smaller than in sheep. Results from Mitchell et al. (1967) support this view.

Campling et al. (1963) and Campling & Freer (1966) used lignin as a marker to study the amount of forage digested in and after the reticulo-rumen, when long or pelleted artificially dried grass, hay or oat straw was fed to dry cows in restricted amounts or ad libitum. Their results are presented in Table 6. The proportion of digestible organic matter and digestible crude fibre from pelleted forages leaving the reticulo-rumen was smaller than from long forages, especially when the diets were supplied ad libitum. More than 80% of digestible crude fibre from straw pellets, however, disappeared from the reticulo-rumen, probably because of a too low rate of passage due to a low rumen motility and a low degradation due to lack of nitrogen. The accuracy of the lignin method used, however, may not be high because of a wide variation in recovery of lignin (Kotb & Luckey, 1972).

Kaufmann et al. (1972) found for a dry cow on a diet with grass pellets and fitted with a reentrant cannula in the duodenum, that 29% of digestible energy disappeared from the tract before the duodenum. The long forage, however, was not compared.

In preliminary trials in 1971-1972, performed by students of the Department of Animal Physiology at the Agricultural University in Wageningen, (Wullink, van Ast, Jongbloed; unpublished reports), fistulated dairy cows producing about 5 kg milk/day received long or pelleted hay in restricted amounts or ad libitum. The site of digestion of energy behind the reticulorumen was little changed, if at all, with pelleting. Also the proportion of structural carbohydrates digested in the large intestine hardly tended to increase with the pelleted hay. In any case, this proportion was low (4-7%). As the digestibility of energy from the diets offered ad libitum was depressed 4.6 percentage units (8.1%) by pelleting, the reason for these small effects relative to results from sheep is not clear. The higher intake of the diet with pellets, which contained 2-4 kg of long hay and a small amount of concentrates, may have influenced this, although higher intake of pelleted forages and concentrates added to a ration for sheep generally altered the site of digestion more.

Several studies showed a higher content of dry matter in digesta entering the duodenum with pelleted than with long forages (e.g. Campling & Freer, 1966; Thomson, 1972).

The scarce information available from cattle suggests that the effect of processing on site of digestion might be smaller than in sheep, although in both species a reduction in total digestibility was observed with pelleting.

One can only hazard a guess why cattle on rations containing long roughages digested less of the feed in the lower intestine than did sheep. Sheep of course may fractionate the forage to a greater extent than cattle, hence perhaps the higher rate of passage from the rumen in sheep. Also the higher content of dry matter in rumen digesta of sheep (Waldo et al., 1965; Ingalls et al., 1966) may play a role in less favourable conditions for microbial degradation in the rumen than for cattle.

Even if reduced microbial digestion in the rumen is compensated by bacterial growth and by conversions in the large intestine, it is uncertain

Table 6. Effect of grinding and pelleting of forage on digestibility and mass of organic matter and crude fibre digested in the reticulo-rumen expressed as a percentage of total mass of digested constituent.

Forage	Feeding method	Intake of dry(I_T) or organic(I_O) matter (kg)	d_O	d_{XF}	Proportion digested in reticulo-rumen (%)		References
					D_O	D_{XF}	
grass hay (long)	restr.	$I_T = 3.95$	61.8	65.6	59.4	72.1	Campling et al., 1963
grass hay (pelleted)	restr.	$I_T = 3.95$	47.7	38.8	51.4	55.1	"
grass hay (long)	ad lib.	$I_T = 9.25$	63.6	66.2	75.0	76.1	"
grass hay (pelleted)	ad lib.	$I_T = 9.43$	42.9	31.6	58.7	40.8	"
art.dried grass (long)	restr.	$I_O = 3.4$	74.0	74.9	55.8	63.0	Campling & Freer, 1966
art.dried grass (pelleted)	restr.	$I_O = 3.4$	67.9	57.2	42.4	64.9	"
art.dried grass (long)	ad lib.	$I_O = 8.4$	72.2	72.2	50.4	70.4	"
art.dried grass (pelleted)	ad lib.	$I_O = 7.9$	61.8	45.1	32.7	49.2	"
oat straw (long)	restr.	$I_O = 3.5$	47.9	58.3	49.3	53.7	"
oat straw (pelleted)	restr.	$I_O = 3.6$	38.6	40.5	52.6	82.2	"
oat straw (long)	ad lib.	$I_O = 4.7$	43.2	54.1	46.5	56.9	"
oat straw (pelleted)	ad lib.	$I_O = 5.2$	38.8	42.4	32.5	41.3	"

whether these microbes in the large intestine are digested and how far they and their products become available to the animal or are lost in faeces.

The depression of digestibility with processing may mainly be caused by a reduced digestion in the reticulo-rumen, and although some compensation may occur in the intestines, it is uncertain whether an increased microbial digestion in the large intestine plays a significant role in nutrient supply to the cow.

3.2 EFFECT OF GRINDING AND PELLETING OF FORAGE ON METABOLIZABLE ENERGY

Metabolizable energy (M_E) is digestible energy (D_E) minus energy lost in methane (G_E) and urine (U_E):

$$M_E = D_E - G_E - U_E$$

The metabolizable energy can be expressed as a percentage of gross energy (metabolizability; $q = 100\ M_E/I_E$) or as a quotient to mass of dry or organic matter (M_E/I_T, M_E/I_O).

Relative to I_E, Forbes et al. (1925) and Blaxter & Graham (1956) observed lower G_E losses with ground or pelleted instead of long forage. Forbes et al. (1925) found for the sum of G_E and U_E relative to I_E a reduction from 12.9 to 11.9% when long hay was replaced by ground hay in a steer's diet. Blaxter & Graham (1956) showed a decrease with grinding and pelleting, and by increasing the amount of feed consumed by sheep. Wainman et al. (1972) found a tendency for lower G_E losses if sheep were fed almost ad libitum with pelleted dried grasses. They found that the compensation for greater losses of faecal energy by lower losses of G_E and U_E was only between 0.5 and 1% of I_E.

A reduction in methane production relative to I_E by cattle was reported by Moe et al. (1965). As Blaxter & Graham (1956) suggested, the lower G_E with increase in level of feeding and with grinding and pelleting must have reflected a more rapid passage of feed from the rumen.
Blaxter & Clapperton (1965) calculated an equation for sheep to predict G_E relative to I_E at maintenance level from digestibility of energy (d_E):

$$100\ G_E/I_E = 3.67 + 0.062\ d_E$$

By raising the feeding level relative to maintenance by one unit, $100\ G_E/I_E$ was expected to increase by $0.050\ d_E - 2.37$.

Although higher faecal losses with grinding and pelleting in energy balance studies with sheep were partly compensated by lower losses of energy in methane and urine, M_E was still generally lower (Wainman et al., 1972). The same tendency was found in beef cattle by Forbes et al. (1925). Only for sheep fed on poor hay and dried sainfoin had these poorly digestible forages a higher metabolizability when pelleted than when long (Blaxter, 1973).

3.3 EFFECT OF GRINDING AND PELLETING OF FORAGE ON NET ENERGY

The metabolizable energy (M_E) is primarily used for maintenance of the animal. If there is enough M_E, a cow can gain liveweight or produce milk without mobilization of tissue energy. So an increase in M_E may increase milk yield or liveweight as long as the maintenance requirement is already met. In feeding trials, the amount of feed consumed per unit milk yield or unit liveweight gain (feed efficiency) has often been used to compare the feeding value of different rations. To investigate the net effects of feed or the net energy content of feeds, M_E must be split into that required for maintenance and that for production. For a good comparison of feeds based on production only, as done in feeding trials the quotient of M_E used for maintenance to total M_E should be equal for each feed. In most reports of feeding trials, this quotient and reliable data for estimating it are lacking.

Sheep and beef cattle The utilization of M_E from long or processed forages by sheep was different (Blaxter & Graham, 1956; Wainman et al., 1972). The net efficiency of M_E above maintenance from pelleted forages was higher than from long material and more than compensated the depression in D_E or M_E with processing. Wainman et al. (1972) calculated that a better utilization of M_E with pelleting was caused almost entirely by a higher efficiency for growth and fattening, whereas there were only minor differences in efficiency for maintenance. So the net energy content for body gain of pelleted dried grass, fescue hay and lucerne was slightly or much higher than of the long forages (Table 7).

Results of feeding trials with growing sheep and cattle agreed with the conclusion from the energy balance trials, although in many trials no definite conclusion could be drawn because the energy equivalent of liveweight gain was unknown. In a survey of the literature, Beardsley (1964)

Table 7. Metabolizability of gross energy (q) and utilization of $M_{E,f}$(k_f) and R_E/I_E for the same dried herbage fed in long form or ground and pelleted to sheep. Data from Blaxter (1973).

Type of forage	q (%)		k_f (%)		R_E/I_E (%)	
	long	pelleted	long	pelleted	long	pelleted
Mixed herbage	63.2	58.9	42.4	51.6	25.8	28.5
Mixed herbage	63.2	59.9	42.4	50.4	25.8	27.5
Mixed herbage	58.5	48.2	38.0	51.6	21.2	24.8
Mixed herbage	54.4	51.6	38.8	51.3	17.9	22.9
Lucerne	48.8	41.4	31.0	43.3	15.1	20.8
Fescue hay	40.9	40.9	17.7	42.8	5.0	17.7
Poor quality hay	38.1	44.4	24.2	54.1	8.7	22.4
Dried sainfoin	37.4	40.7	-	-	-	-

showed that an improvement in daily gain of sheep and steers was mainly attributable to a higher feed intake from ground and pelleted forages than from the long material. Minson (1963) and Wilkins (1973) showed that the production response to grinding and pelleting was highest with the feed of lowest digestibility and that rate of gain from wafers was intermediate between that from ground and long forage. Stone et al. (1966) and Cottijn & Boucqué (1971) supported the conclusion of Beardsley (1964). When pelleted or long forages were consumed in almost equal amounts, however, there was a small or insignificant increase in daily liveweight gain (Dijkstra & Frens, 1963; Minson, 1963; Meyer et al., 1965; Wilkins, 1973).

The effect of pelleting an already ground high-roughage ration on growth and feed conversion was relatively small, whereas for ground rations containing 20-30% roughage, this effect was even negative (Beardsley, 1964).

For growing and fattening sheep and beef cattle, the net energy content of ground and pelleted forages seemed to be as high as or higher than of the long forage. This effect of processing tended to be higher for poorly digestible forages and rations with little or no concentrates.

Dairy cattle Several feeding trials were carried out on the effect of processing of forages on milk yield and composition.

Porter et al. (1953) compared baled, ground and pelleted lucerne as the sole roughage with a small amount of concentrates in a ration for lactating cows. No significant differences in yield of fat-corrected milk (FCM) were found in the first year, whereas in the second year a lower feed intake, ascribed to hard pellets, depressed milk yield. A similar effect of hard pellets was reported by O'Dell et al. (1968). Bringe et al. (1958) reported no significant difference in milk yield between long hay and large pellets. Ronning et al. (1959) found higher FCM production and liveweight gain on a ration with pelleted lucerne hay than with chopped hay, but feed intake with pellets was higher too. Similar results were reported by Keith et al. (1961) when a diet of lucerne and cocksfoot hay was offered ad libitum in long, chopped, ground or pelleted form as the sole feed.

Hutton et al. (1964) observed a slight increase in milk yield and a faster liveweight gain with lucerne wafers than with baled lucerne hay. A slightly lower milk production but an increased liveweight gain was found by Ronning & Dobie (1967) and Waldern & Baird (1967) for dairy cows on wafered lucerne hay than on baled lucerne hay. These effects of wafering were obviously mainly due to the higher intake of wafered forage.

Stone et al. (1966) found only insignificant differences in FCM produced by dairy cows with long, ground or pelleted hay in the diet, although the differences in milk yield tended to follow the effects of processing on feed intake, as found also by O'Dell et al. (1968). Journet & Jarrige (1967) reported a slightly higher milk yield on diets of silage, fodder beet and concentrates with lucerne hay as pellets than as long hay. These differences could be explained by differences in feed intake. With lucerne cobs, cows had a lower FCM production, lower fat content in milk and a higher gain in liveweight than with chopped lucerne. These effects were not reduced by adding barley to the diet (Koriath & Piatkovski, 1971).

According to their calculations, Speth et al. (1970) found an improvement of 12% in net energy for production (above maintenance) for lactating cattle with pelleted over baled lucerne as a supplement to a ration of baled lucerne hay. Their assumptions in calculating the net energy content, however, seem disputable. Rijpkema et al. (1971) replaced hay and concentrates by grass pellets in a dairy ration and found no significant difference in FCM production between these rations. They concluded, however, that the Kellner correction factor of 0.29 per percentage unit of crude fibre, used to calculate the starch equivalent, of pellets should be slightly higher.

From feeding trials, it is difficult to draw conclusions about the precise difference in net energy content between long and processed forages. One reason is that the energy equivalent of gain or loss in liveweight is not known and can only be estimated roughly; another is differences in feed intake or in amount of concentrates which upset the calculation of differences in net energy content between long and processed forages.

Frequency of digestive disorders and depression of the fat content of milk often increased on diets with ground and pelleted roughages without any long forage (e.g. Porter et al., 1953; Minson, 1963; Moore, 1964; O'Dell et al., 1968; Koriath & Piatkovski, 1971; Rijpkema et al., 1971). This certainly affected the milk yield and could have resulted in a less accurate estimate of the feeding value of pelleted forages. Moore (1964) and Connell (1973), however, suggested that a small proportion of long hay or straw added to a pelleted dairy ration should largely prevent these side-effects.

The small differences in response of dairy cows to long or pelleted forages in about equal amounts do suggest that the net energy content of the two types do not differ much, although the values of net energy content are not very precise. More precise values could be obtained from energy balance trials, but none on long or pelleted forages for dairy cows had been reported when this study began.

3.4 POSSIBLE EXPLANATION OF EFFECTS OF PROCESSING ON UTILIZATION OF ENERGY

Blaxter & Graham (1956) concluded that in sheep the depression in digestibility and methane production divided by mass of feed consumed was mainly due to a more rapid passage of pelleted forages, especially at high level of feeding. The heat losses were considerably lower on pelleted forages; energy losses in urine were not affected. Several reasons for lower heat losses from pelleted forage were given:

- reduction in time required for eating and ruminating (Forbes et al., 1925; Blaxter & Graham, 1956);
- less heat of fermentation in the rumen;
- differences in the proportions of products of digestive processes or differences in the rate at which these products reach the tissues, resulting in reduced heat loss during their utilization in intermediary metabolism (Blaxter & Graham, 1956).

Osuji (1971) calculated the energy cost of eating pellets by sheep on 100 cal/min but over 200 cal/min for unpelleted diets. In the experiment of Blaxter & Graham (1956), this would have resulted in about 7-8 kcal less energy for eating 1500 g pellets than of chopped hay, which would only be about 0.1% of the intake of gross energy.

Webster et al. (1974) tried to measure heat production in the digestive tract of conscious sheep. Differences in the temperature and oxygen content of aortic and portal venous blood and measurements of blood flow were used to estimate total and aerobic thermogenesis in the gut. The differences between the two was assumed to be heat of fermentation, which was on average 7.2% of M_E and tended to be lower for pellets than for long forages. Aerobic heat production in the digestive tract accounted for 15 and 11% of M_E for chopped and pelleted feeds, respectively. They concluded that the difference between the two might be attributable to differences in the work of digestion, as suggested by Kellner (1905), Forbes et al. (1925) and Blaxter & Graham (1956).

Differences in heat increment with supply of acetate and propionate to sheep and cattle (Armstrong et al., 1961; Holter et al., 1970) could partly be responsible for lower heat losses on diets of processed forages, because in several studies the rumen showed a lower acetate to propionate ratio (e.g. Moore, 1964; Journet & Hoden, 1973; see Section 2.3). As shown by Journet & Hoden (1973) and Koriath & Piatkovski (1971), this altered $r(C_2/C_3)$ and related effects might promote liveweight gain rather than milk production.

3.5 CONCLUSION

At about the same level of feeding relative to maintenance, there was usually no significant difference in digestive capacity of sheep and cattle. Digestibility coefficients of organic matter obtained from wethers fed at maintenance level can be used in predicting digestibility by cattle.

Increase in the level of feeding generally reduces the digestibility of organic matter and energy, mainly by an increased rate of passage and a lower retention time of digesta in the reticulo-rumen. The effect of level of feeding on digestibility seems to be related to forage species and quality, ratio of forage to concentrates, content of crude fibre and physical structure of the diet, and processing of the forage. Greatest depressions are usually with mixed rations containing a high proportion of concentrates.

Grinding and pelleting of the forage usually decreases digestibility; the effect was greater at higher levels of feeding. This effect of a reduction in mean particle size of a forage is generally greater for the fibrous parts of the diet than for organic matter and energy and tends to be lower for nitrogen. This effect seems to depend on forage species and quality. Pelleting of already ground forage or finer grinding causes small or insignificant decreases in digestibility.

It is not certain whether pelleted feeds cause a change in site of digestion by cattle from the reticulo-rumen to the small and large intestine, as found in sheep.

In sheep and possibly also in cattle, lower methane energy losses, mainly due to a lower retention time of digesta in the reticulo-rumen, and a considerable reduction in heat losses compensate for the higher faecal energy losses with grinding and pelleting of forages. Pellets of a poor forage may even have a higher net energy content than the long material, perhaps also in cattle. A better utilization of metabolizable energy for growth and fattening seems to be the reason for the equal or higher net energy content of pelleted than of long forages rather than an improvement in utilization of energy for maintenance. Differences in feed intake and unknown energy equivalent of liveweight changes hamper the interpretation of many feeding trials but accord with conclusions from energy balance experiments.

Feeding trials with dairy cows, given equal amounts of long or pelleted forages suggest no difference in feeding value, as long as the ration contains sufficient structural components to prevent digestive disturbances and great depressions in fat content of the milk. However, no precise conclusions can be drawn about the effect on net energy content of pelleted forages, because the net energy equivalent of liveweight change is not known. Also the rations of productive dairy cows, requiring much nutrients and energy, must contain a high proportion of concentrates and must be fed in great amounts; they often differ in composition from those of beef cattle.

The lack of data on net energy content of processed forages for dairy cows justified the initiation of a program of energy and nitrogen balance experiments.

4 Methods for balance experiments with dairy cows

To obtain comparable results of energy conversion of pelleted and unpelleted forages, the cows should be well adapted to the environmental circumstances of an energy balance experiment. In a preliminary period, the cows were trained to wear a harness and to stay in a respiration chamber until their lying period in the chamber approximated in length to that in the stall. In the same period, the cows were accustomed to the ration.

The rations should contain a sufficient amount of protein, minerals and vitamins to prevent any deficiency. With pelleted feeds, special attention is necessary to the fibrousness of the ration or to the structural components, which are almost destroyed by grinding or pelleting (Balch, 1971; Connell, 1973). In dairy cows, there is an increased risk of digestive disorders, of decreased rumination intensity and of depression in milk fat, which indicate disturbance of the normal digestion and rumen fermentation. To prevent such a situation in our experiments, 3-4 kg long hay or artificially dried grass was included in all rations.

To obtain results valid for more practical situations, we tried to avoid extremely positive or negative energy balances by supplementing the forages with concentrates supplied according to production.

The following definitions have been used:

$$D_E = I_E - F_E$$
$$M_E = D_E - U_E - G_E$$
$$R_E = M_E - H$$
$$R_N = I_N - F_N - U_N$$

Rate of heat production (H) is calculated as follows, using the constants advised at the 3rd Symposium on Energy metabolism in Troon (Brouwer, 1965) (see List of Symbols)

$$H = a \cdot \dot{V}_{CO_2} - b \cdot \dot{V}_{O_2} - c \cdot \dot{V}_G - d \cdot \dot{U}_N$$

where a is 1.200 kcal/litre, b is 3.868 kcal/litre, c is 0.518 kcal/litre and d is 1.431 kcal/g.
Energy balance (R_E) can be calculated from carbon and nitrogen balance by the equation

$$R_E = a \cdot R_C - b \cdot R_N$$

where a is 12.388 kcal/g and b is 4.636 kcal/g.
For conversion to joules,

1 kcal = 4.184 kJ

4.1 PROCEDURES

For separate collection of urine and faeces, a urinal was fastened to a harness (van Es & Vogt, 1959) worn by the cows. The urine flowed through the urinal into a 20-litre plastic flask while the faeces fell into big galvanized containers and were transferred into a galvanized or plastic covered boiler about 2-3 times a day. Any urine, which escaped collection in the urinal, fell into the big container and was collected as free from faeces as possible. The proportion of spilled urine seldom exceeded 5%.

Heat production was estimated from the production of carbon dioxide and methane and the consumption of oxygen in respiration chambers. The respiration trials were in one of the four respiration chambers in the Department of Animal Physiology of the Agricultural University (van Es, 1961; van Es, 1966; Verstegen, 1971). In these chambers, the temperature can be kept constant within ± 0.3 °C. The range of the installations is for temperature from 5 to 35 °C, for air velocity from about 10 to 80 cm/s and for relative humidity from 50 to 95% with an accuracy of about 5%. The experiments were at 15 °C and a relative humidity of about 75%.

4.1.1 Weighing and sampling

The rations, roughages and concentrates in separate plastic bags were weighed with an ordinary balance with an imprecision less than 0.2%. Another balance was used to weigh milk, urine and faeces, also with a weighing imprecision less than 0.2%.

All the daily rations of one experimental period were weighed out on the same day. Immediately before weighing each bag, a spoonful of concentrate mixture or of roughage pellets was put into a bottle with a tight-fitting stopper to get a composite sample. This sampling was done in duplicate. During the filling of every single bag with a day's or half-day's ration of long forage, a handful of material was put into a 30-litre sample container to obtain a composite sample of these forages. This sampling was done in triplicate.

Feed residues were collected each day, dried at 60-70 °C and after cooling stored until the end of the experimental period. Where residues were very small and mostly of hay, they were assumed to contain 95% dry matter and to have the same chemical composition as the dry matter of hay. Feed residues greater than 1% of the ration were weighed, sampled and analysed.

Immediately after milking, the milk was weighed. After mixing, a single sample of a constant proportion of the total amount (usually 1 or 2%) was put into a bottle with a tight-fitting stopper and with 1.8 – 2.4 g $HgCl_2$ as preservative. The sample was stored at 2-4 °C.

The urine collected each day was weighed and sampled in the same way as milk, but in duplicate. One of the composite sample bottles was acidified with sulphuric acid (relative density 1.19) to prevent losses of nitrogen. If the solution turned neutral or alkaline after a fresh portion of urine was added, more sulphuric acid was added. Into the other sample bottle, 2 ml formalin (relative density 1.1) was used as a preservative. This sample was used for estimating carbon and the sum of free and bound carbon dioxide. The urine samples were also stored at 2-4 °C.

The faeces were weighed each day and then thoroughly mixed by hand. A constant proportion by mass was taken by random sampling and bulking into a vessel containing 10 or 15 ml formalin (relative density 1.1) as a preservative. This vessel was also stored at 2-4 °C.

From the samples of the concentrate mixture, and of pelleted and long forages, 200.0 g were weighed, dried at 60-70 °C and weighed again after 3 to 4 h cooling in a room of normal humidity before being ground with a small hammer mill through a 1.25-mm sieve.

At the end of the experiment, the composite samples of the milk were heated to 40 °C, mixed and immediately analysed. The composite samples of urine were mixed and analysed. The composite samples of faeces were intensively kneaded and mixed. Random subsamples were taken and immediately analysed for dry matter and crude protein. Afterwards a 1000.0-g sample was dried at 60-70 °C, weighed after a cooling period of 3 to 4 h and ground.

Other components not listed above and dry matter were estimated in ground air-dry material.

4.1.2 Analytical methods

All the analytical methods for dry matter, ash, ether extract, carbon and energy of combustion of feed, faeces and urine have been described by van Es (1961) and by Nijkamp (1969, 1971). Nitrogen was estimated by the Kjeldahl method. In a few experiments, ether extract was also estimated by ether extraction after boiling the sample with dilute hydrochloric acid (Berntrop method). Milk fat was estimated by the Gerber method.

4.1.3 Correction for added preservatives

The addition of sulphuric acid to the urine sample and of formalin to the samples of urine and faeces altered the composition somewhat. Corrections for addition of sulphuric acid and formalin were as used by van Es (1961).

The hydrochloric acid used by van Es (1961) was replaced by sulphuric acid to obtain correcter values for carbon and energy in urine (Nijkamp, 1969). No correction was made for addition of $HgCl_2$ to the milk.

4.2 EQUIPMENT AND ITS USE

Until 1971, only the respiration chambers designated 3 and 4 were used (van Es, 1966). Afterwards these chambers were used alternately with Chambers 1 and 2 (Verstegen, 1971), which could be used for dairy cows after a few alterations.

After 1967, the volume of air leaving Chambers 3 and 4 was not measured with a wet gas-meter or a mercury pump but by dry gas-meters with a maximum capacity of 30 m^3/h as in Chambers 1 and 2.

Gas from all chambers was sampled in the way as did Verstegen (1971). Air entering and leaving was analysed for CO_2 and O_2 with a modified Sonden gas analysis apparatus (van Es, 1958) and for CH_4 analysis an infrared gas-analyser SB_2(IRGA, Grubb and Parsons, Ltd, New Castle upon Tyne) was used. This instrument was calibrated with air samples analysed with the Sonden. Before and after use, correct functioning was checked by passing through it gas of known composition from a high-pressure cylinder.

Computation of O_2 consumption and CO_2 and CH_4 production CO_2 and CH_4 production and O_2 consumption during a respiration trial were computed from the volume of outgoing air and the composition of entering and outgoing air and of the air in the chamber at the start and the end of the trial as follows. First the volume of outgoing air measured by the dry gas-meter was converted to reference conditions (dry, 0 °C and 760 mmHg) with the following equation

$$V_x = V_g \times C_g \times (p - p_w)/p_0 \times (T_0/T_g)$$

V_x = volume of outgoing air converted to reference conditions
V_g = volume measured with the gas-meter
C_g = calibration factor of the gas-meter determined with the mercury pump
p = average barometric pressure during the respiration experiment
p_w = partial pressure of water vapour in the gas-meter
p_0 = reference pressure
T_g = average thermodynamic temperature of dry gas-meter
T_0 = reference thermodynamic temperature, 273 K

It is assumed that the partial pressure of water vapour in the gas-meter equals that in the respiration chamber. As the temperature of the gas-meter and the chamber do not differ more than a few degrees, this introduces an error in the vapour pressure up to only 0.2 mmHg in a few trials. According to Verstegen (1971), p_w is computed as

$$p_w = \phi /100 \times (3.999 + 0.45547\ t_{ch} + 0.001708\ t_{ch}^2 + 0.000486\ t_{ch}^3)$$

in which ϕ = relative humidity in the chamber in % and t_{ch} = temperature in the chamber in °C.

The volume of air entering under reference conditions differs from the volume of outgoing air under reference conditions, when the volume of O_2 consumed and of CO_2 and CH_4 produced by the cow are not equal. As the production or fixation of inert gases like nitrogen by farm animals can be neglected (Costa et al., 1968) the volume of air entering the chamber may be computed as

$$V_i = V_x\ (100 - C_x - O_x - G_x)/(100 - C_i - O_i)$$

In this formula C, O and G are volume fraction of CO_2, O_2 and CH_4 (%), respectively and the suffixes i and x indicate air entering and leaving.

Finally the rate of O_2 consumption ($-\dot{V}_{O_2}$), CO_2 production ($\dot{V}_{CO_2}$) and CH_4 production ($\dot{V}_G$) are computed as follows:

$$\dot{V}_{CO_2} = C_x \cdot \dot{V}_x - C_i \cdot \dot{V}_i + \Delta_c$$
$$\dot{V}_G = G_x \cdot \dot{V}_x$$
$$\dot{V}_{O_2} = O_i \cdot \dot{V}_i - O_x \cdot \dot{V}_x + \Delta_o$$

in which Δ_c and Δ_o is the correction for the composition of gas in the chamber at the start and at the end of the trial. If the volume fractions of O_2 and CO_2 in the chamber are different at the start and the end, this correction is necessary because then the sample collected during the trial does not contain only CO_2 produced and O_2 consumed by the cow. The volume of air in the chamber to compute this correction is assumed to be 10000 litres during a respiration trial when a cow is inside the chamber. For each time feed was given through a small airlock (about 200 litres capacity), a loss of 2 litres CO_2 and a gain of 2 litres O_2 to the internal atmosphere was assumed for the calculations.

Calibration of the gas-meters and the mercury pump All dry gas-meters were calibrated just before the first 2-day respiration trial of a 2-week experiment, once or twice during the experiment and after the last trial, in order to measure the actual volume of air passing through the meters. A gas-meter was always calibrated at about the same flow rate as used. Therefore the outlet of a gas-meter was connected to the inlet of the mercury pump by filling or emptying the U-shaped bends of the connecting pipes as described by van Es (1961). For each calibration, the mercury pump was twice allowed to rotate 50 times and the known calibration factor of the mercury pump was used to calculate the factor of the dry gas-meter. Before each experiment (once a month), the mercury pump was also calibrated with a small dry gas-meter in a similar way to that used by van Es (1961) for the mercury pump with a small wet gas-meter. The calibration factor of the dry gas-meter for each trial was found by rectilinear interpolation between two measured values. The average ± standard deviation of the calibration factors estimated during the last three years with the number of calibrations stated in brackets were for Gas-Meter 1 0.9892 ± 0.0033 (40); Gas-Meter 2 1.0149 ± 0.0031 (34); Gas-Meter 3 1.0109 ± 0.0048 (59) and

Gas-Meter 4 1.0367 ± 0.0064 (59). In 1970, Gas-Meter 2 was exchanged for a reserve meter.

These figures show that it was not necessary to calibrate the gas-meters frequently. However, we still did to be sure that the values had not changed during an experiment through malfunction of the equipment.

Test experiments To check for possible sources of errors, tests were occasionally made. During the tests, no animals were in the chamber. Van Es (1961) showed that the measurement of the volume and the sampling of air leaving the chamber can easily be checked with CO_2. If a CO_2 test gives good results, the system of measuring the volume, sampling of air and analysing of CO_2 is taken to be correct. The system of analysing O_2 concentration can be checked by measuring the concentration of O_2 in ingoing air, which is almost constant. Moreover O_2 consumption is always calculated from the difference in concentration of O_2 in the air entering from that leaving the chamber, thus automatically correcting for most systematic errors of O_2 analysis. Furthermore one must be sure that the O_2 concentration of the sample does not change during the collection period of 48 h by leakage or diffusion through the wall of the sampling tube. Little or no changes in composition of the sample could be detected when analysed immediately and within 3-7 days of taking the last sample. In any case, nearly all the samples were analysed within 48 h of sampling.

A CO_2 test was usually done before a series of energy balance experiments started or just after the cows had left the chambers. Just before a test, about 200 g CO_2 was passed into the chamber from a cylinder to produce a CO_2 concentration of air in the chamber of 0.7 to 1.1%. To prevent loss of CO_2 by leakage of the pressure cylinder or its needle valve, the cylinders were placed and weighed on a balance (inaccuracy 5 g or less) inside the chamber just before ventilation and sampling started. Immediately after sampling started, CO_2 was released from the cylinder at almost 1% of the the ventilation rate. The valves of the cylinders could be opened from outside with rubber gloves set in the large door of the chamber. The test usually lasted 24-48 h. The results of the tests from October 1970 to October 1973 are presented in Table 8. These tests showed that there is generally a good recovery of the weighed amount of CO_2 introduced into the chamber. In a few tests (Chamber 1 on 25-27 March 1973; Chamber 2 on 13-14 December 1971; Chamber 4 on 21-22 June 1972) a too low flow rate of CO_2 into the chamber, caused by a badly functioning flow meter, resulted in a

Table 8. Results of CO_2 test experiments in the 4 respiration chambers of the Department of Animal Physiology, Agricultural University, Wageningen.

Date	Length (h)	CO_2 (litre) introduced	Recovery (%)
Chamber 1			
1971-12-13/14	25	4422	100.0
1972-01-12/13	23	6159	99.4
1972-06-28/29	29	3079	100.9
1972-09- 6/8	40	4479	100.2
1973-03-25/27	48	2565[1]	101.3
1973-04-25/27	46	5097	100.3
Chamber 2			
1971-12-13/14	25	1394[1]	100.7
1972-01-12/13	23	5394	99.6
1972-5/6-31/2	40	4635	100.6
1972-06-28/29	29	4529	100.6
1972-09- 6/8	40	6427	100.1
1973-03-25/27	48	7129	100.2
1973-04-25/27	48	7915	99.3
Chamber 3			
1970-10-15/16	30	3343	100.5
1970-12-29/31	45	8368	99.3
1971-10-27/28	29	4297	99.6
1972-06-21/22	24	3055	98.1
1972-8/9-30/1	44	4769	98.5
1973-03-8/9	25	5091	99.6
1973-05- 1/3	46	4893	99.9
Chamber 4			
1970-10-15/16	30	4381	98.1
1970-12-29/31	45	8221	101.2
1971-10-27/28	29	4451	100.0
1972-06-21/22	24	1674[1]	98.7
1972-8/9-30/1	44	7093	100.3
1973-03- 8/9	25	11287	98.7
1973-05- 1/3	46	7410	99.7

1. A too low flow rate of CO_2 into the chamber, caused by a badly functioning flowmeter.

very low concentration of CO_2 in the air leaving the chamber. Perhaps because the experimental errors are relatively more important in such faulty tests, the recovery of CO_2 could differ more from 100% than in normal tests. The increase in error was, however, only small. The average recovery for each chamber was very close to 100%. We concluded that no other test experiments with O_2 or N_2 were necessary.

4.3 EXPERIMENTS WITH ANIMALS

4.3.1 Animals

The energy utilization of pelleted forages was studied with full-grown Dutch Friesian dairy cows, producing between 10 and 30 kg milk and between 450 and 650 kg liveweight. These cows, from the herd of the Experimental Farm of the Department of Animal Physiology, at Wageningen, were kept during the experiments in the digestion stall or in one of the respiration chambers. Occasionally one or two cows were bought from farmers, if too few cows of the herd were at an early stage of lactation at the beginning of a series of experiments.

During the experiment, the cows were weighed once a week between 09h00 and 11h00. In the preliminary period, the cows were let out into a small fenced yard, if the weather was reasonable.

Appendix A gives name, age, month of parturition and liveweight of the cows and the experiment in which they were used.

4.3.2 Treatments

If the effect of pelleting of forages on voluntary feed intake by dairy cows is positive, part of both the concentrates and of the long forage are generally replaced in the ration by pelleted forages. It is essential to know what the energetic and protein values are of pelleted forages as a substitute for both concentrates and unprocessed forages. Pelleted forages can be compared with different types of concentrates and unprocessed forages. But to establish the effect of grinding and pelleting as such, the processed forage must be compared with the same forage long in rations with equal quantities.

In 1967 and 1968, two series of energy balance experiments were conducted with lactating cows on rations in which an attempt was made to replace concentrates by about the same amount of net energy from pellets of ground hay cut early or late, or oat straw. These types of rations were thought suitable for commercial use too. Table 9 presents the experimental scheme of these experiments (Exp. 94-97 and 104-107).

In several other experiments from 1969 to 1973 with dairy cows, we used rations with large amounts of artificially dried, ground and pelleted forages. The utilization of these rations with pellets from early or late

Table 9. Survey of the energy balance experiments with lactating cows.

Exp. No	Year-month	n[1]	Ration			
			basal[2]	experimental[3]	concentrates	code
94-97	1967-05/09	4 × 6	4 kg hay	5 or 10 kg hay pellets, e.c.	3½-7½ kg	HPE
			4 kg hay	5 or 10 kg hay pellets, l.c.	6 -10 kg	HPL
			4 kg hay	4 or 8 kg straw pellets	7 - 8 kg	SP
			4 kg hay	concentrates	9 -11 kg	CONC
104-107	1968-05/08	4 × 6	4 kg hay	5 or 10 kg hay pellets, e.c.	5 -10 kg	HPE
			4 kg hay	5 or 10 kg hay pellets, l.c.	4 - 9 kg	HPL
			4 kg hay	8 kg straw pellets	6 - 8 kg	SP
			4 kg hay	concentrates	7 -11 kg	CONC
117-118	1969-09/12	2 × 6	3 kg hay	10 kg lucerne pellets	6 kg	LP0F
			3 kg hay	10 kg lucerne pellets + 2% fat	5.3 kg	LP2F
			3 kg hay	10 kg lucerne pellets + 4% fat	4.5 kg	LP4F
124-126	1970/71-11/01	3 × 6	4 kg hay	10 kg grass pellets, e.c.	6 kg	GPE
			4 kg hay	10 kg lucerne pellets, e.c.	6 kg	LPE
			4 kg hay	10 kg lucerne pellets, l.c.	6 kg	LPL
HR 1-3	1971-02/04	3 × 4	-	12 kg art.dried grass	5 - 7 kg	G
			3 kg dried grass	9 kg grass cobs	5 - 7 kg	GC
			-	12 kg grass wafers	5 - 7 kg	GW
131-133	1971/72-11/01	3 × 6	-	11 kg hay	7 - 9 kg	H
				11 kg art.dried grass	7 - 9 kg	G
			3 kg hay	8 kg grass pellets	6 - 9 kg	GP
134-135	1972-02/03	2 × 4	7 kg lucerne wafers	9 kg grass pellets	5 - 6 kg	GP0F
			7 kg lucerne wafers	9 kg grass pellets + 3% fat	4 - 5 kg	GP3F
136-137	1972-04/05	2 × 6	4 kg hay	4 kg hay + 4 kg hay pellets	7½- 9 kg	HP4
			4 kg hay	8 kg hay pellets	7 - 9 kg	HP8
138-140	1972/73-11/01	3 × 6	4 kg hay	10 kg lucerne pellets, e.c.	5 - 6 kg	LPEI
			4 kg hay	10 kg lucerne pellets, l.c.	6 kg	LPLI
			4 kg hay	10 kg lucerne pellets, 2nd cut	5 - 6 kg	LPII
141-142	1973-03/04		4 kg hay	4 kg hay + 4 kg hay pellets	6 - 7 kg	HP4
			4 kg hay	8 kg hay pellets	6 - 7 kg	HP8

1. 4 × 6 means 4 successive experiments each with the same 6 cows. Each lasted 28 days with a prelimary period of 12 days and an experimental period of 14 days, including 4-6 days in a respiration chamber.
2. 'Hay' here means grass hay. 3. Early cut, e.c.; late cut, l.c.

cut grass or lucerne could be compared with that of ordinary rations, found in earlier balance experiments with dairy cows in the Department. The ordinary rations were composed of hay or silage as roughages with concentrates provided to meet Dutch energy standards (CVB, 1970b). In Table 9, these experiments are presented as Exp. 117-118, 124-126, 131-133, 134-135 and 138-140.

In 1970-1973, pelleted forage was compared with the original long material in dairy rations in the experiments HR 1-3, 131-133, 136-137 and 141-142 (Table 9). In HR 1-3, we also tried to measure the effect of wafering.

To make the most of these experiments, the contribution of the test feed to the experimental ration should be as great as possible. In our experiments with pelleted forages, the amount of test feed was restricted for two main reasons. First pellets cannot be the sole feed because of the high risk of digestive disorders, abnormal rumen metabolism and low milk fat because of lack of structured material. To compensate this lack of structured material in pelleted feeds, at least 3-4 kg hay or artificially dried grass was provided in long form. In Exp. 134-135 and HR 1-3, artificially dried wafered lucerne or grass was thought to provide enough structured material to maintain normal rumen function. Secondly the high requirements of energy and protein by dairy cows can be met only by using large amounts of concentrates in the diet, because feed intake capacity is limited.

So the amount of forage pellets in a dairy ration is restricted by the need to feed some long forage as well as quite a lot of concentrates. The precision of a comparison between tested forage pellets and the control feed is therefore lower than in one in which the ration consists only of forage pellets. The results of experiments with productive cows and with rations which are also suitable for commercial use are, however, of such interest that these disadvantages can be tolerated.

In Exp. 136-137 and 141-142 (Table 9), a higher consumption of hay was attempted by adding 4 kg hay pellets to the ration with long hay. A daily ration of 4 kg long hay and 8 kg pellets of the same hay, ground through a 6 mm-screen, was compared with a ration of 8 kg long hay and 4 kg pelleted hay. For successive balance experiments with the two rations, a given cow received an equal amount of concentrates according to expected milk production.

4.3.3 *Feeding method*

The cows were fed twice a day. At about 07h00, half the daily ration was given, first the concentrates and the forage pellets and about half an hour later the long forage. The rest was given in the same way at about 16h00. Feed residues were removed before fresh feed was supplied. In all the experiments, we tried to supply an amount of forage that could be consumed, whereas the amount of concentrates was kept constant according to milk production. By keeping the amount of concentrates constant over two or three experiments, statistical analysis was simplified. Only to avoid an excessively high positive or negative balance of energy was the amount of concentrates changed between experiments.

4.3.4 *Balance experiments*

Each series of experiments with pelleted forages lasted 2, 3 or 4 months and was divided into 2, 3 or 4 experiments. Each experiment began with a preliminary period of at least 12 days, after which nitrogen and energy balances were estimated over 12-14 days of which 4-6 were spent in a respiration chamber. Collection and sampling of milk and urine started 14-15 h after experimental feeding began and of faeces 38-40 h. The balances were measured over a period of 12-14 days, unless some hitch caused it to be stopped earlier. However balance experiments of less than 7 days are not recorded.

During a balance experiment, each cow spent two or three periods of 48 h in a respiration chamber to measure its O_2 consumption and CO_2 and CH_4 production over 48 h. Occasionally we could measure them only for 24 h because of hitches with the equipment. The cows were led into the chamber at least half an hour before a respiration trial began. During such a period of about 20-30 min without ventilation, the CO_2 concentration in the closed chamber rises to about 1%. Ventilation was then started and kept constant for the whole trial. The ventilation rate was adjusted before a respiration trial to maintain CO_2 concentration at about 1% during the whole trial. Gas samples were taken continuously from air entering and leaving a chamber at a constant rate by lowering a piston in a glass cylinder as described by van Es (1966). At the start and end of a respiration trial, the concentrations of CO_2 and O_2 in the air of the chamber were measured by a diaferometer. Methane was burned over a heated Nichrome wire to prevent a misreading for oxygen. The trials to measure respiratory exchange started between 08h00 and 11h00 after cows had been fed.

5 Results of balance experiments with dairy cows

In general, the balance experiments proceeded without much digestive disturbance and without many days off feed so that the few times a cow had to be removed from an experiment were mainly due to mastitis or leg troubles (stiffness), which occurred rarely.

5.1 CHEMICAL COMPOSITION OF FEEDSTUFFS

Table 10 presents the chemical composition of the feedstuffs. Forage cut early usually had a higher content of crude protein and a lower content of crude fibre than forage cut late. In the later experiments, crude fibre was not estimated and the total of crude fibre and N-free extract is given. Content of crude protein in hay pellets of Exp. 94-97 and 104-107 was lower than of the lucerne pellets (Exp. 117-118, 124-126, 138-140), grass hay and grass hay pellets (Exp. 136-137, 141-142) and of grass pellets (Exp. HR 1-3, 131-133, 134-135). In the experiments with lucerne pellets, the higher content of crude protein of the lucerne pellets often resulted in an excess of digestible crude protein, because a normal concentrate mixture was given in these experiments and in those with grass pellets.

Grinding and pelleting resulted only in a small change in chemical composition. Particularly the content of ether extract tended to be higher for pellets. The literature on pelleted forages usually reports a lower content of crude fibre and a higher content of ether extract (Lindahl & Reynolds, 1959; Journet & Jarrige, 1967; Piatkovski & Koriath, 1970; Cottijn & Boucqué, 1971; Wainman et al., 1972; van der Honing et al., 1971; van der Honing & Schlepers, 1971). Only small changes in chemical composition with grinding and pelleting were found by Beever et al. (1972) and Jarrige et al. (1973a). Differences in crude protein and ash with pelleting were more variable, perhaps partly through sampling errors and small losses of some parts of the material during handling the forage. Lindahl & Reynolds (1959) observed a higher content of crude fat in lucerne pellets but the gross energy content of pellets and meal were not different. They argued

Table 10. Chemical composition and gross energy content of ration components. See List of Symbols.

Exp. No	Treat-ment code[1]	Feedstuff[2]	Dry matter (%)	In dry matter (%)						gross energy in d.m. (kcal/g)
				XP	XL	XF	XX	ash	C	
94-97		hay	89.64	11.60	2.6	32.8	45.8	7.28	45.62	4405
	HPE	hay pellets, e.c.	89.20	12.70	3.0	28.7	46.9	8.76	45.07	4370
	HPL	hay pellets, l.c.	89.69	9.56	2.0	32.6	45.3	10.54	43.74	4228
	SP	straw pellets	87.45	3.72	1.3	45.5	40.5	9.06	45.06	4294
	CONC	concentrates	86.98	18.17	4.3	10.8	58.9	7.80	44.44	4373
104-107		hay	88.89	12.81	2.3	34.6	43.0	7.28	45.78	4439
	HPE	hay pellets, e.c.	88.98	13.62	2.3	31.4	44.1	8.60	45.25	4381
	HPL	hay pellets, l.c.	90.28	8.75	2.0	36.0	44.7	8.60	44.72	4292
	SP	straw pellets	90.36	2.70	1.6	48.1	41.4	6.22	46.50	4413
	CONC	concentrates	86.39	18.37	4.2	11.2	58.2	8.05	44.21	4338
117-118		hay	87.54	17.64	2.4	31.1	38.4	10.50	44.11	4282
	LP 0 F	lucerne pellets	89.95	17.11	2.7	37.0	34.1	9.10	46.22	4480
	LP 2 F	lucerne pellets + 2% fat	90.38	17.64	5.7	34.9	32.7	9.05	47.15	4602
	LP 4 F	lucerne pellets + 4% fat	89.90	16.80	7.7	35.3	31.3	8.86	47.76	4698
		concentrates	87.04	18.24	5.6	11.5	55.4	9.28	44.32	4336
124-126		hay	88.21	11.10	2.0	79.5[3]		7.43	45.24	4376
	GPE	grass pellets	90.35	14.21	3.8	65.8		16.11	41.60	4042
	LPE	lucerne pellets, e.c.	89.81	20.48	3.6	63.5		12.40	44.28	4330
	LPL	lucerne pellets, l.c.	90.65	14.94	1.7	71.3		12.03	44.37	4255
		concentrates	87.02	18.44	5.9	66.2		9.54	44.51	4373
HR 1-3	G	long dried grass	87.32	19.32	3.1	64.2		13.37	43.11	4215
	GW	wafers	90.08	18.50	3.7	63.1		14.78	42.78	4173
	GC	cobs	92.17	18.00	3.6	60.4		17.94	41.19	3984
		concentrates	86.51	18.75	7.1	64.0		10.16	44.54	4348
131-133	H	hay	87.49	14.50	2.7	73.4		9.40	44.72	4344
	G	long dried grass	90.57	14.13	3.3	72.8		9.85	44.72	4348
	GP	grass pellets	91.08	17.59	4.3	66.6		11.57	44.25	4339
		concentrates	89.31	21.40	4.8	66.0		7.81	44.43	4405

134-135		*lucerne wafers*	*86.60*	*17.31*	*2.0*	*69.4*	*11.30*	*44.74*	*4316*
	GP 0 F	*grass pellets*	*86.16*	*16.13*	*3.4*	*62.6*	*17.91*	*41.28*	*3988*
	GP 3 F	*grass pellets + 3% fat*	*89.74*	*16.38*	*6.0*	*61.0*	*16.64*	*42.66*	*4186*
		concentrates	87.74	19.06	8.3	64.0	8.58	45.42	4526
136-137	HP 4/8 (S)	hay, 1st cut	90.16	17.75	3.6	70.4	8.31	45.46	4464
		hay pellets, 1st cut	90.88	17.75	4.0	69.9	8.31	45.42	4454
	HP 4/8 (A)	hay, autumn	89.59	18.94	3.4	68.4	9.28	44.84	4467
		hay pellets, autumn	90.22	18.88	4.0	66.7	10.40	44.62	4435
		concentrates	89.29	19.72	4.9	66.3	9.14	44.09	4338
138-140		hay	90.08	13.69	1.6	77.0	7.64	45.85	4435
	LPE I	lucerne pellets, e.c.	89.12	19.90	2.9	66.2	10.98	44.86	4364
	LPL I	lucerne pellets, l.c.	90.56	16.44	2.4	71.8	9.30	45.36	4414
	LP II	lucerne pellets, 2nd cut	87.82	16.84	2.7	66.2	14.18	43.37	4197
		concentrates	87.29	19.48	4.9	65.8	9.88	44.19	4356
141-142	HP 4/8 (S)	hay, 1st cut	88.89	21.13	2.5	65.6	10.84	44.26	4356
		hay pellets, 1st cut	90.83	20.75	2.9	64.8	11.52	43.76	4292
	HP 4/8 (A)	hay, autumn	90.61	22.56	3.2	65.0	9.24	45.28	4480
		hay pellets, autumn	89.80	22.44	3.3	64.7	9.50	45.14	4451
		concentrates	87.48	15.84	4.2	71.1	8.93	43.46	4278

1. See Table 9.
2. Early cut, e.c.; late cut, l.c.; 'hay' means grass hay.
3. The sum of crude fibre and nitrogen-free extracts, because crude fibre was not analysed.

that a 1.13% higher content of fat would have altered the gross energy content by 0.07 kcal/g so that it was likely that the increase in ether extract was partly due to cellular rupture during pelleting and increase in non-fat ether-soluble matter. For ground and pelleted hay, Demarquilly & Journet (1967) reported 0.9 and 4.5 percentage units lower content of crude fibre than for chopped hay, and also decreases in content of cellulose and lignocellulose so that they concluded that processing made cellulose more susceptible to hydrolysis by dilute acid and reduced the amount of crude fibre found by analysis.

The difference in composition of long artificially dried grass and grass pellets (Exp. 131-133) was possibly due to contamination of pellets with small amounts of other material during production. The pellets and the long grass were not produced in the same drying plant and in the almost fully automated drying and pelleting process, it was impossible to prevent mixing of different roughages dried in sequence.

Although the chemical composition may be slightly altered with grinding and pelleting, increasing the content of ether extract and lowering the content of crude fibre, processing did not alter gross energy content in our experiments.

5.2 FEED INTAKE AND DIGESTIBILITY

Appendix B presents the intake of dry matter (I_T) of each cow. I_T ranged between cows from 9.6 to 18.8 kg per day, and between treatments from 13 to 17 kg. The amount of feed offered was usually restricted to avoid large feed residues. Because we tried to feed by energy requirement, a high feed intake was necessary in some experiments. In general, however, these experiments do not give much reliable information about the effect of grinding and pelleting on feed intake. In some (Exp. 136-137, 141-142), the feed residues from diets with the greatest proportion of pelleted forages tended to be smaller than from diets with a higher percentage of long forage. This tendency was also shown by intake from our 130 balance experiments compared with intake for 204 balance experiments with cows in which long forages were used. The average intake of dry matter from diets with pelleted forages was 16.0 and from diets with long forages 13.9 kg/day, with a standard deviation of 1.5 and 1.9 kg/day, respectively.

In Exp. 134-135, many lucerne wafers were left uneaten by some cows. Perhaps the dustiness of the wafers, containing much fines because of a low

Table 11. Average (av.) and standard deviation (SD) of percentage long roughage in total I_T (P_L), apparent digestibility (d) and metabolizability of gross energy (q) for lactating cows in the rations of the different treatments. See List of Symbols.

Exp. No	Treatment codes[1]	Cows (n)	P_L		d_O		d_N		d_{XL}		$d_{(XF + XX)}$		d_E		q	
			av.	SD	av.	SD	av.	SD	av.	SD	av.	SD	av.	SD	av.	SD
94-97	HPE	6	23.3	1.2	67.0	2.3	59.4	1.5	68.6	5.4	68.3	2.5	63.7	2.4	54.4	2.4
94-97	HPL	6	21.5	1.2	64.8	3.2	57.1	3.9	71.8	5.5	65.9	3.2	61.6	3.2	52.4	3.0
94-97	SP	6	21.3	1.9	58.6	4.6	53.1	3.9	74.1	3.9	58.8	4.8	55.6	4.6	47.4	3.9
94-97	CONC	6	27.8	1.7	73.3	1.5	64.0	1.1	83.2	1.5	74.8	1.7	70.5	1.2	61.5	0.9
104-107	HPE	6	21.8	1.7	65.9	3.0	61.8	2.2	67.4	4.3	66.7	3.3	62.4	3.0	52.8	2.9
104-107	HPL	6	23.5	3.1	64.3	3.5	57.8	4.0	64.7	5.4	65.4	3.6	60.8	3.6	51.5	3.2
104-107	SP	6	24.2	2.4	61.1	3.2	57.6	2.4	68.7	3.4	61.4	3.4	57.8	3.2	48.8	2.7
104-107	CONC	6	30.8	4.6	74.1	0.6	66.0	1.3	77.3	1.9	75.8	0.7	71.2	0.6	61.1	0.8
117-118	LP0F	4	15.0	0.0	61.5	1.5	63.2	1.4	64.1	2.3	61.0	1.6	58.4	1.5	49.9	1.0
117-118	LP2F	4	15.5	0.6	61.3	2.0	64.1	2.5	73.7	2.0	59.6	2.0	58.3	2.2	50.0	1.6
117-118	LP4F	4	16.8	0.5	62.2	1.3	63.8	1.6	79.5	1.1	60.1	1.6	59.6	1.2	51.2	0.8
124-126	GPE	6	19.3	0.8	65.1	1.4	57.0	1.6	71.6	2.2	66.4	1.5	61.6	1.3	52.9	0.8
124-126	LPE	6	19.7	0.5	64.1	1.9	63.5	1.7	71.3	2.5	63.8	2.0	61.0	1.9	51.9	1.2
124-126	LPL	6	20.0	2.0	58.5	0.6	61.5	1.1	69.3	2.9	57.4	0.6	55.7	0.6	47.0	0.7
HR 1-3	G	4	65.3	2.2	67.7	1.1	63.1	1.0	67.9	3.8	69.1	1.1	63.5	1.0	53.2	0.8
HR 1-3	GW	4	64.8	4.5	65.8	2.1	62.6	2.6	69.7	2.8	66.4	2.3	62.2	2.1	52.5	1.3
HR 1-3	GC	4	16.5	1.3	64.6	2.5	62.4	2.2	68.4	3.0	64.9	3.2	60.8	2.6	51.6	1.9
131-133	H	6	58.2	4.4	74.0	0.2	65.6	1.8	72.6	3.3	76.2	0.3	70.4	0.5	60.0	0.7
131-133	G	6	59.2	3.6	72.9	0.7	60.1	1.6	73.8	1.8	75.9	0.6	69.2	0.6	58.9	0.7
131-133	GP	6	16.8	1.5	69.7	1.4	60.6	2.7	73.1	2.6	71.9	1.3	66.1	1.5	57.0	1.2
134-135	GP0F	4	25.5	13.4	63.6	2.2	58.4	1.4	72.9	3.3	64.3	2.8	60.5	2.0	52.3	1.7
134-135	GP3F	4	35.5	19.3	63.8	3.6	58.6	2.6	74.1	4.2	64.3	4.8	61.0	3.6	52.7	2.9
136-137	HP4(S)	3	35.3	2.5	70.9	1.4	68.4	1.2	70.2	0.3	71.7	1.6	67.9	1.3	58.7	0.5
136-137	HP8(S)	3	19.0	1.0	69.2	1.8	68.1	2.2	61.7	0.2	70.0	1.8	66.2	1.7	57.2	0.9
136-137	HP4(A)	3	32.7	2.3	68.4	0.8	64.8	0.2	64.5	2.2	69.8	0.9	65.0	0.7	55.3	0.4
136-137	HP8(A)	3	18.7	1.5	66.1	1.1	64.7	1.0	49.3	3.5	67.5	1.1	62.5	1.2	53.1	1.0
138-140	LPE I	6	18.7	2.7	62.4	2.0	64.2	1.8	68.8	4.0	61.5	2.1	59.5	2.1	50.6	1.6
138-140	LPL I	6	18.5	3.3	59.1	0.9	61.2	1.9	68.8	1.1	58.1	0.9	56.3	0.9	47.7	0.5
138-140	LP II	6	18.0	1.4	60.7	1.9	62.1	1.9	68.8	1.9	59.9	2.2	57.5	1.6	48.4	1.2
141-142	HP4(S)	2	40.0	1.4	71.8	1.4	68.8	0.0	67.4	2.8	72.9	1.7	68.3	1.2	58.2	1.1
141-142	HP8(S)	2	19.0	1.4	68.9	1.8	67.0	0.3	65.9	3.3	69.5	2.5	65.3	1.7	55.8	0.8
141-142	HP4(A)	4	41.5	2.5	72.0	1.0	69.1	0.9	65.4	2.1	73.2	1.2	68.3	1.0	57.6	0.7
141-142	HP8(A)	4	21.0	1.4	70.9	1.4	69.0	1.3	65.7	3.0	71.7	1.6	67.2	1.4	56.8	1.4

1. See Table 9.

durability, might have reduced their palatability.

Table 11 presents average digestibility (d) and the metabolizability of gross energy (q) for each treatment. Our experiments were planned to investigate net energy content of the digestible feed rather than digestibility, for which a greater number of cows would have been used in an appropriate scheme. A comparison of digestibility was possible, though not with great precision.

5.2.1 Replacement of concentrates by pelleted forages

In Exp. 94-97 and 104-107, pelleted hay cut early or late or straw replaced part of the concentrates in a diet containing 4 kg long hay. Figure 3 shows the depression of d_E resulting from replacement of concentrates by forage pellets. This depression appeared to be greater for straw (squares) than for hay and for late cut hay (triangles) than for early cut

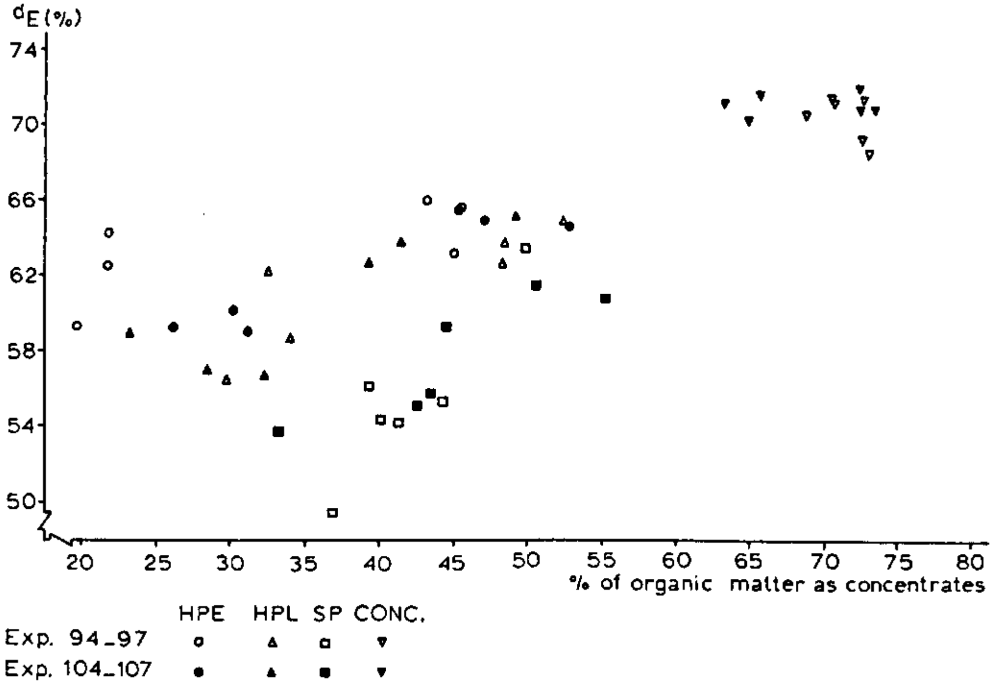


Fig. 3. Relation between digestibility of energy (d_E) and contribution of concentrates to total intake of organic matter (P_C) in Exp. 94-97 and 104-107. Rations contained pelleted hay cut early (HPE) or late (HPL), straw pellets (SP) or no pelleted forage (CONC).

Table 12. Regressions of apparent digestibility (d) and metabolizability of gross energy (q) on the percentage of concentrates in total intake (P_C) for the experimental rations HPE, HPL and SP compared to the control ration CONC in Experiments 94-97 and 104-107. The general regression is $Y = a \cdot P_C + c$. See further List of Symbols.

Y	Treatment codes[1]	a		c	R^2	RSD	CV
		av.	SD				
d_E	HPE - CONC	0.21	0.02	55.7	0.85	1.80	2.7
d_E	HPL - CONC	0.30	0.02	50.0	0.91	1.68	2.5
d_E	SP - CONC	0.52	0.03	34.4	0.92	2.23	3.5
d_O	HPE - CONC	0.20	0.02	59.7	0.81	1.90	2.6
d_O	HPL - CONC	0.28	0.02	54.2	0.88	1.89	2.7
d_O	SP - CONC	0.50	0.04	38.2	0.90	2.40	3.6
d_N	HPE - CONC	0.12	0.02	56.6	0.62	1.81	2.9
d_N	HPL - CONC	0.24	0.03	48.0	0.82	2.10	3.4
d_N	SP - CONC	0.35	0.04	40.4	0.79	2.66	4.4
d_{XL}	HPE - CONC	0.36	0.03	55.2	0.88	2.67	3.6
d_{XL}	HPL - CONC	0.41	0.04	52.1	0.84	3.29	4.4
d_{XL}	SP - CONC	0.34	0.05	56.6	0.67	3.52	4.6
$d_{(XF+XX)}$	HPE - CONC	0.21	0.02	60.3	0.79	2.16	3.0
$d_{(XF+XX)}$	HPL - CONC	0.29	0.03	54.9	0.85	2.18	3.1
$d_{(XF+XX)}$	SP - CONC	0.55	0.04	36.3	0.91	2.59	3.8
q	HPE - CONC	0.21	0.02	46.1	0.89	1.50	2.6
q	HPL - CONC	0.29	0.01	41.1	0.95	1.20	2.1
q	SP - CONC	0.48	0.02	27.3	0.95	1.55	2.8

1. See Table 9.

hay (circles). Similar results were found for d_O, d_N, d_{XL} and $d_{(XF+XX)}$.

The relation between digestibility of the different components and the percentage (P_C) of total organic matter ingested as organic matter from concentrates fitted well to a linear equation (Table 12). Each treatment with pelleted forage was compared with the same control diet with 4 kg hay + concentrates. A further small reduction in residual standard deviation (RSD) and a significant negative regression coefficient was found except for d_{XL}, when total intake of organic matter (I_O) was used as an additional variable in multiple regression analysis alongside P_C. This might be due at least partly to the effect of an increase in level of feeding, which generally decreased digestibility (Section 3.1.2).

The lower digestibility of rations with great amounts of forage pellets was caused mainly by lower digestibility of the forages than of concentrates. The effect of grinding and pelleting on the digestibility of the forage could not be derived from these experiments. In digestibility trials with

Table 13. Average (av.) and standard deviation (SD) of apparent digestibility (d) and metabolizability of gross energy (q) of 130 balance experiments with rations containing pelleted roughages (P) and of 204 or 136 experiments with rations without pelleted roughages (L). See List of Symbols.

n	P_L		d_O		d_N		d_{XL}		$d_{(XF+XX)}$		d_E		q	
	av.	SD	av.	SD	av.	SD	av.	SD	av.	SD	av.	SD	av.	SD
130(P)	23	10	64.4	4.3	61.7	4.5	69.1	5.5	64.8	5.2	61.2	4.2	52.1	3.7
204(L)	51	11	71.3	3.4	63.3	3.8	71.6	7.9	73.0	4.2	68.1	3.4	58.1	3.2
136(L)	50	12	71.3	3.5	64.3	3.1	73.9	6.9	72.9	4.4	68.1	3.4	58.1	3.3

sheep fed the forage used in Exp. 94-97 either long or pelleted at about maintenance level, d_O was reduced with grinding and pelleting. The d_O of pelleted hay cut early and late and straw was 62.1, 59.7 and 42.1, which was 3.3, 4.0 and 6.8 percentage units, respectively, from the d_O of the original long forage. This agreed with the tendency reported by Heany et al. (1963), that the effect of grinding and pelleting increased for less digestible forages.

5.2.2 Comparison of digestibility between diets with long or pelleted forages

These results are from experiments at the Department of Animal Physiology, Wageningen, up to 1973. The comparisons include 130 energy balance experiments with dairy cows on diets with forage pellets and 204 experiments with only long forages, like hay or silage. Table 13 presents averages and standard deviations of digestibility and the percentage of dry matter provided by long forage in total intake (P_L). For the diets with pellets a lower d_O and d_E (both 6.9 units) was found than with 'long' diets. The difference in d_N and d_{XL} was somewhat smaller and that in $d_{(XF+XX)}$ slightly greater than for d_O and d_E.

The following factors might cause a lower digestibility of the diets containing forage pellets:

- a lower digestibility of the original forages in 'pellet' diets than in 'long' diets;
- a lower roughage-to-concentrates ratio in 'long' than in 'pellet' diets;
- a higher level of feeding in 'pellet' than in 'long' diets;
- a lower digestibility of pelleted forages due to grinding and pelleting.

The quantitative effect of each of these factors or any combination could not be determined from this information, but indirectly we can get an idea of the main factors in lower digestibility of 'pellet' diets.

No evidence was found for a lower digestibility of the forages in 'pellet' diets than in 'long' diets, as the digestibility in vitro of organic matter (method described by van der Koelen et al., 1974) was 63.6 ± 7.9 and 63.3 ± 8.7, respectively. These figures were only available for forages of 30 'long' diets (136 balance experiments) and for those of 28 'pellet' diets (130 balance experiments). However Table 13 shows that average values of the 136 balance experiments, were no different from the 204, of which they formed part.

Intake of forages could be increased by grinding and pelleting the forage (Chapter 2), so reducing the amount of concentrates necessary to meet energy requirement. Intake of concentrates organic matter as a percentage of total intake of organic matter (P_C) from 30 'long' diets (136 experiments) was 50.7 ± 11.2 and from 28 'pellet' diets (130 experiments) 35.6 ± 5.4. The 15 percentage units lower P_C reduced digestibility of organic matter, because d_O of concentrates was on average about 20 units higher than d_O of forage. This reduction was estimated to be about 3 units (0.15 × 20). The difference found between 'long' and 'pellet' diets was 6.1 units, which suggested that a reduction of 2-3 units was due to other factors, if the average d_O of concentrates of 'long' and 'pellet' diets was no different.

I_T of the 204 and 136 experiments with 'long' diets was 13.9 ± 1.9 and 14.0 ± 1.8 kg/day, respectively, whereas I_T of the 130 experiments with 'pellet' diets was 16.0 ± 1.5 kg/day. This suggested a slightly higher level of feeding for the cows receiving 'pellet' diets. However, the lower M_E content in dry matter of 'pellet' diets resulted only in a 0.5 Mcal or 1.3% higher intake of M_E for 136 'long' experiments than for 130 'pellet' experiments. Because of a slightly higher liveweight of cows receiving 'pellet' diets, the M_E intake per $kg^{\frac{3}{4}}$ was no different between the two types of diets. So the effect of level of feeding on digestibility could be neglected.

The effect of processing on digestibility as such could be partly derived from an indirect comparison. In a finely ground sample of the forage of 28 'pellet' and 30 'long' diets the digestibility in vitro of organic matter (van der Koelen et al., 1974) was estimated. In this analysis, the effect of processing the forage, especially on increase in rate of passage from the reticulo-rumen, could be neglected. So a predicted d_O of the rations consumed by the cows was calculated from digestibility in vitro of organic matter of forages and from a d_O for concentrates derived from the digestibility of ingredients of the mixture presented in the Dutch Feeding Table

(CVB, 1970a). The predicted d_O was compared with the d_O found in the balance experiments with dairy cows. The mean d_O and standard deviation found in the cow experiments was for 30 'long' diets 71.1 ± 3.6 and for 28 'pellet' diets 65.0 ± 4.0, compared with the predicted figures of 73.9 ± 3.9 and 70.2 ± 4.5 for 'long' and 'pellet' diets, respectively. Because the high level of feeding, which reduced the d_O in the cow experiments, the predicted value was too high since both d_O (in vitro) and the d_O from the feeding table apply to sheep fed at maintenance level. For 'long' and 'pellet' diets, this systematic error is assumed to be of the same magnitude. The difference between the predicted and the experimental d_O was for 28 'pellet' diets on average 5.24 ± 2.10 and for 30 'long' diets 2.83 ± 1.49. The greater difference for 'pellet' diets than 'long' diets (5.24 - 2.83 = 2.41 percentage units for d_O) was thought to be due mainly to the grinding and pelleting of part of the forages in the diet. Using Student's test, the average value of 2.41 units seemed significant at $P < 0.01$:

$$2.41/(1.49^2/30 + 2.10^2/28)^{\frac{1}{2}} = 2.41/0.48 = 5.0$$

In conclusion, two main factors caused the lower d_O of the diets with pelleted forages:

- The higher forage-to-concentrates ratio, which reduced the d_O by about 3 percentage units
- the grinding and pelleting of the forage, which resulted in an average reduction in d_O of the diet by 2-3 percentage units.

The contribution of pelleted forage to total intake of organic matter (P_P) mainly varied from 30-60%. Provided that processing did not affect the digestibility of the other components of the ration, this should mean a reduction in d_O of the forage due to pelleting of about 3 to 9 percentage units or 5 to 15%.

5.2.3 Comparison of processed with long forage

From Exp. HR 1-3, 131-133, 136-137 and 141-142, long and processed forage from the same material could be directly compared. Table 14 presents the differences in digestibilities between diets with long and processed forage. P_P ranged from 22 to 64%. Assuming that the differences in digestibility between diets with long and processed forages were entirely due to processing of the forages, the depression in digestibility could be extrapolated to 100% processed forage in the diet. Calculated in this way, processing of forage to pellets or cobs reduced d_O by 5.4 to 14.1 percentage units, d_N by

Table 14. Effect on apparent digestibility (d) of rations with processed forage (P) compared with rations containing the same forage in long form (L); differences between diets (P-L) and the estimated effect of processed forage when extrapolated to 100% I_O from processed forage (100% P_{est}). See List of Symbols.

Exp. No	Treatment codes[1]	P_P in diets L/P	d_O			d_N			d_E		
			L diet	P-L	100% P_{est}	L diet	P-L	100% P_{est}	L diet	P-L	100% P_{est}
131-133	G/GP	0/42	72.9	-3.2	-7.7	60.1	0.5	0.9	69.2	-3.0	-7.3
136-137	HP4/HP8	23/43	71.0	-1.8	-8.7	68.4	-0.3	-1.3	67.9	-1.6	-8.2
136-137	HP4/HP8	22/41	68.4	-2.4	-12.4	64.8	-0.0	-0.1	65.0	-2.5	-13.0
141-142	HP4/HP8	22/43	71.8	-3.0	-14.1	68.8	-1.7	-8.2	68.3	-2.9	-13.9
141-142	HP4/HP8	22/43	72.0	-1.1	-5.4	69.1	-0.1	-0.3	68.3	-1.1	-5.2
HR1-3	G/GC	0/50	67.7	-3.2	-6.3	63.1	-0.7	-1.4	63.5	-2.7	-5.4
HR1-3	G/GW	0/64	67.7	-1.9	-3.3	63.1	-0.4	-0.7	63.5	-1.4	-4.7
Average (except GW)					-9.1			-1.7			-9.6

1. See Table 9.

-0.9 to +8.2 units and d_E by 5.2 to 13.9 units.

From the analysis of variance in each series, a significant effect of pelleting was found in Exp. 131-133, 136-137 and 141-142. The diets HP4 in 136-137 and 141-142 and G in HR 1-3 and 131-133 were called 'long' diets and the treatments HP8, GC and GP in these experiments 'pellet' diets. The mean difference in d_E between 'long' and 'pellet' diets was calculated from the average difference within each series as

$$(-0.89 + 2.97 + 2.03 + 1.68)/4 = 1.53 \text{ percentage unit.}$$

The standard error of this mean difference in d_E was calculated from the sum of variances of the differences in Exp. HR 1-3, 131-133, 136-137 and 141-142 as

$$\tfrac{1}{4}(2.3879 + 0.2116 + 0.0924 + 0.2377)^{\frac{1}{2}} = 0.428$$

The degrees of freedom of the residual variances were 4, 7, 5 and 4 and therefore a Student's test with 4 degrees of freedom was used to test for significance of the mean difference in d_E. Four degrees of freedom may be rather low but by this procedure the significance of a difference in d_E between 'long' and 'pellet' diets cannot be overestimated. The mean difference in d_E of 1.53 percentage unit was found to be significant ($P < 0.05$). It is still questionable whether the differences found in Exp. 131-133 and 136-137 were entirely due to processing. Diets G and GP of Exp. 131-133 showed small differences in composition, which might be due to some contamination with other forage during drying (van der Honing & Rijpkema, 1974). In Exp. 136-137, the differences between 'long' and 'pellet' diets might include some variation with time, because 'long' diets were fed in 136 and 'pellet' diets in 137.

For the different types of pellets of grass hay and artificially dried grass as such, there were only a few significant differences with processing (Table 14) and a strong tendency for a depression in digestibility, since all the differences between 'pellet' and 'long' diets were negative. Most differences were insignificant through low precision of the comparison attributable to the small number of animals used and to the small proportion of processed forages, 19-50%, in the diet that replaced long material (wafered forage excluded). The average depression of d_O and d_E extrapolated to 100% processed forage in the diet was 9.1 and 9.6 percentage units, respectively, which was about 15%, if a digestibility of 65 was assumed. The depression of d_N was small and on average below 1.7 percentage unit or 3%.

The depression in d_E with grinding and pelleting as calculated in Section 5.2.2 was slightly less than the average effect calculated in this section. In the experiments of this section only processed artificially dried grass or grass hay was used, whereas in the experiments of Section 5.2.2 also ground and pelleted legumes were supplied. According to the results found with sheep, reported by Jarrige et al. (1973a), the depression in digestibility with processing might be greater for grasses than for lucerne in dairy cows too and so explain the differences in d_E found in Section 5.2.2 and in this section.

5.3 METABOLIZABLE ENERGY CONTENT OF THE DIETS

Table 11 presents the averages and standard deviations of the metabolizability (q) of each treatment. Since M_E is digestible energy (D_E) minus energy in methane (G_E) and urine (U_E), attention will also be paid to the effect of processing on G_E and U_E.

5.3.1 Replacement of concentrates by pelleted forages

Figure 4 shows the effect of a substitution of concentrates by pelleted hay or straw on metabolizability (q). Metabolizability was plotted against the percentage of concentrates organic matter in total intake of organic matter (P_C). An increase in the amount of forage pellets was associated with a decrease in P_C. The depression in q seemed greater for straw (squares) than for hay and for late cut hay (triangles) than for early cut hay (circles) as found for digestibility of energy too (Fig. 3).

Table 12 showed that the relation between q and P_C fitted well to a linear equation (R^2 = 0.89-0.95). The intake of organic matter (I_O), added as a second variable to P_C in multiple regression analysis, gave a significant negative regression coefficient for I_O and a small reduction in RSD. This may be due mainly to a depression of d_E by an increase in level of feeding (Section 5.2.1), which was not completely compensated by lower losses of energy as methane and urine, although Moe et al. (1965) found a lower quotient of methane production (G_E) to I_E at a higher level of feeding (Section 3.2).

Average M_E/D_E as a percentage was 87.2, 85.3, 85.1 and 85.5 in Exp. 94-97 and 85.8, 84.5, 84.7 and 84.6 in Exp. 104-107 for the Diets CONC, SP, HPL and HPE, respectively. The diet with 4 or 5 kg forage pellets generally tended to be intermediate between CONC (no forage pellets) and the diets with 8 or 10 kg forage pellets. The lower sum of G_E and U_E as a percentage

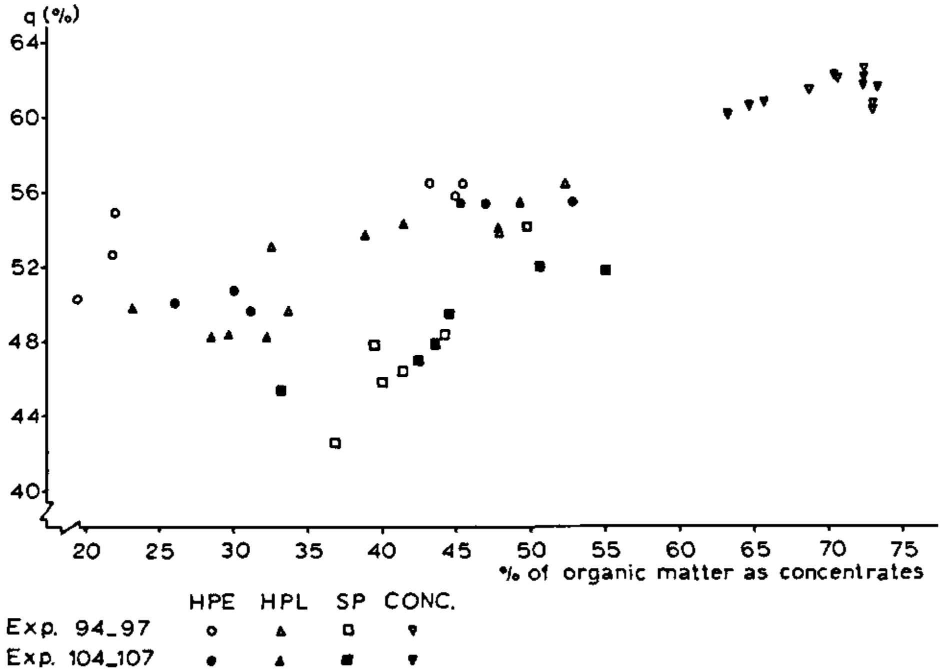


Fig. 4. Relation between metabolizability (q) and contribution of concentrates to total intake or organic matter (P_C) in Exp. 94-97 and 104-107. Rations contained pelleted hay cut early (HPE) or late (HPL), straw pellets (SP) or no pelleted forage (CONC).

of D_E on Diet CONC was mainly due to the higher metabolizability and digestibility of energy, since 9.6, 8.6, 9.2 and 9.4% of gross energy was lost in methane and urine on the Diets CONC, SP, HPL and HPE, respectively. Losses of energy in urine relative to energy intake were slightly lower for HPL and SP than for CONC and HPE (2.9 and 2.5% compared with 3.3 and 3.2%, respectively). Only G_E/I_E tended to be slightly lower for SP than for the other treatments (SP 6.1% compared to 6.3% for the other treatments).

5.3.2 Comparison of metabolizability between diets with long or pelleted forages

In Table 13, the averages and standard deviations of metabolizability (q) of 130 balance experiments with 'pellet' diets were 52.1 ± 3.7, and of 204 with 'long' diets 58.1 ± 3.2. This difference of 6.0 percentage units agreed well with the difference in d_E, 6.9 units. There was hardly any difference in M_E/D_E in 'long' and 'pellet' diets (85.4-85.2%). $(U_E + G_E)/I_E$, however, was 10.0 for 'long' diets and 9.1 for 'pellet' diets. This difference was mainly due to lower G_E/I_E on 'pellet' diets, 0.9 percentage unit. Because of the lower d_E of 'pellet' diets, the M_E/D_E of 'long' and 'pellet' diets were the same. According to the formula of Blaxter & Clapperton (1965), derived from sheep data used to predict G_E/I_E from d_E and feeding level, G_E/I_E on the 'pellet' and 'long' diets was predicted as 6.9 and 7.3% but 5.5 and 6.4% were found in the experiments with dairy cows, respectively. The slightly greater difference might be due to the processing of the forage, as found in sheep trials by Blaxter & Graham (1956) and Wainman et al. (1972), though we could not exclude other factors, such as P_C. Blaxter & Wainman (1964) showed that the G_E/I_E increased with increase in the proportion of maize in a beef cattle diet until this proportion was 60-80% and then declined markedly. If this effect was also found by increasing P_C in a dairy ration, the difference in methane production on 'long' and 'pellet' diets might at least partly be due to the lower P_C in 'pellet' than in 'long' diets. In these data, no effect was observed of processing forage on U_E.

In conclusion, the decrease in $G_E + U_E$ with forage processing seems far too small to compensate the parallel decrease in d_E in these dairy rations.

5.3.3 Comparison of metabolizability between processed and long forage

Table 15 presents a direct comparison of metabolizability (q) in 'long' and 'pellet' diets of Exp. 131-133, 136-137, 141-142 and HR 1-3. As for d_E in Section 5.2.3, the depression in q due to processing was extrapolated to 100% processed forage in the diet, assuming that the difference between 'long' and 'pellet' diets was entirely due to the processed forage.

Processing to pellets or cobs caused a calculated decrease in q of the forage of 7.0 percentage units, range between experiments 3.2–12.4. Reduction in q by wafering was calculated at 1.1 percentage units. But these figures were not very precise, because only 2-6 cows were used for each treatment and because the difference between compared diets, by substitution of pellets for part of the long forage, represented 19-50% of total intake of organic matter.

From the analysis of variance, there were significant differences in q between 'long' and 'pellet' diets in Exp. 131-133, 136-137 and 141-142 but not in Exp. HR 1-3. The calculated mean difference in q for all series was

$$(-0.97 + 1.90 + 1.86 + 1.33)/4 = 1.03 \text{ percentage unit}$$

Table 15. Effect on metabolizability of gross energy (q) of rations with processed forages (P) compared with rations containing the same forage in long form; differences between diets (P-L) and the estimated effect of processed forage when extrapolated to 100% I_O from processed forage (100% P_{est}). See List of Symbols.

Exp. No	Treatment codes[1]	P_P in diets L/P	q L diet	q P diet	q P-L	q SD_{P-L}	q 100% P_{est}
131-133	G/GP	0/42	58.92	57.02	-1.90	0.56	- 4.5
136-137	HP4/HP8	23/43	58.68	57.19	-1.49	0.59	- 7.4
136-137	HP4/HP8	22/41	55.34	53.11	-2.23	0.60	-12.4
141-142	HP4/HP8	22/43	58.25	55.82	-2.43	0.94	-11.0
141-142	HP4/HP8	22/43	57.59	56.80	-0.79	0.79	- 3.8
HR 1-3	G/GC	0/50	53.15	51.56	-1.59	1.06	- 3.2
HR 1-3	G/GW	0/64	53.15	52.47	-0.68	0.77	- 1.1

1. See Table 9.

with a standard error of

$$\tfrac{1}{4}(0.8975 + 0.3814 + 0.0681 + 0.2017)^{\frac{1}{2}} = 0.311$$

As for d_E (Section 5.2.3), this mean value of q was significantly less for 'pellet' diets ($P < 0.05$). For the same reasons as for d_E in Exp. 131-133 and 136-137 (Section 5.2.3), it is still questionable whether the effects can be attributed entirely to processing.

Table 15 showed that the effect of processing was negative in all experiments. Most differences were not significant, mainly because of the low precision. But they support the conclusion that grinding and pelleting of the forage decreased its q. This decrease in q extrapolated to 100% processed forage was on average 7 percentage units, about 13% if the q of long forage was 55. The effect of processing on q tended to be somewhat smaller than for d_E, which was 15%, although this conclusion is uncertain because of the low precision of the figures.

Through processing of part of the forage to pellets or cobs, the mean d_E of 'long' diets of Exp. 131-133, 136-137, 141-142 and HR 1-3 was 1.53 percentage unit higher than for 'pellet' diets. The difference in q was on average 1.03 percentage unit, which means a compensation of 0.50 unit or about 30% of the decrease in d_E. Between experiments this compensation ranged from -9 to +36%.

The smaller difference in q than in d_E between 'long' and 'pellet' diets was almost completely due to lower G_E losses on 'pellet' diets. The measured

$(G_E + U_E)/I_E$ was 10.06% on 'long' diets and 9.61% on 'pellet' diets and differed on average 0.45 (range from 1.15 in Exp. 131-133 to 0.08 in HR 1-3).

5.3.4 Relation of metabolizable energy to digestible energy and digestible organic matter

In Exp. 94-97, M_E/D_E was 87.2, 85.3, 85.1 and 85.5% for treatment CONC, SP, HPL and HPE, respectively, and in Exp. 104-107 these values were 85.8, 84.5, 84.7 and 84.6. So this quotient was slightly higher for a diet with a large proportion of concentrates which was in line with a similar tendency found within one treatment between diets containing 4 or 5 kg and those with 8 or 10 kg of pelleted forage (Section 5.3.1).

The M_E/D_E of 204 and 136 balance experiments with 'long' diets (Section 5.2.2) coincided precisely at 85.33% and of 130 experiments with 'pellet' diets 85.19%. The slightly higher value for 'long' diets might be due to the higher proportion of concentrates than for 'pellet' diets. There was less effect of proportion of concentrates than expected from results of Exp. 94-97 and 104-107.

In Exp. 131-133, 136-137, 141-142 and HR 1-3, mean M_E/D_E for 'long' and 'pellet' diets was 83.67 and 84.42%, respectively. The difference between 'pellet' and 'long' diets of 0.75 percentage unit, range from -0.25 to +1.11 between experiments, suggested a small increase in M_E/D_E of about 0.9% due to the processed forage in 'pellet' diets.

If the effect of processing of forage on M_E/D_E was really opposite to the effect of a higher proportion of concentrates, this should have resulted in only a small difference in M_E/D_E between 204 balance experiments on 'long' and 130 on 'pellet' diets, depending on the size of the effect of both factors. This might explain the small difference in these experiments. The effect of grinding and pelleting on M_E/D_E seemed small and negligible.

M_E/D_O of 204 and 136 balance experiments with 'long' diets was 3.89 and 3.91 Mcal/kg, respectively and of 130 on 'pellet' diets 3.90. In the direct comparison of pelleted forage with the original long material in Exp. 131-133, 136-137, 141-142 and HR 1-3 for 'pellet' diets, a mean value of 3.92 was found, range 3.87–3.99 between experiments and for 'long' diets 3.90 (3.81-3.99). The quotient was on average 0.6% higher for 'pellet' than for 'long' diets and varied from -0.5 to +1.8% between experiments. The difference in M_E/D_O of 'long' and 'pellet' diets was small and could be neglected.

5.4 UTILIZATION OF METABOLIZABLE ENERGY

Not all the metabolizable energy is used for milk production. We must subtract the heat of fermentation in the reticulo-rumen, which may be 7-10% of M_E intake (Osuji, 1973; van Es, 1974). The requirements for maintenance and, in heifers, for growth must be met. Some M_E may be converted into milk energy (L_E), provided that the cow is genetically and physiologically capable. Surplus M_E can be utilized to gain liveweight (mainly fat) and at low M_E intake tissue energy may be mobilized to supply additional energy for milk synthesis. Utilization of energy for milk, growth and fattening involves heat losses. In the energy balance experiments we estimated total heat production (i.e. heat of fermentation, metabolizable energy for maintenance and heat losses in the utilization of metabolizable energy for milk and fattening). In Chapter 4, energy balance (R_E) was calculated in two ways:

- as the difference between metabolizable energy (M_E) and the sum of milk energy and total heat production (L_E + H)
- from C and N balances.

Since heat of fermentation could not be measured separately from maintenance heat, no conclusion about the effect of processing of the forage on fermentation heat could be drawn. Energy stored during growth of heifers is expressed in the same term, R_E, as energy deposited as fat reserves by older cows. Because only net energy in milk and body tissue could be measured in these experiments and not net energy for maintenance, which constituted part of heat losses, models were used to study the utilization of M_E to account also for net energy for maintenance. This section describes models and gives results of regression analysis on data from the energy balance experiments with diets containing only long forages and those with pelleted forage in the ration.

5.4.1 Models used to study the utilization of metabolizable energy

The sum of energy in milk (L_E) and energy balance (R_E) can be seen as the result of utilization of M_E left for production after subtracting metabolizable energy for maintenance ($M_{E,m}$) from total M_E. Because maintenance requirement was related to metabolic body size ($W^{\frac{3}{4}}$), this requirement could be described as $c \cdot W^{\frac{3}{4}}$, where c is a constant (van Es, 1961, 1972). Multiple regression analysis showed too that no significant differences could be detected in efficiency of utilization of M_E (k) for maintenance and for production in the dairy cow (van Es et al., 1970; Moe et al., 1972). Since the evidence suggests that during lactation the efficiency of energy utilization for production of body fat was the same as for milk, a model could be used in which M_E is utilized with equal efficiencies for maintenance and production:

$$R_E + L_E = k(M_E - c \cdot W^{\frac{3}{4}}) \qquad (5.1)$$

According to van Es et al. (1970), negative energy balances (negative R_E) should be multiplied by a factor 0.8 because results of balance experiments showed that for negative energy balances, mobilized tissue energy was utilized with an efficiency of about 80% for milk synthesis, as it is directly available in intermediary metabolism and no energy was lost in heat of fermentation in the rumen nor in absorption of nutrients. So for negative R_E, 0.8 R_E was used instead of R_E. Moe et al. (1972) used a factor of 0.84 and Schiemann et al. (1974) found 0.81, which are very close to the value used here.

Blaxter (1967) showed that in growing and fattening animals, the efficiency of utilization of $M_{E,m}$ (k_m) and of $M_{E,f}$ (k_f) was related to the quality of the ration as indicated by metabolizability (q). Moreover the effect on k_f was considerably greater than on k_m:

$$k_m = 54.6 + 0.30\ q$$

$$k_f = 3.0 + 0.81\ q$$

Also in the lactating cow, the utilization of M_E depended on q. No differences in this relation could be detected for maintenance, lactation or fattening. To account for differences in utilization of M_E due to the origin of M_E, the following equation could be used for the dairy cow:

$$R_E + L_E = (a + b \cdot q)\ \{M_E - (d + e \cdot q)\ W^{\frac{3}{4}}\} \qquad (5.2)$$

in which q could be any quality factor, for instance metabolizability. Instead of q, other related factors might be used, for instance the content of digestible nutrients in organic matter or a linear or a curvilinear combination of such information. Also the contribution of long forage to total intake of dry matter (P_L) might affect the utilization of M_E. Additional energy would also be needed to synthesize and excrete nitrogen as urea by means of urine (U_N) (van Es & Boekholt, 1971; Moe et al., 1972), so that

Equation 5.2 might be extended to

$$R_E + L_E = (a + b \cdot q + c \cdot P_L) \{ M_E - d \cdot U_N - (e + f \cdot q + g \cdot P_L) W^{\frac{3}{4}} \} \qquad (5.3)$$

This could be simplified somewhat by dividing $W^{\frac{3}{4}}$ (indicated by * sign):

$$R_E^* + L_E^* = (a + b \cdot q + c \cdot P_L) \{ M_E^* - d \cdot U_N^* - (e + f \cdot q + g \cdot P_L) \} \qquad (5.4)$$

Van Es et al. (1973) found by multiple regression analysis that most products of two or more of the single independent variables M_E^*, q, P_L and U_N^* did not lower the RSD of the regression any further. Only q^2 gave a very small reduction. Therefore Equation 5.4 could be simplified to

$$R_E^* + L_E^* = a \cdot M_E^* + b \cdot q + c \cdot P_L + d \cdot U_N^* + e \qquad (5.5)$$

Another method of comparing the utilization of M_E from 'long' and 'pellet' diets would be to calculate the efficiency, k, from the total net energy for maintenance and production of the rations using a constant net energy requirement of 65 kcal/kg$^{\frac{3}{4}}$ for maintenance and assuming no differences in efficiency of utilization of M_E for maintenance, milk or body tissue. The value 65 was found in a preliminary regression analysis on 297 energy balance experiments in Wageningen (van Es et al., 1973). It agreed well with data of Moe et al. (1972), reporting a value of 68.
If so,

$$k = (R_E^* + L_E^* + x)/M_E^* \qquad (5.6)$$

where x is 65 kcal/kg$^{\frac{3}{4}}$. The assumption of a constant net energy requirement per unit metabolic body size may not hold true between individuals, but could be useful if 'pellet' and 'long' diets are given to the same animal, because a slightly wrong estimate would then influence the efficiency of utilization of M_E from 'pellet' and 'long' diets to about the same extent.

5.4.2 Results of multiple regression analysis of energy balance data from diets with long or processed forages

The results of 204 energy balance experiments at Wageningen with 'long' diets and of 130 with rations containing pelleted forages ('pellet' diets)

Table 16. Average (av.) and standard deviation (SD) of data used in the multiple regression analysis of Table 17. See List of Symbols.

	n	$L_E^* + R_E^*$[1]		M_E^*		q		P_L		U_N^*	
		av.	SD	av.	SD	av.	SD	av.	SD	av.	SD
L diets	204	124.7	29.3	302.9	46.7	58.1	3.2	50.6	11.0	1.18	0.30
P diets	130	123.2	20.8	322.5	35.1	52.1	3.7	23.4	10.5	1.45	0.47
L+P diets	334	124.1	26.3	321.5	42.5	55.8	4.5	40.0	17.1	1.29	0.40

1. Negative R_E^* was multiplied by 0.8; see also text.

were analysed according to Equation 5.5, because no appreciable reduction in RSD was found when the products of two or more single variables were used in the regression. Table 16 presents average and SD of the variables. The mean values for $L_E^* + R_E^*$ and M_E^* hardly differed between 'pellet' and 'long' diets but, for 'pellet' diets, q and P_L were much lower and U_N^* was higher than for 'long' diets.

Table 17 shows the results of multiple regression analysis. Considering the regression with only the independent variable M_E^*, the regression coefficient a was significantly lower on 'pellet' than on 'long' diets. The calculated maintenance requirement ($M_{E,m}$) was on 'pellet' diets 53.1/0.547 = 97 kcal/kg$^{3/4}$ and for 'long' diets 68.1/0.601 = 113 kcal/kg$^{3/4}$, respectively. The

Table 17. Multiple regression analysis of $L_E^* + R_E^* = a \cdot M_E^* + b \cdot q + c \cdot P_L + d \cdot U_N^* + e$ from energy balance data of 204 experiments with long forages (L) and 130 with pelleted forages (P) in the rations.

	n	a	b	c	d	e	RSD	CV (%)
L diets	204	0.601				- 68.1	8.5	6.8
		0.555	1.620			-147.6	7.1	5.7
		0.557	1.349	-0.219		-121.1	6.8	5.4
		0.580	1.389	-0.204	-6.96	-123.4	6.6	5.3
		0.581	1.644		-7.67	-148.2	6.9	5.5
P diets	130	0.547				- 53.1	8.1	6.6
		0.510	0.724			- 79.1	7.8	6.3
		0.496	0.903	-0.145		- 80.3	7.7	6.2
		0.563	0.867	-0.080[1]	-8.06	- 90.0	7.1	5.7
		0.574	0.771		-8.46	- 89.9	7.1	5.7
L+P diets	334	0.586				- 64.3	8.5	6.8
		0.560	0.796			-100.3	7.8	6.3
		0.540	1.190	-0.188		-108.3	7.3	5.9
		0.577	1.111	-0.211	-7.63	-105.2	6.8	5.5
		0.594	0.689		-6.49	- 96.8	7.5	6.0

1. Insignificant at $P < 0.05$.

lower regression coefficient for M_E^* suggested a lower utilization of M_E from 'pellet' diets, although this might partly be compensated by a lower $M_{E,m}$ on 'pellet' diets. However since the mean of q, P_L and U_N^* was different for 'long' and 'pellet' diets and showed different regression coefficients for q and P_L, the conclusion about utilization of M_E from a regression on only M_E^* could be misleading.

All the regression coefficients in Table 17 were found to be significant ($P < 0.05$), except coefficient c = 0.080 for P_L (130 balance experiments on 'pellet' diets), and reduced the RSD. It was concluded that the influence of P_L and U_N^* was small relative to that of q. Between M_E^* and q, a positive correlation was found of 0.41 and 0.48 for data from 'long' and 'pellet' diets, respectively. So a higher level of feeding was related to a higher value of q. Between M_E^* and U_N^*, only a small positive correlation and between M_E^* and P_L a small negative correlation was found in both groups of data. However, a negative correlation (-0.35) between q and P_L was found for data from 'long' diets, whereas a positive correlation (+0.27) was derived from data of 'pellet' diets, mainly because with 'long' diets P_L decreased through use of more concentrates at higher milk yields, whereas with 'pellet' diets a decrease was also due to replacement of long forage by pelleted forages. The lower proportion of forages to concentrates in the ration increased q, whereas replacement of long forage by pelleted forages usually decreased q. Moreover in the regression analysis, P_L showed significant skewness and kurtosis. As these facts argued against the use of P_L as an independent variable to compare utilization of M_E from 'long' and 'pellet' diets and the RSD was only slightly lowered by use of P_L, multiple regression was calculated also without P_L as a variable (Table 17). The positive regression coefficient of q could be interpreted as an improvement in utilization of M_E as the value of q increased, whereas a high output of U_N^* decreased the utilization of M_E.

To compare 'long' and 'pellet' diets for utilization of M_E for milk and body tissue, we calculated differences between $L_E^* + R_E^*$ (y) actually found in the experiments and a predicted value ($\hat{y}$) using the equation derived from the 204 experiments with 'long' diets:

$$\hat{y} = 0.581\ M_E^* + 1.644\ q - 7.67\ U_N^* - 148.2$$

Table 18 presents the difference $y - \hat{y}$. In the 130 experiments with 'pellet' diets, on average $(L_E^* + R_E^*)/M_E^*$ was 7.7% more than with 'long' diets. In this comparison, the same maintenance energy requirement on both types of

Table 18. Net energy in milk and body tissue ($L_E^* + R_E^*$) and difference ($y-\hat{y}$) from a predicted value ($\hat{y} = 0.581\ M_E^* + 1.644\ q - 7.67\ U_N^* - 148.2$) and the estimated total net energy as a percentage of M_E or I_E assuming that net energy for maintenance was 65 kcal/kg$^{\frac{3}{4}}$. See List of Symbols.

Exp. No	Treatment codes[1]	Animals (n)	$L_E^* + R_E^*$	$y-\hat{y}$	k	e_{NE}
204 on	L diets	204	124.7	0.1	59.10	34.36
130 on	P diets	130	123.2	9.5	58.42	30.47
94-97	CONC	6	133.7	7.1	63.75	39.20
94-97	HPE	6	128.5	9.2	60.86	33.16
94-97	HPL	6	131.1	9.2	59.62	31.29
94-97	SP	6	114.9	16.2	60.10	28.48
104-107	CONC	6	108.5	4.0	63.02	38.51
104-107	HPE	6	119.3	7.1	58.45	30.88
104-107	HPL	6	108.0	10.1	59.86	30.88
104-107	SP	6	94.1	12.8	59.66	29.13
117-118	LPOF	4	123.9	14.2	58.18	29.03
117-118	LP2F	4	120.8	15.1	58.88	29.47
117-118	LP4F	4	127.3	14.5	59.38	30.40
124-126	GP	6	134.6	7.5	58.66	31.02
124-126	LPE	6	130.6	7.3	56.55	29.36
124-126	LPL	6	104.7	10.7	55.92	26.27
134-135	GPOF	4	101.0	15.1	61.30	32.11
134-135	GP3F	4	102.3	11.4	60.33	31.85
138-140	LPIE	6	125.6	10.8	57.11	28.91
138-140	LPIL	6	120.7	14.1	57.21	27.31
138-140	LPII	6	106.1	9.7	55.82	27.00
HR 1-3	G	4	99.8	2.6	55.56	29.52
HR 1-3	GC	4	112.8	14.7	58.85	30.34
HR 1-3	GW	4	103.9	9.1	57.88	30.38
131-133	G	6	158.6	1.0	59.28	34.93
131-133	GP	6	150.2	8.4	60.20	34.33
136	HP4 (S)	3	136.6	-8.1	56.05	32.89
137	HP8 (S)	3	155.1	0.4	57.25	32.74
136	HP4 (A)	3	128.5	-2.7	55.82	30.89
137	HP8 (A)	3	143.5	8.8	57.42	30.50
141-142	HP4 (S)	2	144.0	0.1	57.41	33.44
141-142	HP8 (S)	2	142.8	9.3	59.03	32.94
141-142	HP4 (A)	4	141.9	0.9	56.84	32.74
141-142	HP8 (A)	4	151.4	9.6	58.73	33.38

1. See Table 9.

diets was assumed. As net energy for maintenance is about half the net energy for production ($L_E^* + R_E^*$), the difference $y - \hat{y}$ was about 2 x 7.7/3% = 4.8% of total net energy. If it be assumed that this improvement was completely due to the processing of forage in the diet and given that pelleted forage mainly ranged from 30 to 60% of the organic matter ingested (Section 5.2.2), this improvement in utilization of M_E could compensate for a reduction in M_E with processing of about 8 to 16%. This was at least as great as the depression in M_E estimated in Section 5.3.3.

A comparison of the efficiency of utilization of M_E, according to Equation 5.6, between the experiments with 'long' and 'pellet' diets showed a difference of 59.10% - 58.42% = 0.78 percentage unit or 1.3% in favour of the experiments with 'long' diets. The q of 'pellet' diets was 6 percentage units lower and U_N^* 0.29 units higher than of 'long' diets. As shown by the regression equations of Table 17, a lower efficiency of utilization of M_E could therefore be expected for 'pellet' diets of about

100(6 × 1.644 + 0.29 × 7.67)/190 = 6.3%, whereas only 1.3% was found. This suggested also that k for 'pellet' diets was about 5% higher.

5.4.3 Comparison of utilization of metabolizable energy of diets in which concentrates were replaced by pelleted forages

From the data of Exp. 94-97 and 104-107, in the same way as in Section 5.4.2, $y - \hat{y}$ was calculated using the same equation derived from data of 'long' diets (Table 18). This difference tended to be greater for diets with forage pellets (HPE, HPL, SP) than for those without (CONC). The difference for Diet SP was twice as high as for Diet HPE and HPL which might indicate that the improvement in utilization of M_E tended to be higher for poor forages. This was also reported by Wainman et al. (1972) with pelleted forages offered to fattening sheep. Because of the high SD of $y - \hat{y}$ for each type of diet, no differences between treatments were significant.

The value of k was calculated with Equation 5.6 for each diet (Table 18). Values of k for CONC were higher than for diets with forage pellets. This tendency was also found when 5 instead of 10 kg hay pellets replaced part of the concentrates in the diet. For the Diet HPE, k was 61.6 and 57.7% and for HPL 61.6 and 57.9% with 5 or 10 kg hay pellets in the diet, respectively. Only for SP was such a tendency absent, probably because some of the 8 kg straw pellets was often left and the variation in the proportion of concentrates in these diets was much smaller than for hay pellets.

Forage pellets can replace concentrates, although the utilization of M_E of diets with pellets is lower through the lower q of such diets. The mean net energy for production found in the experiments was for all treatments higher than the predicted value from a relation derived from normal rations with long forages and concentrates. Perhaps M_E from diets rich in concentrates or those including pelleted forages was utilized by dairy cows slightly more efficiently than M_E from rations of about half long forages and half concentrates.

5.4.4 Utilization of metabolizable energy from long or pelleted forages

The average of $y - \hat{y}$ was calculated, just as in Section 5.4.2, for the different treatments of Exp. HR 1-3, 131-133, 136-137 and 141-142 (Table 18). Diets G and HP4 were called 'long' diets and GC, GP and HP8 'pellet' diets. The analysis of variance showed that the average of $y - \hat{y}$

$(-12.0 - 7.3 - 10.0 - 8.9)/4 = -9.6$ kcal/kg$^{\frac{3}{4}}$ with a standard error of 3.2 was significantly different between 'long' and 'pellet' diets ($P < 0.05$), and in each series, the value $y - \hat{y}$ was greater for 'pellet' than for 'long' diets. Because only a small proportion of M_E was provided by pelleted forages that replaced the long material, an improvement in utilization of M_E with pelleting of the forage should only result in a small improvement in utilization of M_E from 'pellet' diets. The tendency towards a small improvement might still indicate an improvement in utilization of M_E from pelleted forages. Although 64% of I_O consisted of wafers, the effect of wafering in Exp. HR 1-3, was not significant and even tended to be smaller than the effect of pelleting in that series.

Table 18 presents values of k calculated from Equation 5.6. Differences in k in Exp. 136-137 and 141-142 between 'long' and 'pellet' diets were significant ($P < 0.05$). The calculated mean difference in k between 'long' and 'pellet' diets of Exp. HR 1-3, 131-133, 136-137 and 141-142 was

$(-3.46 - 0.92 - 1.40 - 1.80)/4 = -1.90$

percentage unit with a standard error of 0.413. By Student's test with 4 degrees of freedom, k was significantly higher for 'pellet' than for 'long' diets ($P < 0.05$). Here also the effect of pelleting might be exaggerated in Exp. 131-133 and 136-137 through contamination or time (Section 5.2.3). In Exp. HR 1-3, the calculated effect of wafering on k was only 2.2 percentage units, against 3.5 units with pelleting of artificially dried grass. This agreed with the expected difference between wafers and pellets because a great deal of the forage in wafers would be in rather long form and Diet GW would be intermediate between G and GC.

The proportions of forage pellets that replaced long forages were 50, 42, 19 and 21% of I_E in Exp. HR 1-3, 131-133, 136-137 and 141-142, respectively. The effect of pelleting of forage on the efficiency of utilization of M_E from forage pellets as such could only be calculated if it was assumed that differences in k between 'long' and 'pellet' diets were completely due to processing of the forage that replaced long material. As the k of concentrates and forages was not known, only an approximation could be made by dividing the difference in k between 'long' and 'pellet' diets by the proportion of pelleted forage replacing long material. In this way the extrapolated mean improvement in k with processing for 100% forage was 6.9, 2.2, 7.4 and 8.6 percentage units in Exp. HR 1-3, 131-133, 136-137 and 141-142, respectively. This improvement in k (about 11%, ranging from 4 to 15%) could compensate for a depression in metabolizability of the forage with processing. From the analysis of variance of q in these experiments the extrapolated depression for 100% pelleted forage was 4.7 percentage units or about 8-9% of q. The precision of these figures, however, was low, because the standard error of these figures increased in inverse proportion to the part of the diet that was replaced by processed forage.

This comparison between the same forage in long and pelleted form in a dairy ration showed that a decrease of digestible and metabolizable energy due to grinding and pelleting seemed to be more than compensated by an improvement in utilization of M_E.

5.5 NET ENERGY CONTENT OF DIETS WITH PELLETED FORAGES

Sections 5.3 and 5.4 showed that a depression in metabolizability with grinding and pelleting was compensated by an improvement in net energy through a more efficient utilization of M_E. Net energy divided by I_E (e_{NE}) could be calculated in a similar way to the quotient of net energy to metabolizable energy (k) (Equation 5.6), by the following equation:

$$e_{NE} = (R_E^* + L_E^* + x)/I_E^* \qquad (5.7)$$

In this equation, a constant value of 65 kcal/kg$^{\frac{3}{4}}$ was assumed for net energy for maintenance (x). Especially for an experiment of change-over design, this estimate is useful for comparing results of 'long' and 'pellet' diets as both types of diets are fed to the same cow. A slightly wrong estimate of net energy for maintenance has little effect on the difference, whereas a higher or lower net energy for maintenance with processing, than the assumed value, results in a lower or higher M_E available for production of milk or body tissue and in a higher or lower utilization of M_E for production.

Table 18 presents the efficiency of utilization of I_E (e_{NE}) calculated

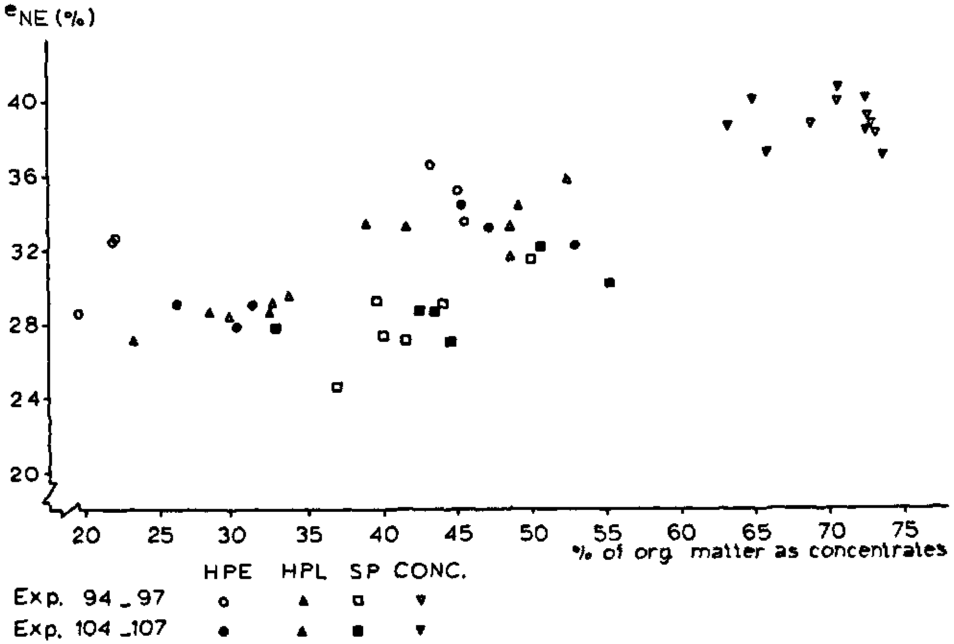


Fig. 5. Relation between efficiency of utilization of energy (e_{NE}) and contribution of concentrates to total intake of organic matter (P_C) in Exp. 94-97 and 104-107. Rations contained pelleted hay cut early (HPE) or late (HPL), straw pellets (SP) or no pelleted forage (CONC).

from Equation 5.7. The average of 204 balance experiments with 'long' diets was 3.9 percentage units or about 11% higher than of 130 experiments with 'pellet' diets. This difference, however, was not due only to processing as argued already in Section 5.2.2, so that no conclusion about the effect of processing could be drawn from these values.

In Exp. 94-97 and 104-107, e_{NE} was positively correlated ($r = 0.85-0.95$) with the proportion of concentrates (P_C) in the diet (Fig. 5). This relation fitted fairly well to a rectilinear regression for each of three combinations HPE to CONC, HPL to CONC, SP to CONC ($R^2 = 0.79-0.92$). According to the regression coefficients of P_C, the replacement of concentrates by forage pellets HPE, HPL and SP resulted in a reduction in e_{NE} of 0.19, 0.24 and 0.36 percentage units, respectively, for each percentage unit of P_C. So a replacement of concentrates by forage pellets reduced the net energy of the diet more for SP than for HPE and HPL. To maintain the same intake of net energy from a diet, each kilogram concentrates must be replaced by more than 1 kg forage pellets, but the P_C of the diet will change still more.

When I_O was used in multiple regression analysis as a second variable to P_C with the Diets HPE and HPL, there was a significant negative regression coefficient and a small reduction in RSD, but not with SP. This might indicate a small negative effect on net energy by increasing the level of feeding as was found also for d_E, but this conclusion is contestable, because of the high correlation coefficient, 0.7-0.8, between P_C and I_O and the change in value of the regression coefficient of P_C when I_O is used too.

Information in Section 5.3.1 and 5.4.3 suggests that the decrease of e_{NE} of diets where concentrates were replaced by forage pellets was mainly due to the lower metabolizability of the forage pellets than of the concentrates.

A comparison of processed forages with the original long material in a dairy ration could be obtained from Exp. HR 1-3, 131-133, 136-137 and 141-142. Analysis of variance of e_{NE} in these experiments showed no significant difference between 'long' diets, containing little or no forage pellets, and 'pellet' diets, with large amounts of forage pellets. The estimated mean difference in e_{NE} between 'long' and 'pellet' diets was

$(-1.02 + 0.60 + 0.27 - 0.26)/4 = -0.10$ percentage unit

with a standard error of 0.31. Although grinding and pelleting resulted in greater faecal losses of energy, these losses therefore seemed to be compensated by slightly lower G_E and a decrease in heat production on 'pellet' diets and so e_{NE} of 'long' and 'pellet' diets was not much different.

About the precision of that conclusion, the following approximation could be used to provide some information. In the diets of Exp. HR 1-3, 131-133, 136-137 and 141-142, 50, 42, 19 and 21% of I_E, respectively, was provided by pelleted forage that replaced an equal amount of long forage. If the difference between 'long' and 'pellet' diets was completely due to processing, as assumed before, the effect of processing could be extrapolated to 100% pelleted forage in the diet. The standard error in the difference between 'long' and 'pellet' diets, however, had to be increased to find the standard error in the effect of processing of the forage as such. This factor was calculated from an equation, given by Schürch (1969), to derive the standard error of the digestibility of a feed, which was measured by a difference method, and which feed was added to a basal ration of known digestibility. This factor was 2.23, 2.75, 6.8 and 6.1 when the test feed was 50, 42, 19 and 21% of the total feed. So the standard error of the difference in e_{NE}, for instance between 'long' and 'pellet' diets, had to be multiplied by this factor to calculate the standard error of the difference between long and processed forage. A 95% confidence interval could be calculated with this standard error and Student's value $t_{0.05}$. This interval in Exp. HR 1-3 was estimated between -8.7 and +4.6 percentage units of e_{NE}, and in Exp. 131-133, in Exp. 136-137 and in Exp. 141-142 between -0.9 and +3.8, between -0.9 and +3.8, and between -9.5 and +7.0, respectively. These estimates showed that although the mean effect of pelleting on e_{NE} was almost zero, differences with processing of 10 to 20% of the net energy content of forages could well exist. In these comparisons between 'long' and 'pellet' diets, the 95% confidence interval was of course much smaller than for the pellets themselves: in Exp. HR 1-3 between -4.0 and +2.0, in Exp. 131-133 between -0.3 and +1.5, in Exp. 136-137 between -0.1 and +0.6 and in Exp. 141-142 between -1.6 and +1.1. Except for Exp. HR 1-3, the difference in e_{NE} of 'long' and 'pellet' diets was less than 5%. In Exp. 131-133 and 136-137, small differences between long and processed forage, and some variation with time (Section 5.2.3) might have influenced the estimated effect of pelleting. The extent of this influence, however, could not be assessed.

Wafered forage in Exp. HR 1-3 increased the e_{NE} over that of the 'long' diet by 0.83 percentage unit, which was slightly lower than the effect of cobs in the same series. The 95% confidence interval for the difference between long and wafered forage, calculated in the same way as for pellets, was between -6.5 and +3.2. The effect of wafering tended to be somewhat smaller than of processing to cobs of artificially dried forage.

5.6 DISCUSSION OF RESULTS OF ENERGY BALANCE EXPERIMENTS

The effect of grinding and pelleting of forages on d_E and q measured in these experiments with dairy cows generally agreed well with that found by others (Wainman et al., 1972; Jarrige et al., 1973a; Blaxter, 1973). The estimated depression in digestibility of the forage with processing of 5-15 percentage units was within the range reported by Jarrige et al. (1973a) and Blaxter (1973). This decrease in digestibility was thought to be mainly due to an increased rate of passage of digesta and probably to a lower cellulolytic activity of the rumen microbes because of the altered conditions for microbial fermentation (Section 3.4). Our results conform with this view, since faecal losses were higher and G_E lower, indicating a reduction in microbial activity of the rumen.

The literature (Section 3.4 and 3.5) suggested that the decrease in heat losses with processed forage in the diet might be caused by lower heat of fermentation and a higher k for maintenance or production or even both. Heat of fermentation was assumed to vary in direct proportion to methane production (Blaxter & Clapperton, 1965). Webster et al. (1974) concluded that apparent heat of fermentation and aerobic heat production in the digestive tract of conscious sheep was lower for pelleted than for chopped forages. They stated that it seemed reasonable to attribute the lower heat production to differences in "work of digestion" rather than to differences in efficiency of utilization of energy from absorbed products of digestion.

By multiple regression analysis with Equation 5.5, 130 energy balance experiments with 'pellet' diets showed a lower regression coefficient of q than 204 experiments with 'long' diets but a similar value to the total of 334 experiments with 'long' or 'pellet' diets (Table 17). Also the regression coefficient of U_N^* was slightly higher for 'pellet' than 'long' diets. According to Moe et al. (1972) a greater surplus of protein from diets of lucerne and concentrates and the resulting greater U_N would require an increasing amount of energy. In our experiments, U_N was higher for 'pellet' diets. The lower mean value of q in 'pellet' than in 'long' diets indicated a lower quality of the forages used for pelleting and a lower proportion of concentrates in 'pellet' diets (Sections 5.2.2 and 5.3.2). So far as q was a parameter of the quality of forages, a depression of q with processing led to an underestimate of the quality of the original forage. As described in Section 3.2, the depression of q tended to increase for poorer diets. If the efficiency of utilization depended more on the quality of the original feeds than on that of the processed forages this would lower the regression coefficient for q with 'pellet' diets and with the total for 'long' and 'pellet' diets too. If this suggestion were true, the predicted value for $R_E^* + L_E^*$ (= $\hat{y}$) would also be too low and the difference $y - \hat{y}$ would be overestimated. For each percentage unit which q was too low, an overestimate of $y - \hat{y}$ of about 1.3% (1.64/123) of $R_E^* + L_E^*$ was made.

For the average of q and U_N^*, extrapolation of the regression line to $M_E^* = 0$ (Equation 5.6) gave a net energy for maintenance of 61.7 and 62.0 kcal/kg$^{\frac{3}{4}}$ for the results of energy balances on 'long' and 'pellet' diets, respectively, and of 66.7 for the total of 'long' and 'pellet' diets. So the difference in the regression coefficient of q between 'pellet' and 'long' diets was not due to any real difference in maintenance net energy requirement between these diets.

The improvement in k for pelleted forages described in a contribution to the 6th symposium on Energy Metabolism of Farm Animals (van der Honing &

van Es, 1974) was lower because we used a slightly different regression in which U_N^* was neglected and a lower regression coefficient for q was found because we analysed fewer experiments and probably because some experiments with high-concentrates rations were not included. As argued before, it seemed reasonable to use U_N^*. Further the regression from a greater number of experiments and with more variable diets might have improved the fit of the regression to other experimental data.

Although the effect of processing on the utilization of M_E might be overestimated, e_{NE} of diets with pelleted forages did not differ markedly from e_{NE} of diets with the same forages long. On average, an improved efficiency of utilization of metabolizable energy could well compensate for the decrease in metabolizability with processing.

5.7 SUMMARY

In 130 energy balance experiments with pelleted forages in the diet ('pellet' diets) and of 204 with long forages ('long' diets), average daily intake of organic matter was 16.0 and 13.9 kg. The proportion of concentrates (P_C) was higher for 'long' than for 'pellet' diets.

Replacement of concentrates by pelleted forage of hay cut early or late, or straw decreased d_E and q, proportionally to concentrates in the diet. The lower the digestibility of the forage pellets, the greater the depression.

Digestibility of organic matter and energy from 'pellet' diets was 6.9 percentage units lower than from 'long' diets, because of a lower P_C, responsible for a decrease of 3-4 percentage units, ahd because of processing. The pelleted forage formed about 30-60% of the diet and the calculated depression in d_E of the forage due to processing was about 3-9 percentage units or 5-15%. Depression of q was about 6 percentage units, the same order of magnitude as the decrease in d_E.

A comparison of processed forage with the original long material in dairy rations showed a calculated reduction due to processing of the forage of 5 to 14 percentage units for d_O, -1 to +8 for d_N and 5 to 14 for d_E. Probably because no legumes were used in this comparison, the difference in d_E tended to be slightly higher than the difference between the 204 and 130 experiments with 'long' and 'pellet' diets. The decrease in q was slightly lower than in d_E, mainly because of lower G_E on 'pellet' diets. M_E/D_O was no different for 'long' and 'pellet' diets.

The efficiency k was improved on 'pellet' diets and could compensate a depression of M_E of processed forage of about 8-16%.

Direct comparison of processed forage with the original material in dairy rations showed that an improvement of 11% in k with processing compensated a decrease in q of 8-9%.

If it were assumed that net energy for maintenance was 65 kcal/kg$^{\frac{3}{4}}$, e_{NE} was lower for the 130 experiments with 'pellet' diets than for the 204 with 'long' diets, but mainly because of the difference in P_C. For comparison of processed and long forage from the same material, e_{NE} was no different. This supported the conclusion that a depression of d_E and q with processing was compensated by an improvement in k. But the precision of the calculated effects of processing of forage with rations in which forage pellets were less than half the diet was rather low.

The efficiency k was correlated with the quality of the diet indicated by q. However, this effect of q was greater for 'long' than for 'pellet' diets. The lower regression coefficient for q in Equation 5.5 could be ascribed to a hypothetical underestimation of the quality of 'pellet' diets, q being lowered by processing. An estimate of the magnitude of any resulting error in the prediction of net energy was calculated.

6 Prediction of the feeding value of processed forages for dairy cows

Several feeding systems have been developed to predict production of animals from rations ingested: e.g. Kellner's system of starch equivalents (SE) and the various fodder unit systems derived from it, the net-energy-fat system (Schiemann et al., 1971), the United States system of total digestible nutrients (TDN), the metabolizable energy system (ARC, 1965), the NE_{milk} system (Moe et al., 1972). Recently Blaxter (1974) discussed the implications of new experiments for the ARC system. Also an EAAP working group drew up proposals for feed evaluation systems for growing and fattening as well as lactating ruminants (van Es, 1974).

All feeding systems start from the measured or predicted contents of digestible nutrients in feedstuffs or rations because of the considerable variation in digestibility between feedstuffs. Digestibility is usually measured in a trial with sheep, sometimes with cattle. Digestibility of organic matter (d_O) is often predicted from tests in vitro, for instance by the method of Tilley and Terry, adapted by several laboratories (Joshi, 1972; van der Koelen et al., 1974), or from chemical composition of the feeds. In the Netherlands, the content of crude fibre in forages is used to predict d_O and SE (CVB, 1965).

To estimate the net energy content of the feedstuffs both digestibility and conversion of digested matter must be predicted. In the SE system, the feeding values of feeds and digested nutrients are assumed to rank in the same order, regardless of whether they are used for maintenance, growth and fattening, or milk production. When different efficiencies of utilization of digestible or metabolizable energy for maintenance, growth and fattening, and milk production are assumed (as in the ARC system, k_m and k_f), different feeding values for maintenance and production result. It makes the commercial use of the various values in livestock feeding rather complicated.

Most feeding systems are based on trials with mature fattening ruminants but were also applied to dairy cows. For dairy cows, recommended feed requirements are based on results of trials expressing feeding values in starch equivalent or fodder units. Since the recommendations and the feeding values incorporate the same systematic errors, they could be satisfactory in practice. Conventional rations contain a great deal of forage, like hay and silage. However, accurate conclusions cannot be drawn about more extreme rations or about those ration components which differ considerably in composition, because great variation in composition of dairy rations is not allowable. The error in feeding trials is rather high and the number of such trials low. So it is not known whether the feeding value for lactation of some feedstuffs in the rations was overestimated and that of others underestimated. A factorial approach could overcome these difficulties (van Es, 1974).

In Section 5.4.1, it was concluded that the influence of quality (e.g. q) on the efficiency of utilization of metabolizable energy by dairy cows was not much different for maintenance and milk production, and during lactation the production of 1 kcal body fat required about as much M_E as 1 kcal milk energy. Hence for lactating cows, it is permissible to give only one feeding value for each feedstuff. Therefore in this study on the prediction of feeding value of pelleted forages for lactating cows, we assumed a single feeding value, regardless of the way the feed was utilized.

In this chapter, the prediction will be studied of digestible, metabolizable and net energy of pelleted forages for dairy cows from digestible organic matter estimated in vitro or in a sheep trial, and compared with similar predictions for long forages.

6.1 PREDICTION OF THE DIGESTIBILITY OF RATIONS WITH LONG AND PROCESSED FORAGES

Joshi (1972) reviewed several published attempts and trials of his own to predict the digestibility of a forage and concluded that digestibility measured with sheep, could be predicted with a higher accuracy by fermentation in vitro than by any of the chemical methods he tested. This agreed with the results of studies in the Netherlands (van der Koelen & van Es, 1973).

Because of an effect of level of feeding on digestibility (Section 3.1.2), most feeding tables present digestibility coefficients, measured with sheep fed at maintenance level or just above. Such digestibility coefficients at maintenance level are considered a good basis for feed evaluation. In the present study, the digestibility of organic matter at maintenance level ($d_{O,m}$) from the forages used in the dairy rations was measured with wethers. For pelleted forages, a difference trial technique was used with a basal ration of 200 g long hay of known digestibility. The $d_{O,m}$(sheep) of the forage was compared with d_O(in vitro), as measured by the method of van der Koelen et al. (1974). Both these values of d_O for single feedstuffs were used to compute a predicted value of d_O for the experimental rations for comparison with d_O actually found for experiments with cows. The digestibility of the concentrates used in these rations was either measured with sheep, by the difference trial technique, or was calculated from the average digestible nutrients of the components in the mixture as found in the Dutch feeding table (CVB, 1970a).

6.1.1 Comparison of digestibility of organic matter in vitro and in sheep

Van der Koelen & Dijkstra (1971) calculated the relation between d_O(in vitro) (x) and $d_{O,m}$(sheep) (y) and found for 104 samples of grass hay

$y = 0.763x + 16.67$, SD 2.24

and for 33 ground and pelleted forages

$y = 0.766x + 11.18$, SD 2.73

In our experiments, this relation could be calculated for 28 long forages (hay or artificially dried grass) and for 22 pelleted forages. The correlation coefficient between y and x was 0.978 and 0.972 for long and pelleted forages, respectively. For long forages, we found the regression

$y = 0.968x + 4.31$, SD 1.63

and for pellets

$y = 0.965x + 1.41$, SD 2.17

As the regression coefficient for x did not differ between long and pelleted forage in our equations and those of van der Koelen & Dijkstra (1971), the value of the intercept could be assumed to express the mean difference in digestibility with grinding and pelleting if d_O(in vitro) was not affected by this processing. The assumption that d_O(in vitro) was not affected seemed to be acceptable because this value hardly differed between the long and pelleted forages in Exp. 131-133, 136-137 and 141-142: 72.2, 71.3, 66.2, 70.3 and 69.6 for long forages and 72.2, 73.4, 67.0, 71.0 and 72.0 for pellets, respectively. Similar figures were reported by Lonsdale & Tayler (1971) for wafered and pelleted dried grass.

In our experiments, this mean difference in predicted digestibility was 4.31 - 1.41 = 2.90 percentage units, whereas van der Koelen & Dijkstra (1971) found a difference of 16.67 - 11.18 = 5.49 percentage units. They offered ground or pelleted forage as the sole feed, whereas in our experiments 200 g long hay was offered as a basal ration. The absence of long forage in the sheep rations might have caused a greater depression in digestibility with grinding or pelleting in the experiments of van der Koelen & Dijkstra. Probably the small amount of hay in our experiments slightly reduces the rate of passage of pellet digesta from the rumen of the sheep and so the depression in d_0 with pelleting was slightly decreased. These calculations showed that the composition of the ration might be a factor in the digestibility of forage pellets. Because the forage pellets in dairy rations were always used with some long forage, it seems preferable to measure digestibility of forage pellets in a difference trial with sheep on a basal diet containing long forage as 20-25% of the total intake of dry matter.

6.1.2 Prediction of digestibility of organic matter in rations with long or pelleted forages

In Section 3.1.1 it was concluded that in general the digestive capacities between sheep and cattle are equal provided the feeding levels are not different.

To predict the digestibility of rations for lactating cattle, the effect of feeding level had to be considered. Section 3.1.2 showed that the effect of feeding level on digestibility differed between feedstuffs and diets. In general for long forages, digestibility declined slightly with feeding level but this decline seemed to increase with a greater proportion of ground pelleted forage or concentrates in the diet.

The d_0 of the dairy rations used in the experiments in Wageningen, d_0(cow), was predicted by multiplying the amount of organic matter of each feed ingested by its $d_{0,m}$(sheep) found in an actual trial with wethers (forages and some concentrates) or, for most of the concentrates, taken from the Dutch feeding table. In another approach for the forages, the d_0(in vitro) was used instead of $d_{0,m}$(sheep) to predict d_0(cow). Hereafter the method of prediction of mixed rations, using d_0(in vitro) for forages will be referred to as 'd_0(in vitro) method'.

The two predictions could be tested for 29 diets with long forages and concentrates ('long' diets) and for 26 diets with processed forages ('pellet' diets). Each diet was fed to 2-6 cows and the mean d_0(cow) found in the balance experiments was used to study the precision of the predictions.

The average d_O(cow) actually found was 71.2 ± 3.6 for 'long' diets, which was 4.2 ± 1.5 and 2.7 ± 1.4 percentage units less than the predicted value from $d_{O,m}$(sheep) or from d_O(in vitro), respectively. The d_O(cow) for 'pellet' diets was 65.0 ± 4.0, which was 5.4 ± 2.0 and 5.1 ± 2.1 percentage units less than predicted from $d_{O,m}$(sheep) and d_O(in vitro), respectively. The average feeding level relative to maintenance was 3, if the $M^*_{E,m}$ was assumed to be 110 kcal/kg$^{\frac{3}{4}}$ (Moe et al., 1972; Section 5.4.2). The decrease in digestibility for each unit increase in feeding level was 4.2/2 = 2.1 and 5.4/2 = 2.7 percentage units for 'long' and 'pellet' diets, respectively. Most literature indicated a greater effect of feeding level on digestibility than we found (Section 3.1.2). Our experiments suggested that the depression in d_O with higher level of feeding tended to be slightly greater on 'pellet' than 'long' rations.

In multiple regression analysis, only a slight improvement in the prediction of d_O(cow) of 'pellet' diets could be obtained by using level of feeding (M_E^*/110) as a second variable in the regression to $d_{O,m}$(sheep) or d_O(in vitro). However, this lowered the regression coefficient of $d_{O,m}$(sheep) and d_O(in vitro), whereas a positive regression coefficient of level of feeding was found, and a correlation coefficient of 0.72 existed between level of feeding and $d_{O,m}$(sheep) or d_O(in vitro). Interpretation is therefore difficult, since a negative effect of level of feeding was expected because of the influence on rate of passage of reduction in particle size of processed forages.

To facilitate comparison of differences in regressions for 'long' and 'pellet' diets an equation with the intercept 0 was also computed. However to examine the effect of P_C and feeding level, this procedure was not used in multiple regression analysis.

The average d_O(cow) was for 'pellet' and 'long' rations 5.1 and 2.7 percentage units or 7.9 and 3.9% less than the average value predicted from d_O(in vitro). This difference was mainly caused by processing of the forage, although it may also be attributable to the different proportions of concentrates in the two types of rations. Also lower regression coefficients were computed for the prediction from d_O(in vitro) for 'pellet' rations and the prediction from $d_{O,m}$(sheep) (Table 19).

In the regression of Table 19, the d_O(in vitro) was used as such, whereas it might have been better to use the estimate of $d_{O,m}$ from d_O(in vitro) (Section 6.1.1). So by using the relation between $d_{O,m}$ and d_O(in vitro) for long forages, the digestibility of the original long forages from which

Table 19. Correlation between quantities measured in balance experiments with cows on rations with long (L) or pelleted (P) forages and digestibility estimated with cows in the same experiment, with wethers either by measurement or from CVB (1970a), or in vitro. The linear regression is: $y = a \cdot x + b$ For other symbols, see List of Symbols.

Ration		$\bar{y}$	$\bar{x}$	a	b	RSD	If b = 0		Mult. corr. improved by	
type	N						a	RSD	$M_E^*/110$	P_C
$y = d_O$, $x = d_{O,m}$(sheep)										
L	29	71.2	75.5	0.922	1.66	1.45	0.944	1.46	no	no
P	26	65.0	70.5	0.824	6.92	1.85	0.922	1.91	yes	no
$y = d_O$, $x = d_O$(in vitro for forage; from CVB for concentrates)										
L	29	71.2	74.0	0.854	8.09	1.28	0.963	1.35	no	no
P	26	65.0	70.1	0.805	8.53	1.98	0.926	2.06	yes	no
$y = d_E$, $x = d_O$(cow)										
L	29	68.1	71.2	0.940	1.20	0.64	0.956	0.64	no	yes
P	26	61.8	65.0	0.952	-0.07	0.25	0.951	0.25	no	no
$y = d_E$, $x = d_{O,m}$(sheep)										
L	29	68.1	75.5	0.867	2.67	1.50	0.902	1.50	no	no
P	26	61.8	70.5	0.786	6.37	1.76	0.877	1.81	yes	no
$y = q$, $x = d_O$(cow)										
L	29	58.1	71.2	0.873	-4.05	1.02	0.817	1.04	yes	yes
P	26	52.8	65.0	0.826	-0.95	0.60	0.812	0.60	no	no
$y = q$, $x = d_{O,m}$(sheep)										
L	29	58.1	75.5	0.810	-2.95	1.59	0.771	1.60	no	no
P	26	52.8	70.5	0.705	3.09	1.40	0.749	1.42	yes	no
$y = M_E/I_O$, $x = d_{O,m}$(sheep)										
L	29	2786	75.5	35.8	- 88	88	36.9	88	no	yes
P	26	2547	70.5	33.0	223	89	36.1	90	yes	yes
$y = M_E/I_O$, $x = d_O$(in vitro for forage; from CVB for concentrates)										
L	29	2786	74.0	31.9	426	91	37.7	94	no	no
P	26	2547	70.1	31.2	358	101	36.3	103	yes	yes

the pellets were made could be predicted from the d_O(in vitro) of the pellets. In this way, a prediction of d_O of the cow rations with pelleted forages was obtained, which was higher than the value actually found in the experiments. It could be used to predict metabolizable and net energy of 'pellet' and 'long' rations with the same equations.

6.1.3 Prediction of digestible and metabolizable energy of rations with long or pelleted forages

From our data for dairy cows, the relation between digestible energy (d_E) and d_O(cow) was computed (Table 19). Digestible energy could be very well predicted from d_O without any other factor, although the proportion of concentrates in organic matter (P_C) showed a significant regression coefficient for rations with long forages, but hardly reduced RSD. A similar relationship was found by Schiemann et al. (1971). They calculated for cattle:

$d_E = 1.02\ d_O - 4.4$, RSD 0.7

and for sheep:

$d_E = 1.03\ d_O - 5.4$, RSD 0.6

Prediction by Schiemann's equation would result in slightly lower values than the equation in Table 19, which was the same for 'long' and 'pellet' diets, probably through the same proportional depression in d_O and d_E with pelleting of forages.

Table 19 also shows the result of linear regression of d_E of the cow ration on the predicted digestibility of organic matter from $d_{O,m}$(sheep). For 'pellet' diets, feeding level as a second variable slightly improved the prediction, but changed the regression coefficient markedly and the correlation coefficient between d_E and level of feeding was high (0.73), so that this factor could better be neglected for the prediction. So for 'pellet' diets, d_E could be predicted from $d_{O,m}$(sheep) with a coefficient of variation of 2.8%.

The relation between metabolizability (q) and d_O(cow) was similar for 'long' and 'pellet' diets (Table 19). Multiple regression analysis showed significantly positive coefficients for P_C and level of feeding as additional variables to $d_{O,m}$(sheep) and a slightly lowered RSD for 'long' rations. Schiemann et al. (1971) reported the following respective equations for cattle and sheep:

$q = 0.88\ d_O - 7.9$, RSD 0.8

$q = 0.88\ d_O - 7.5$, RSD 1.2

Their experiments were mainly at a lower level of feeding and this might explain their lower values of q relative to d_O than ours, because of the relatively lower losses of energy as methane and urine in our experiments with dairy cows.

The prediction of q in the cow ration from $d_{O,m}$(sheep) by linear regression (Table 19) resulted in a slightly higher regression coefficient of $d_{O,m}$(sheep) for 'long' than 'pellet' rations. Only for 'pellet' rations did level of feeding as a second variable show a significant positive regression coefficient and slightly reduced RSD. However, the high correlation coefficient of 0.71 between q and level of feeding and lack of significance for level of feeding in the regression of q on d_E with 'long' diets argued against use of this factor for predictions.

The M_E/D_O was 3913 ± 101 and 3917 ± 85 kcal/kg for 'long' and 'pellet' rations, respectively. So for both types of rations, the same value could be used and little or no improvement in the prediction was obtained by using d_O(sheep), P_C or feeding level in a regression.

Table 19 showed that M_E/I_O in the cow rations could be predicted from $d_{O,m}$(sheep). The negative regression coefficient for P_C and the positive one for feeding level were significant, slightly reducing RSD, only with 'pellet' diets. As this was not found in 'long' rations in which P_C showed a much greater variation and because the correlation coefficient between M_E/I_O and level of feeding in 'pellet' rations was 0.72, these factors could not be used to predict M_E/I_O. Computed to the intercept 0, a slightly lower regression coefficient was found for $d_{O,m}$(sheep) with 'pellet' diets, mainly because of the lower proportion of concentrates in the diets. A regression of M_E/I_O on d_O(in vitro) showed a slightly greater difference between regression coefficients for 'long' and 'pellet' diets, mainly because d_O(in vitro) was not depressed by processing, in contrast to $d_{O,m}$(sheep).

By taking a value of 3650 kcal/kg for M_E/D_O, in which D_O is calculated from $d_{O,m}$(sheep) the M_E of the 'long' and 'pellet' rations for dairy cows was predicted with a coefficient of variation of about 3.5%.

6.1.4 Prediction of net energy content of rations with long and pelleted forages

Sections 6.1.1-3 examined the prediction of d_O and of d_E and q for the dairy ration from digestibility of the components, obtained from sheep trials or in vitro. In a similar way, one could predict utilization of M_E for maintenance, production of milk and fattening. However, this certainly would result in different equations for 'long' and 'pellet' rations, because a higher efficiency (k) was found for 'pellet' than 'long' rations of the same quality (Section 5.4). For practical reasons, it is difficult to use a different value of k for rations with long or with pelleted forage in a feed evaluation system. Moreover, the higher value of k in 'pellet' rations compensated for the reduction in q with processed forages in the ration, so that it seemed more attractive to start from the digestibility of processed forage in its original long form and use the same relation as for long forages to predict metabolizable and net energy for pelleted forages. The predicted M_E of 'pellet' rations will then be overestimated, but the predicted net energy will be close to the actual net energy in the balance experiment, because of the lower value for k used to calculate utilization of M_E.

In a new feed evaluation system for dairy cattle (van Es, 1974), which will be introduced in the Netherlands in 1977, the same relation is proposed for predicting net energy content of long and of processed forages, provided that for pelleted forages the digestibility of the original long material be used. According to this approach, the predicted net energy content of the 'pellet' and 'long' rations was calculated and compared with the value from the balance experiments. Attention was paid especially to the difference between the calculated and actually measured net energy content of rations with pelleted or long forages.

According to the proposal of van Es (1974), the M_E of concentrates was predicted from content of digestible nutrients for sheep, fed at the maintenance level, as presented in the Dutch feeding table (CVB, 1970a) with the equation

$$M_E = a \cdot D_{XP} + b \cdot D_{XL} + c \cdot D_{XF} + d \cdot D_{XX} \qquad (6.1)$$

in which the coefficients a, b, c and d have respective values of 4360, 9960, 3610 and 3660 kcal/kg. For forages, M_E can be predicted by

$$M_E = a \cdot D_O \qquad (6.2)$$

in which a has the value 3600 kcal/kg.
The utilization of M_E (k) was derived from the metabolizability of gross energy (q) as

$$k = 0.463 + 0.0024q \qquad (6.3)$$

A depression in M_E with higher levels of feeding increased the requirement of metabolizable energy for the same quantity of net energy for maintenance and production by 1.8% for each increase in feeding level relative to maintenance of one unit (van Es, 1974). Level of feeding was calculated as the M_E intake in kilocalories divided by 110 times metabolic body size, assuming that daily requirement of metabolizable energy for maintenance was 110 kcal/kg$^{\frac{3}{4}}$. The $\hat{M}_{E,m}$ of cow rations in our experiments predicted from $d_{O,m}$(sheep) or d_O(in vitro), was corrected from the maintenance to the production level of feeding by multiplying by

$$1/(1 + (M_E/110W^{\frac{3}{4}} - 1) \times 0.018)$$

The predicted metabolizability should be derived by dividing the predicted M_E at production level of feeding by I_E. In the system of van Es, however, the feeding level is not known for individual feedstuffs and therefore the predicted metabolizability of a ration ($\hat{q}$) is derived from 100 $\hat{M}_{E,m}/I_E$. In the following comparison, we also used the method proposed by van Es for prediction of $\hat{q}$ from $d_{O,m}$(sheep) or d_O(in vitro), which would result in a slight overestimate on the net energy content of the ration.

We here assumed net energy requirement for maintenance in the prediction of net energy in the rations of the cow energy balance experiments to be 70 kcal/kg$^{\frac{3}{4}}$, as proposed by van Es (1974).

Total net energy from a dairy ration was calculated as the sum of $L_E + R_E + x \cdot W^{\frac{3}{4}}$, in which x is 70 kcal/kg$^{\frac{3}{4}}$, whereas for negative energy balances $0.8R_E$ was used.

It was assumed that the estimated $d_{O,m}$ of the original long material of the processed forage could be predicted from d_O(in vitro) from the relation between $d_{O,m}$(sheep) (y) and d_O(in vitro) (x), derived from dry long forages. As shown in Section 6.1.1, this relation was described by van der Koelen & Dijkstra (1971) as

$$y = 0.763x + 16.67 \qquad (6.4)$$

whereas our results gave the following equation:

$$y = 0.968x + 4.31 \qquad (6.5)$$

The net energy expected from a dairy ration as calculated from the $d_{O,m}$ predicted from d_O(in vitro) with Equation 6.4 or 6.5 for forages and 6.1 for concentrates was compared with the net energy calculated from

Table 20. Predicted values of metabolizable and net energy as a percentage of actually measured metabolizable and net energy of dairy rations from balance experiments with cows. Net energy was calculated as the sum of $L_E + R_E + 70\ W^{\frac{3}{4}}$. See List of Symbols. A value of 100 means exact correspondence.

Ration type[3]	N	Exp. No	Correspondence						
			Net energy[1]				Metabolizable energy[1]		
			(a)	(b)	(c)	(d)	(b)	(c)	(d)
Hay	16	-	98.9	102.9	103.5	103.4	102.6	103.1	102.9
Silages	13	-	99.6	100.9[2]	100.3	101.9	100.4[2]	99.9	101.2
Pelleted forages	26	-	98.8	103.7	104.3	102.3	103.4	103.9	102.3
G	1	131-133	100.2	103.0	105.2	104.3	101.4	103.1	102.4
GP	1	131-133	98.1	104.5	106.6	104.6	104.5	106.2	104.6
HP4 (S)	1	136-137	105.1	106.3	108.5	108.4	100.2	101.8	101.7
HP8 (S)	1	136-137	102.9	106.3	108.8	107.4	101.8	103.8	102.6
HP4 (A)	1	136-137	104.1	108.3	109.5	108.6	102.6	103.5	102.8
HP8 (A)	1	136-137	100.5	107.6	109.0	105.9	105.0	106.0	103.6
HP4 (S)	1	141-142	102.6	97.0	99.0	98.7	94.8	96.4	96.2
HP8 (S)	1	141-142	99.5	99.4	101.6	99.3	99.2	100.9	99.1
HP4 (A)	1	141-142	103.9	98.0	100.1	99.8	94.6	96.2	96.1
HP8 (A)	1	141-142	100.2	96.5	98.7	95.9	96.2	98.0	95.7
G	1	HR 1-3	103.4	110.2	111.5	.	104.8	105.8	.
GC	1	HR 1-3	97.4	108.4	109.9	.	108.6	109.8	.
GW	1	HR 1-3	99.7	107.9	109.1	.	106.5	107.1	.

1. a. $q = 100\ M_E/I_E$; $k = 0.463 + 0.0024\ q$; predicted net energy $= k \cdot M_E$; M_E and q as found in balance experiments with cows.
   b. $\hat{q} = 100\ \hat{M}_E/I_E$; $\hat{k} = 0.463 + 0.0024\ \hat{q}$; predicted net energy $= \hat{k} \cdot \hat{M}_E$ $\hat{M}_E$ calculated from digestibility in vitro by Equations 6.4 and 6.2 for forages and from $d_{O,m}$ in CVB (1970a) by Equation 6.1, and corrected by reduction of 1.8% per unit increase in level of feeding.
   c. The same as b, except that the Equation 6.5 was used for forage.
   d. The same as b, except that $d_{O,m}$(sheep) was used for long forage and $d_{O,m}$(sheep) of the processed material for processed forage.
2. For silages $d_{O,m}\text{(sheep)} = 0.777\ d_O\text{(in vitro)} + 17.11$ (van der Koelen & Dijkstra, 1971).
3. See Table 9.

$d_{O,m}$(sheep) of the forages and Equation 6.1 for concentrates. For pelleted forages, the $d_{O,m}$(sheep) of the processed forage was used rather than of the original long forage, because the digestibility of the long forage was not often measured.

For comparison, first the net energy predicted from q and M_E as found in the balance experiments with cows was calculated. Table 20 presents the predicted values for metabolizable and net energy in the dairy rations relative to the values found in the cow experiments.

The average predicted net energy of rations with hays, silages and pelleted forages by Equation 6.3 (Table 20, Column a) agreed well with the actual net energy (100%) (sum of $L_E + R_E + 70\ W^{\frac{3}{4}}$), although for individual rations differences ranging from 95-107% were found. Part of this variation may be due to experimental error. Average predicted value was about 1% less than the measured value. Although for rations with pelleted forages a lower percentage was expected, this was not found, perhaps because of great differences in composition between 'long' and 'pellet' diets, especially for proportion of concentrates.

The predicted net energy content of rations with pelleted forages (Table 20, Exp. 131-133 to HR 1-3) was, compared with rations containing the same forage long, somewhat lower, as expected from the better utilization of M_E of pelleted forages. Predicted from $d_{O,m}$(sheep) of long and pelleted forage (Table 20, Column d), only small differences were found between diets with the same forage long and pelleted, although for both types of diet differences raging from -2 to +11% between predicted and actually measured value were found, partly because of experimental errors in the measured value. As shown in Table 20, the predicted M_E (Column d) of diets with pelleted forages tended to be slightly overestimated compared with the predicted M_E of rations with long forages. When the $d_{O,m}$(sheep) of long forages was used (not presented in Table 20), the predicted net energy in 'pellet' rations relative to 'long' in Exp. 131-133, 141-142 (hay cut in spring, S) or (autumn, A) were 0.4, 2.1 and 2.2 percentage units higher. In Exp. 136-137 (S) and (A), however, values were 0.4 and 0.9 percentage units lower. On average, the predicted net energy value of the 'pellet' diets was 0.7% higher than of 'long' diets, whereas by using $d_{O,m}$(sheep) of the pelleted forages the predicted net energy of 'pellet' diets was 1.3% lower than of 'long' diets. Mainly through the small proportion of pelleted forages, differences were not great and therefore it was difficult to conclude what the best procedure is for predicting net energy content. From the average values, it was concluded that use of $d_{O,m}$(sheep) of the pelleted forages in their original long form was preferable.

Prediction of net energy in the rations from d_O(in vitro) from Equation 6.4 or 6.5 did not result in important differences, neither between these two nor between these predicted values and that from $d_{O,m}$(sheep). M_E predicted from d_O(in vitro) (Table 20, Columns b and c) resulted also in an overestimate of the actual measured M_E of 'pellet' rations compared with 'long' rations. Average difference between relative values of net energy, according to Column b and c of Table 20, from 'long' or 'pellet' diets in Exp. 131-133, 136-137, 141-142, and HR 1-3 (G and GC) was 0 and -0.1 percentage unit, though ranging from -2.6 to +1.8 percentage units for individual diets. From these results, it is concluded that for the prediction of net energy of rations with pelleted forages from d_O(in vitro) it seems preferable to use the relation between d_O(in vitro) and $d_{O,m}$(sheep) for long forages over that for pelleted forages.

By multiple regression analysis, we examined whether the prediction of net energy from $d_{O,m}$(sheep) or d_O(in vitro) could be improved by using level of feeding or P_C as additional variables. There was no significant regression coefficient or reduction in RSD, when all 55 rations were used in the analysis. Only when 26 rations with pelleted forages were analysed was a significant negative regression coefficient for P_C found and a small reduction in RSD. The use of feeding level or P_C as a second variable to $d_{O,m}$(sheep) or d_O(in vitro) was not preferable, as these factors showed little or no improvement in the prediction of net energy in rations with pelleted forages and made a simple prediction procedure more complicated.

Total net energy content of the various rations in Table 20 was predicted by the different methods reasonably precisely. As the rations varied widely in composition, this may indicate that the system could be adapted for the separate feedstuffs as well as for rations.

The prediction of starch equivalent of long or ground and pelleted forages in the Netherlands (CVB, 1965) is based on an equation relating $d_{O,m}$ and the content of crude fibre in the forage. For grass hay, artificially dried grass and artificially dried lucerne, the equation used is identical for long and processed (i.e. ground or pelleted) forages. Also the 'Kellner' correction factor for crude fibre used in the calculation of starch equivalent is the same for long and processed forages. For grass hay 0.58 is used and for artificially dried forages 0.44. In view of the results of this study, this will result in as good a prediction of net energy content in ground and pelleted forages as in the same material in long form.

6.2 CONCLUSIONS

Equations to predict $d_{O,m}$(sheep) from d_O(in vitro) slightly differ between long and pelleted forages. The difference is largely attributable to the lower $d_{O,m}$ of processed forage in the sheep trial, estimated at 2.9 percentage units in our trials, in which the rations always contained some long forage. It seems advisable to provide at least 20 or 25% long forage in the diet, on a dry matter basis in digestibility trials with either cows or sheep.

Digestibility of organic matter in a ration for cows can be predicted from $d_{O,m}$(sheep) or d_O(in vitro). Differences in values predicted from $d_{O,m}$(sheep) and d_O(in vitro) between rations with long or pelleted forages are mainly due to processing of the forage, which reduces $d_{O,m}$(sheep) but scarcely reduced d_O(in vitro). From d_O(in vitro) a good estimate could be made of digestibility of the processed forage in its original long form.

Digestibility and metabolizability of energy can be related to digestibility of organic matter, the relations being influenced sometimes by level of feeding and P_C. Digestibility of energy could be precisely predicted from d_O of the cow diet or from $d_{O,m}$(sheep) without any other factor. The M_E/D_O in the cow experiments was 3913 $\pm$ 101 and 3917 $\pm$ 85 kcal/kg for rations with long or processed forages, respectively. The M_E/D_O can be calculated from the predicted digestible organic matter based on $d_{O,m}$(sheep) by using 3650 kcal/kg.

In the feed evaluation system proposed by van Es (1974) net energy of processed forage can be well predicted from the digestibility of organic matter in the original long material, using the same equation for long and for processed forages.

7 Final remarks on the use of ground and pelleted forages in dairy farming

Ground and pelleted forages have several favourable properties over long forages, especially for transport and provendering by machine. Only nutritional aspects of grinding and pelleting forages for dairy cows have been investigated in this study.

Voluntary intake of forages by cows is usually higher when a great deal of the forage is processed. However to avoid abnormal digestive processes in the reticulo-rumen, sufficient structured material must be given. Long forage should constitute about 30% of total intake of dry matter. The increase in intake from forage by processing generally depends on forage quality, composition of the diet, in particular the proportion of concentrates, and the cow's energy requirement. Greatest improvement in forage intake with processing is with poor forage and with low proportions of concentrates. In productive cows, yielding more than 25 kg milk, the increase in intake of forage will usually be less than 10 or 20%.

The net energy content, in other words the efficiency of utilization, of ground and pelleted forages in dairy rations equals that of the long forages, provided that rumen function is normal through provision of sufficient structured material in the diet.

In dairy rations, the addition of 1 kg pelleted forage may reduce intake of concentrates by about 1 kg. The increase in voluntary feed intake with processed forages so can be used to restrict partly the amount of concentrates required, particularly for cows of moderate milk production. It will depend mainly on prices of the feeds whether the extra costs for processing make the use of processed forages attractive in dairy rations.

Summary

Ground and pelleted forages have increased in popularity, because they are easier to transport and to supply to livestock and because cattle eat more of them than of bulky long forages. Research was therefore initiated on intake and utilization of energy from ground pelleted forages by dairy cows.

As energy supply of cattle depends on intake and energy content of the feed, the following aspects were examined:

- feed intake of processed compared with long forages by ruminants, especially dairy cows, and factors that influence and may explain the effect of processing on intake
- energy content of processed forages compared with the original long forages in dairy rations and the effect of processing on utilization of energy by dairy cows.

Section 1.2 defines terms for processed forages as used in this study. 'Processing' is used only for the grinding, pelleting, wafering or cobbing of forages.

Chapter 2 reviews the literature on feed intake of processed forages. It sketches regulation of feed intake by ruminants and surveys the effect of grinding, pelleting, wafering or chopping of forages on intake. It describes factors that could influence and that might explain the effect of processing.

Grinding and compression reduce particle size. Particle size distribution can be only roughly assessed by the sieving methods now used. The reduction in particle size with processing depended on type, stage of maturity, method of drying and content of dry matter of the forage, type of grinder and speed of operation, the screen and the type of press.

Intake from long forages seems to be limited mainly by physical factors like the capacity of the forestomachs and the rate of disappearance of digesta from the reticulo-rumen. The reticulo-omasal orifice prevents passage of long, coarse feed particles. Rumination and microbial breakdown increase the rate of disappearance of feed from the rumen. The reduction in particle

size of long forage with grinding or pelleting therefore seems the main reason for the higher intake from processed forages. Lower palatability of processed forages, for instance if they crumble to dust or are too hard, may, however, still decrease feed intake.

The average effect of processing on intake (Tables 1-3) was greater for sheep and beef cattle than for dairy cows. This difference was associated with a greater energy requirement for dairy cows, and therefore greater feed intake and higher proportion of concentrates in the ration. Intake by dairy cows on rations with highly digestible forage or a considerable proportion of concentrates seemed to be regulated by metabolic rather than physical factors. Hence, perhaps, the effect of processing decreased with increasing digestibility of forage (Fig. 1) and proportion of concentrates, and even became negative with more than 60% concentrates (Table 4).

The substitutive value of forage was defined as the quotient of decrease in intake of concentrates to increase in amount of forage supplied. On a dry matter basis it was about 0.2-0.6 for long and 0.8-1.0 for pelleted forages.

Processing usually increased eating rate and decreased mastication, rumination and salivation. Abnormal rumination on rations with only ground forages could be largely prevented by offering some long hay or straw. Processing seemed to decrease rumen motility and often altered the rumen microflora and its cellulolytic activity. Carbohydrate in rations with processed forages is more in rapidly available form. In most studies, therefore, rations with processed forages increased concentration of volatile fatty acids, lowered pH and altered the proportions of the acids. Usually the proportion of acetate decreased and those of propionate or butyrate increased. The same happened with increasing proportion of concentrates in the ration. But diets with excessive amounts of concentrates caused rapid fermentation and could lower pH even below 5.5-6, disturb the stability of the microflora and increase the concentration of lactate in the rumen.

Forage particles less than 2 mm in size can probably pass the reticulo-omasal orifice of mature cattle and so increase rate of passage of digesta from the reticulo-rumen, unless gut fill distal to the rumen prevents or inhibits passage. So the reduction in particle size with processing may not always increase intake, when gut fill distal to the rumen or metabolic factors become important in the regulation of feed intake.

Chapter 3 reviews literature on the effect of processing on digestibility and energy value of rations for ruminants. Digestive capacity was the same for sheep and cattle at the same level of feeding, although crude protein was sometimes slightly less digestible for cattle than for sheep.

Increase in feed intake by dairy cows usually depressed digestibilities of organic matter and energy. The depressions were low on rations with long forages only, but greater on rations containing a considerable amount of concentrates or processed forages. They seemed to increase with poorer forages and greater proportion of concentrates in the ration. The main reason for the depression of digestibility with increasing level of feeding seemed to be the increased rate of passage and the shorter retention time in the rumen, which especially reduced the microbial breakdown of cellulose--rich constituents of the feed.

Processing likewise usually depressed digestibility, more for crude fibre, 15%, than for organic matter, 10%, and energy, 5%. Values varied considerably between experiments (Table 5). The depression could be attributed mainly to an increase in rate of passage and a reduction in cellulolytic activity of the microbes in the reticulo-rumen. The greater surface area of processed forages may permit a more rapid fermentation by rumen microbes and may partly compensate the lower retention time in the forestomachs.

Sheep on rations with processed forages digested a greater proportion of the digestible feed, especially the cellulose-rich fraction, in the small and large intestine than with long forages. What little information exists on site of digestion for cattle suggests a smaller contribution of the small and large intestine to digestion of the fibrous fraction than for sheep. So it is doubtful whether an increase in bacterial fermentation in the large intestine plays a significant role in the energy supply of cows.

Increased faecal losses of energy in sheep with higher level of feeding or with processing are partly compensated by lower losses in urine and methane. However, processed forage usually contained less metabolizable energy than the same forage long.

Utilization of metabolizable energy from processed forage by sheep, especially for growth and fattening, was higher than from long forage. In many energy balance experiments with sheep, this increase in utilization was greater than the depression of metabolizable energy with processing and resulted in higher net energy of processed than of long forages. Most feeding trials with sheep and beef cattle agreed with this conclusion.

The literature on processed forages described no energy balance experiments with dairy cows. Feeding trials with dairy cows on diets with processed forages often had variable results. Rations without long forages frequently caused digestive disturbances and greatly depressed the fat content of the milk. These effects could be much reduced by offering some long hay or straw. As long as rations had sufficient long forage to prevent digestive disorders and to maintain normal digestibility and fat content of milk, equal amounts of long or processed forage caused little or no difference in production of dairy cows. This suggests only small differences in net energy of long and processed forages. Energy balance experiments with lactating cows were required to provide more precise data on the differences in net energy.

Chapter 4 describes methods used in energy balance experiments with mature lactating Dutch Friesian cows, producing 10-30 kg milk and weighing 450-650 kg, at the Department of Animal Physiology of the Agricultural University in Wageningen. 'Open-circuit' respiration chambers were used to measure the energy balance of the cows and to estimate net energy from ground and pelleted forages.

In two series of experiments pelleted hay or straw were substituted for concentrates. In other series, rations included pelleted forages as much as possible. Data were also taken from earlier experiments at Wageningen with long forages and concentrates. In another four series, pelleted forages replaced the original long material.

Chemical composition of the long and processed forages hardly differed.

Daily intake of dry matter from rations with processed or long forages averaged 16.0 kg and 13.9 kg, respectively. However, forage was not offered ad libitum and in rations with processed forage the mean supply of concentrates was much smaller than with long forage, 35 and 50% in total intake of organic matter, respectively.

Digestibility of rations with processed forage as a substitute for concentrates decreased as proportion of concentrates decreased. Digestibility of energy in all rations with processed forages averaged 6 percentage units less than in those with long forages. The 15% lower proportion of concentrates in organic matter of rations with forage pellets would decrease digestibility of energy by 3-4 percentage units, so that 2-3 units were due to other factors, for instance grinding and pelleting of the forage. Replacement of long by processed forages depressed digestibility of energy by 1.5 percentage units. If the differences in digestibility of rations with long and pelleted forage from the same material were attributed only to processing, the depression in digestibility of organic matter, nitrogen and energy was calculated at 5 to 14, -1 to +8 and 5 to 14 percentage units.

Digestibility of energy in processed forage averaged 9 percentage units less or 15%. Mean depression for digestible nitrogen was less than 3% (Table 14).

The depression in digestible energy with processing was only slightly compensated by lower energy losses in methane and urine. Average depression of metabolizability with processing of forages was calculated at 7 percentage units or 13% (Table 15).

Metabolizable energy relative to digestible energy or to digestible organic matter hardly differed between rations with long and processed forages.

Utilization of metabolizable energy (M_E) was studied with a model in which net energy in milk (L_E) and body tissue (R_E) was related to M_E after subtracting that for maintenance, which was assumed to be the product of a constant and metabolic body size ($c \cdot W^{\frac{3}{4}}$). It was further assumed that the utilization of M_E (k) depended on the quality of the ration (e.g. metabolizability, q) and on the amount of nitrogen in urine (U_N). Also the proportion of long forage in total intake of dry matter (P_C) might influence k. From the results of earlier experiments, it was derived that during lactation the influence of q on k was equal for maintenance, for milk production and for body tissue gain. So the next model could be used for multiple regression analysis:

$$R_E^* + L_E^* = a \cdot M_E^* + b \cdot q + c \cdot P_L + d \cdot U_N^* + e \qquad (5.5)$$

in which * means that the quantities are derivatives of metabolic body size ($W^{\frac{3}{4}}$) and a, b, c, d and e are regression coefficients. Negative R_E^* was multiplied by 0.8 because energy for milk production from body reserves is more efficiently utilized than from feed.

In another approach, k was calculated by dividing total net energy for maintenance and production by M_E. Net energy for maintenance divided by metabolic body size was here assumed to be 65 kcal/kg$^{\frac{3}{4}}$ (Table 18).

Multiple regression analysis (Table 17) showed a lower value for the coefficient b on rations with processed than with long forages. Because the effect of P_L was small and for statistical reasons, this factor was neglected. M_E from rations with processed forages was utilized better than from those with long forages and so roughly compensated the depression in M_E with processing. The estimated improvement in utilization of M_E from processed forage was 11%, whereas depression of M_E was about 8-9%.

In rations with long or processed forages, net energy relative to gross energy was greater for long forages. But most of the difference was attributable to a greater proportion of concentrates in the rations. Little or no difference was found in net energy of diets with processed forage replacing the original long material.

Section 5.6 discusses a hypothesis to explain the greater influence of metabolizability on utilization of M_E from rations with processed forages. By using the q of rations with processed forages, the true quality of the ration was suggested to be underestimated because processing reduced metabolizability of forages. Underestimation was supposed to increase with decreasing q of the original long forage and so might have lowered the regression coefficient of q with processed forages. The quantitative effect of this underestimate, however, will be rather small, because only a part of the ration is processed forage and the effect of q on $R_E^* + L_E^*$ is not great.

In Chapter 6, relations were calculated between digestibility of organic matter measured with sheep at maintenance, $d_{O,m}$(sheep), and that derived from digestion in vitro, d_O(in vitro). Digestibility of dairy rations was compared with a value predicted from $d_{O,m}$(sheep) or d_O(in vitro). Equations are given for predicting digestibility and metabolizability of energy in dairy rations with long or processed forages from $d_{O,m}$(sheep). Finally the method of predicting net energy in a new feed evaluation system for dairy cows, soon to be introduced in the Netherlands, was assessed for its applicability to processed forages. Net energy of processed forages could be predicted accurately relative to the long forage by using the $d_{O,m}$(sheep) of the original long forage from which the processed forage was derived.

In Chapter 7 some final remarks on use of processed forage in livestock feeding were made. It will much depend on the relative prices of feedstuffs, whether the favourable properties of processed forages – intake, storage and mechanical handling – compensate the extra costs of grinding and pelleting. If enough structured material is given in the diet to maintain normal rumen fermentation, there is no difference in net energy of processed forage and the same material long. Processed forages can help to restrict the amount of concentrates needed by cows with a moderate milk production.

Samenvatting

In de laatste decennia nam de belangstelling voor het gebruik van gemalen en tot brokjes geperste ruwvoeders - in het vervolg bewerkte ruwvoeders genoemd - enerzijds door de gunstige eigenschappen van dit type ruwvoer voor transport, opslag en voedering, anderzijds door de grotere opname ervan door het rundvee, toe. Dit was de aanleiding om de opname en voederwaarde van dergelijke produkten in melkveerantsoenen te bestuderen.

De energie-voorziening van rundvee wordt in hoofdzaak bepaald door de opgenomen hoeveelheid voer en de energetische voederwaarde. Daarom werd in de studie aandacht geschonken aan:

- de voederopname door herkauwers in het algemeen en melkvee in het bijzonder van bewerkte ruwvoeders in vergelijking tot de oorspronkelijke ruwvoeders, de factoren die deze opname beïnvloeden en de mogelijke oorzaken die de grotere opname van bewerkte ruwvoeders kunnen verklaren;
- de energetische voederwaarde van bewerkte ruwvoeders in rantsoenen voor melkvee wederom in vergelijking tot die met het oorspronkelijke materiaal en de verschillen in de verwerking van de energie van het voer door melkvee tussen beide typen ruwvoer.

In paragraaf 1.2 wordt kort ingegaan op de terminologie van bewerkte ruwvoeders. De gebruikte termen 'wafers', 'cobs', 'pellets' and 'processed forages' zouden in het Nederlands met respectievelijk 'wafels', 'hakselbrokjes', 'brokjes' en 'bewerkte ruwvoeders' kunnen worden aangeduid.

In hoofdstuk 2, een literatuurstudie, wordt eerst een kort overzicht gegeven van de belangrijkste factoren, die een rol spelen bij de regulering van de voederopname door herkauwers. Daarna wordt de invloed van malen, van de verschillende methoden van persen en van hakselen van ruwvoeders op de opname door rundvee beschreven (tabel 1, 2 en 3). Tevens is nagegaan, welke factoren het effect op de voedselopname door het opnemen van bewerkte ruwvoeders in het rantsoen beïnvloeden. Tenslotte is aandacht geschonken aan de veranderingen in het dier veroorzaakt door het eten van bewerkte ruwvoeders die een rol zouden spelen in de regulering van de voederopname.

Op lange termijn zal een dier trachten een evenwicht tussen de opgenomen en afgegeven energie te bewerkstelligen. Het hangt vooral af van de behoefte van het dier en de concentratie van het rantsoen of dit lukt.

De opname van lang ruwvoer wordt volgens de literatuur vooral door fysische factoren (capaciteit van de voormagen en de verdwijningssnelheid van digesta uit de pens) belemmerd. De overgang van netmaag naar boekmaag kan de passage van onvoldoende verkleinde ruwvoerdeeltjes tegenhouden. Herkauwen en microbiële afbraak bevorderen de verdwijningssnelheid van het voedsel uit de pens en netmaag. Het verkleinen van de deeltjesgrootte van lang ruwvoer door malen en/of persen moet dan ook als de belangrijkste oorzaak van een hogere voederopname van bewerkte ruwvoeders worden beschouwd, omdat hierdoor de passagesnelheid van het voer door de pens en netmaag toeneemt en een snellere fermentatie door de microben in pens en netmaag (oppervlaktevergroting door kleinere partikels) mogelijk is. Factoren, die de smakelijkheid van bewerkte ruwvoeders verlagen, zoals stoffig meel of te harde brokjes, kunnen echter de voederopname desondanks verlagen.

De verkleining van de deeltjesgrootte door malen en persen bleek af te hangen van het type ruwvoer, het groeistadium, de methode van drogen en het drogestofgehalte van het materiaal, de soort en het toerental van de molen, de zeef en het type pers dat gebruikt werd.

De invloed van malen en persen op de opname was gemiddeld bij schapen en vleesvee groter dan bij melkvee, hetgeen vooral een gevolg van de grotere energiebehoefte, voederopname en hoeveelheid krachtvoer in het rantsoen van melkvee zou zijn. Dit zou o.a. veroorzaakt worden, doordat de beperking van de opgenomen hoeveelheid voer van rantsoenen met zeer goed verteerbaar ruwvoer en/of aanzienlijke hoeveelheden krachtvoer meer door metabolische dan door fysische factoren bepaald wordt. Hierdoor kan ook verklaard worden waarom de invloed van malen en persen van ruwvoeders geringer wordt naarmate de verteerbaarheid van het ruwvoer hoger is (figuur 1) en het rantsoen meer krachtvoer bevat. Het effect van malen en persen van ruwvoeders op de opname werd negatief wanneer meer dan ca. 60% van het rantsoen uit krachtvoer bestond (tabel 4).

De verdringing van de opgenomen hoeveelheid ruwvoer door toevoeging van krachtvoer bedroeg voor lang ruwvoer meestal ca. 0,2-0,6 kg/kg en voor gemalen en tot brokjes geperst ruwvoer ongeveer 0,8-1,0 kg/kg op basis van droge stof (zie ook figuur 2).

Malen en persen van ruwvoeders verhoogde in het algemeen de snelheid waarmee het rantsoen werd opgenomen, terwijl belangrijk minder werd gekauwd en geherkauwd. Ook zou de speekselafscheiding vaak verlaagd zijn. Abnormale herkauwpatronen op rantsoenen met uitsluitend gemalen ruwvoer konden vaak worden voorkomen door een weinig stro of hooi in lange vorm te verstrekken.

De motiliteit van de pens kan geringer worden door malen en persen van ruwvoer. Ook werden veranderingen zowel van het type microflora in de pens als van de cellulolytische activiteit van de pensbacteriën, als gevolg van het gebruik van bewerkt ruwvoer, gevonden. De resultaten van de verschillende proeven kwamen echter niet altijd overeen, ofschoon in het algemeen de grotere beschikbaarheid van gemakkelijk te fermenteren koolhydraten in rantsoenen met gemalen en tot brokjes geperste ruwvoeders een toename van de produktie van vluchtige vetzuren, een lagere pH en een ruimere verhouding van propionaat en butyraat tot acetaat scheen te veroorzaken. Deze effecten werden ook gevonden wanneer het aandeel krachtvoer in het rantsoen toenam, terwijl in zeer krachtvoerrijke rantsoenen een snelle fermentatie de pH zelfs beneden 5,5 à 6 kon verlagen, de stabiliteit van de microflora verstoren en aanleiding geven tot hogere melkzuur-gehalten in de pens.

Ruwvoerdeeltjes kleiner dan 2 mm zijn waarschijnlijk klein genoeg om de boekmaag opening van rundvee te passeren en kunnen zo de passagesnelheid vanuit de pens vergroten. Hierdoor zou de voederopname van gemalen geperst ruwvoer belangrijk hoger kunnen worden, mits deze niet door een grotere vulling van het distale deel van het maagdarmkanaal wordt belemmerd, of meer door metabolische factoren wordt gereguleerd, zoals bij verstrekking van krachtvoerrijke rantsoenen. Een lage pH en de concentratie aan vluchtige vetzuren in pensvloeistof en bloed zou bij de regulering door metabolische factoren een rol kunnen spelen.

In hoofdstuk 3 wordt de literatuur over de invloed van het malen en persen van ruwvoeders op de verteerbaarheid en energetische voederwaarde bij rundvee samengevat. Bij eenzelfde voederniveau was de verteringscapaciteit van schapen en rundvee vrijwel gelijk, hoewel ruw eiwit soms door rundvee iets slechter werd verteerd dan door schapen. Verhoging van de opgenomen hoeveelheid voer veroorzaakte bij melkvee in het algemeen een daling van de verteringscoëfficienten van organische stof en energie. Deze daling was meestal gering in rantsoenen met alleen lang ruwvoer, maar groter voor gemengde rantsoenen met een belangrijke hoeveelheid krachtvoer of gemalen en geperst ruwvoer. De verteringsdepressie leek toe te nemen naarmate de kwaliteit van het ruwvoer lager en het aandeel krachtvoer in het rantsoen groter was. De versnelde passage van het voedsel en de geringere verblijfstijd in de pens, waardoor de microbiële vergisting van vooral de celstofrijke bestanddelen werd gereduceerd, werd beschouwd als de belangrijkste oorzaak van een verteringsdepressie veroorzaakt door verhoging van het voederniveau.

Het malen en persen van ruwvoer veroorzaakte meestal eveneens een verlaging van de verteerbaarheid, welke groter was voor de ruwe celstof dan voor de organische stof en de energie. Gemiddeld werd een verlaging voor de verteerbaarheid van organische stof, stikstof en ruwe celstof van respectievelijk ongeveer 10, 5 en 25% gevonden, hoewel de resultaten van de diverse proeven een aanzienlijke variatie vertoonden (tabel 5). Een snellere passage door de pens en een lagere cellulolytische activiteit van de microflora in de voormagen werd vooral als oorzaak van deze verteringsdepressie beschouwd. De oppervlakte-vergroting van het ruwvoer door malen en persen, waardoor een snellere afbraak door de pensbacteriën mogelijk werd, zou overigens gedeeltelijk de gevolgen van de kortere verblijfstijd in de voormagen opheffen.

Bij schapen werd van rantsoenen met ruwvoerbrokjes een groter gedeelte van het verteerbare voer en vooral de celstofrijke fractie in de dunne en dikke darm verteerd dan van rantsoenen met lang ruwvoer. De geringe informatie omtrent de plaats van vertering bij rundvee suggereerde een kleinere bijdrage van dunne en dikke darm aan de vertering van de celluloserijke fracties dan bij schapen werd gevonden. Het is derhalve de vraag of een toename van de bacteriële omzettingen in de dikke darm nog een belangrijke rol speelt in de energievoorziening van het rund.

Grotere energieverliezen met de faeces, bijvoorbeeld door verhoging van het voederniveau of het malen en persen van ruwvoeders, werden bij schapen gedeeltelijk gecompenseerd door geringere verliezen via methaan en urine. Toch was ook bij deze proeven met schapen de beschikbare energie van bewerkt ruwvoer meestal lager dan die van hetzelfde voer in lange vorm.

De benutting van beschikbare energie door schapen, vooral voor groei en vetvorming, was van bewerkt ruwvoer beter dan van lang ruwvoer. Hierdoor werd in de energiebalansproeven met schapen het lagere gehalte aan verteerbare of beschikbare energie vaak meer dan gecompenseerd. De resultaten van voederproeven met schapen en vleesrunderen stemden hiermee in het algemeen overeen.

Bij de aanvang van deze studie werden in de literatuur geen energiebalansproeven met melkkoeien gevoerd met bewerkt ruwvoer gevonden. Voederproeven met melkvee met dergelijke rantsoenen vertoonden vaak variabele uitkomsten. Rantsoenen zonder lang ruwvoer veroorzaken meestal frequente verstoringen van voederopname, herkauwgedrag en motiliteit van de voormagen, alsmede een sterk verlaagd melkvetgehalte. Deze invloeden kunnen belangrijk beperkt worden door wat lang stro of hooi te verstrekken. Het gebruik van gelijke hoeveelheden lang dan wel bewerkt ruwvoer in melkveerantsoenen in beide gevallen naast voldoende lang ruwvoer ter voorkoming van de zojuist vermelde moeilijkheden resulteerde in het algemeen slechts in geringe produktieverschillen, hetgeen zou wijzen op een gering verschil in netto-energiegehalte van beide soorten ruwvoer. Om de grootte van deze verschillen nauwkeuriger te kunnen bepalen werd besloten energiebalansproeven met melkgevende koeien uit te voeren.

Hoofdstuk 4 geeft een overzicht van de eigen energiebalansproeven met volwassen, zwartbonte (FH) melkkoeien, met een melkproduktie van 10-30 kg en een lichaamsgewicht tussen 450 en 650 kg, uitgevoerd in Wageningen bij de Afdeling Fysiologie der Dieren van de Landbouwhogeschool. Met behulp van indirecte calorimetrie werd in respiratiekamers volgens het 'open systeem' de energiebalans van de dieren gemeten en het netto-energiegehalte van rantsoenen met gemalen en tot brokjes geperst ruwvoer bepaald. De dieren werden tweemaal per dag gevoerd en gemolken. De verstrekte hoeveelheid ruwvoer werd afgestemd op het opnamevermogen van elke koe, terwijl de hoeveelheid krachtvoer in het rantsoen enerzijds bepaald werd door melkproduktie, anderzijds zoveel mogelijk constant gehouden werd binnen één proefserie. Elke balansproef duurde 12-14 dagen, voorafgegaan door een minstens even lange voorperiode. Twee of drie maal gedurende 48 uur werd tijdens de balansproef de gaswisseling van de dieren gemeten (paragraaf 4.1).

In twee proefseries werden rantsoenen vergeleken, waarin een deel van het krachtvoer al dan niet was vervangen door brokjes van gemalen stro of hooi. In andere series werd een zo groot mogelijke hoeveelheid ruwvoerbrokjes in het rantsoen opgenomen. De resultaten ervan konden worden vergeleken met die van energiebalansproeven met uitsluitend lang ruwvoer en krachtvoer Voorts werden in een viertal proefseries rantsoenen gebruikt, waarin een aanzienlijk deel van het ruwvoer in lange vorm dan wel als ruwvoerbrokjes aanwezig was.

Uit de resultaten (hoofdstuk 5) bleek dat de chemische samenstelling van lang en tot brokjes geperst ruwvoer vrijwel gelijk was.

Van de rantsoenen met bewerkt ruwvoer werd gemiddeld 16,0 kg droge stof opgenomen en van die met lang ruwvoer 13,9 kg. Het ruwvoer werd evenwel niet ad libitum verstrekt en gemiddeld werd in het geval van bewerkt ruwvoer veel minder krachtvoer in het rantsoen opgenomen.

Hoewel deze proeven werden opgezet om het gehalte aan netto energie van de verteerde bestanddelen van bewerkte ruwvoeders te bestuderen kon toch uit de resultaten (paragraaf 5.2) worden afgeleid dat de verteerbaarheid van rantsoenen waarin ruwvoerbrokjes als vervanging voor krachtvoer werden opgenomen lager was naarmate meer krachtvoer werd vervangen. Rantsoenen met ruwvoerbrokjes vertoonden een lagere verteringscoëfficient van de energie (d_E) van 6 eenheden dan gemiddeld voor rantsoenen met lang ruwvoer werd gevonden. Het aandeel krachtvoer in de organische stof van rantsoenen met ruwvoerbrokjes was ongeveer 15% lager dan in die met lang ruwvoer hetgeen op zich al een daling van de verteerbaarheid van de energie van 3-4 eenheden veroorzaakte. Het verschil tussen deze en de totale daling (2-3 eenheden) zou voornamelijk zijn veroorzaakt door het malen en persen van het ruwvoer. Vervanging van lang ruwvoer door ditzelfde materiaal in gemalen en geperste vorm resulteerde in de melkveerantsoenen in een depressie van d_E van 1,5 eenheden. Berekend werd dat de verteerbaarheid van respectievelijk organische stof, stikstof en energie van ruwvoer door malen en persen ongeveer 5 à 14, -1 à +8 en 5 à 14 eenheden lager werd, aangenomen dat het verschil geheel werd veroorzaakt door het malen en tot brokjes persen. De gemiddelde daling van d_E van bewerkt ruwvoer bedroeg 9 eenheden of 15%. De verteerbaarheid van N daalde gemiddeld minder dan 3%.

De daling van d_E bij vervanging van lang door bewerkt ruwvoer werd slechts in geringe mate gecompenseerd door geringere verliezen aan energie in methaan en urine (paragraaf 5.3). De beschikbare energie als percentage van de opgenomen energie (q) was in rantsoenen met bewerkte ruwvoeders ongeveer 1 eenheid lager (het verschil in d_E was 1,5) dan in die met lang ruwvoer. Berekend werd dat q van gemalen en geperst ruwvoer ca. 7 eenheden of 13% lager was dan van het oorspronkelijke lange uitgangsmateriaal.

Het gehalte aan beschikbare energie in de verteerde energie in de rantsoenen werd vrijwel niet beïnvloed door het malen en persen van het ruwvoer. Hetzelfde gold voor het gehalte in de verteerbare organische stof.

De benutting van de beschikbare energie (paragraaf 5.4) werd bestudeerd met behulp van een model, waarin de geproduceerde netto energie in melk (L_E) en in lichaamsweefsel (R_E) afhankelijk werd gesteld van de opname aan beschikbare energie (M_E) door het dier na aftrek van de onderhoudsbehoefte, constant verondersteld per metabolisch gewicht ($c \cdot W^{\frac{3}{4}}$). Verder werd aangenomen dat de benutting van M_E (k) afhankelijk was van de kwaliteit van het rantsoen (bijvoorbeeld van q) en de hoeveelheid stikstof uitgescheiden via de urine (U_N). Ook zou het lange ruwvoer als percentage van de totale opgenomen hoeveelheid droge stof (P_L) k kunnen beïnvloeden. Verder was uit de resultaten van vroegere proeven afgeleid dat voor de melkkoe geldt dat gedurende de lactatie de invloed van de samenstelling van de M_E op de benutting van M_E voor onderhoud en voor produktie van melk- en lichaamsvet-energie vrijwel gelijk is. Dit leidde tot het volgende iets vereenvoudigde model, dat gebruikt werd voor multiple regressie berekeningen:

$$R_E^* + L_E^* = a \cdot M_E^* + b \cdot q + c \cdot P_L + d \cdot U_N^* + e \qquad (5.5)$$

Hierin geeft * aan dat de cijfers gedeeld zijn door het metabolisch gewicht. Een negatieve R_E^* werd met 0,8 vermenigvuldigd omdat energie uit lichaamsreserves voor melkvorming efficienter wordt benut dan M_E uit het rantsoen.

In een andere benadering van de benutting van M_E uit rantsoenen met lang en bewerkte ruwvoeders werd k berekend door deling van 100 maal de totale hoeveelheid netto energie voor onderhoud en produktie van het rantsoen door de M_E-opname. Voor netto energie voor onderhoud werd daarbij een constante waarde per metabolisch gewicht van 65 kcal/kg$^{\frac{3}{4}}$ verondersteld (tabel 18).

Uit de resultaten van de multiple regressie-berekeningen (tabel 17) bleek dat vooral de waarde van de regressiecoëfficient b voor rantsoenen met ruwvoerbrokjes lager was dan voor die met lang ruwvoer. Verder was de invloed van P_L niet erg groot, terwijl ook vanwege statistische bezwaren deze variabele minder bruikbaar was. Uit de berekeningen werd afgeleid dat een betere benutting van M_E van rantsoenen met bewerkte ruwvoeders de daling van de M_E van deze rantsoenen door malen en persen van een deel van het ruwvoer goeddeels compenseerde. Voor het ruwvoer zelf kon, vergeleken met het originele lange ruwvoer, een verbetering van benutting van M_E met ongeveer 11% de berekende daling van het gehalte aan beschikbare energie door malen en persen met 8-9% goedmaken.

Het gemiddelde netto-energiegehalte van de opgenomen bruto energie (paragraaf 5.5) was hoger in rantsoenen met lang dan in die met bewerkte ruwvoeders, maar dit was hoofdzakelijk het gevolg van een groter aandeel krachtvoer in de rantsoenen zonder bewerkt ruwvoer. Er werd vrijwel geen verschil in netto-energiegehalte van de rantsoenen gevonden in de proeven waarbij een deel van het lange ruwvoer werd vervangen door een gelijke hoeveelheid van datzelfde ruwvoer in bewerkte vorm.

In paragraaf 5.6 werd een hypothese besproken ter verklaring van de grotere invloed van q op $R_E^* + L_E^*$ bij rantsoenen met bewerkt ruwvoer.

Daarin werd gesteld dat de ware kwaliteit van rantsoenen met bewerkte ruwvoeders, als gevolg van de verlaging van de oorspronkelijke q van het ruwvoeder door het malen en persen, door gebruik van de gevonden q onderschat wordt. Naarmate de q van het oorspronkelijke ruwvoer lager is, zou deze onderschatting groter zijn, wat als verklaring voor de lagere waarde van b in de regressieberekeningen met de proefuitkomsten van rantsoenen met bewerkt ruwvoer aangevoerd werd. Kwantitatief is het effect van deze onderschatting voor rantsoenen niet zo groot, omdat slechts een deel van het rantsoen uit gemalen, geperst ruwvoer bestaat en de invloed van q op $R_E^* + L_E^*$ betrekkelijk klein is.

In hoofdstuk 6 werd nagegaan hoe de verteerbaarheid van de organische stof en energie van de melkveerantsoenen voorspeld kon worden met behulp van de verteringscoëfficiënt van de organische stof gemeten met schapen nabij het onderhoudsvoederniveau ($d_{O,m}$) of in vitro. Ook voor de beschikbare energie van de melkveerantsoenen werd een voorspellingsformule berekend. Tenslotte werd nagegaan of in een nieuw voederwaarderingssysteem, dat in 1977 zal worden geïntroduceerd in ons land, de netto energie van rantsoenen met geperste ruwvoeders op dezelfde wijze voorspeld kan worden als die met lang ruwvoer. Door uit te gaan van de verteerbaarheid van de organische stof van geperst ruwvoer in de originele lange vorm, bij schapen of in vitro gemeten, werd het netto-energiegehalte goed benaderd.

In een slotbeschouwing (hoofdstuk 7) over de waarde van bewerkt ruwvoer voor melkvee in de praktijk werd gesteld, dat het afhangt van de prijsverhoudingen of de gunstige eigenschappen van dit type ruwvoer ten aanzien van opname, opslag en transport opwegen tegen de extra bewerkingskosten. Wanneer voldoende structuurhoudend lang ruwvoer wordt verstrekt, zodat een normale vertering in de voormagen wordt gehandhaafd, zal het netto-energiegehalte van lang en bewerkt ruwvoer vrijwel gelijk zijn. In rantsoenen van melkkoeien met een matige produktie kan zo door gebruik van ruwvoerbrokjes de hoeveelheid krachtvoer in het rantsoen beperkt worden.

Appendices

Appendix A. Data about the cows used in the balance experiments.

Cow Code No	Name	Year of birth	Time of calving (year-month)	Liveweight (kg)	Exp. No	Cow No within exp.
49	Lampkje 14	1963	1967-03	539-569	94-97	1
50	Lampkje 11	1962	1967-02	502-550	94-97	2
51	Anna 2	1957	1967-03	493-550	94-97	3
38	Gloria 33	1961	1967-04	489-530	94-97	4
52	Anna 5	1959	1967-03	553-586	94-97	5
	"		1968-04	562-577	105-107	2
53	Zwartschoft 12	1962	1967-04	527-578	94-97	6
46	H. Jannie 46	1963	1967-11	482	104	2
57	Gretha 89	1963	1967-12	549-572	104-105	5
60	Hiltje 56	1961	1968-02	514-545	104-107	1
48	Klaasje 8	1963	1968-01	571-615	104-107	3
58	Frieda 10	1959	1968-02	557-572	104-107	4
36	Truida 29	1961	1968-02	534-566	104-107	6
61	Eke 44	1959	1968-02	548-579	106-107	5
	"		1969-08	576-578	117-118	4
	"		1970-08	602-610	124-126	6
65	Geertje 8	1962	1969-08	522-530	117-118	1
	"		1970-11	533-548	HR 1-3	7
66	Jetty 23	1962	1969-08	567-572	117-118	2
68	Hendrika 92	1962	1969-08	505-507	117-118	5
	"		1970-09	490-516	124-126	5
69	Sara 61	1964	1969-08	526-539	117-118	6
70	Hiltje 42	1963	1969-10	564-566	117-118	3
	"		1970-11	570-586	HR 1-3	10
77	Dina 2	1967	1970-09	511-527	124-126	1
	"		1971-09	562-568	131-133	3
67	Martje 22	1964	1970-08	623-641	124-126	2
78	Anna 14	1967	1970-09	479-498	124-126	3
	"		1971-09	505-523	131-133	2
	"		1971-09	477-482	134-135	10
79	Klaasje 9	1966	1970-08	565-594	124-126	4
	"		1971-09	586-593	131-133	4
	"		1971-09	553-554	134-135	7
	"		1973-01	594-608	141-142	1
81	Lampkje 18	1967	1970-10	457-470	HR 1-3	8
82	Anna 15	1967	1970-12	477-498	HR 1-3	9
87	Anna 16	1968	1971-11	479-490	131-133	1
88	Ymkje Ada 63	1968	1971-10	510-521	131-133	5
	"		1971-10	459-470	134-135	8
89	Maartje 14	1964	1971-09	529-550	131-133	6
	"		1971-09	505-512	134-135	9

Appendix A. (continued)

Cow Code No	Name	Year of birth	Time of calving (year-month)	Liveweight (kg)	Exp. No	Cow No within exp.
71	Frieda 11	1967	1972-03	483-488	136-137	1
84	Troost 18	1966	1972-03	598-604	136-137	2
94	Thilda 31	1967	1972-01	562-566	136-137	3
	"		1973-02	586-606	141-142	3
95	Hilligje 56	1967	1972-01	567	136	4
96	Bonte 4	1967	1972-03	538-542	136-137	5
97	Tonia 20	1967	1972-02	524-529	136-137	6
80	Hiltje 62	1966	1972-03	498	137	4
102	Lampkje 21	1969	1972-09	494-512	138-140	1
103	Froukje 166	1968	1972-10	532-538	138-140	2
104	Anna 227	1967	1972-09	542-569	138-140	3
105	Sietske 51	1969	1972-09	501-507	138-140	4
106	Ottink	1969	1972-10	531-565	138-140	5
	"		1972-10	528-536	141-142	5
107	Lolkje 20	1969	1972-10	553-563	138-140	6
108	Gretha 90	1969	1973-01	494-504	141-142	2
109	Martje 23	1969	1972-12	454-460	141-142	4
100	Lampkje 19	1969	1973-01	544-556	141-142	6

Appendix B. Individual data of liveweight (W), roughage in the long form (P_L) as a percentage of total dry matter intake (I_T), metabolizable energy intake (M_E), metabolizability of gross energy (q), milk energy (L_E), energy balance (R_E), milk nitrogen (L_N) and N balance (R_N).

Exp. and Cow No	Cow Code	W (kg)	Ration code	P_L (%)	I_T (g)	M_E (kcal)	q (%)	LE (kcal)	R_E (kcal)	L_N (g)	R_N (g)
94 3	51	527	HPE	23	15559	34304	50.3	15343	-3771	101.3	-3.4
94 4	38	515	HPE	24	14509	35393	55.7	21323	-7602	80.6	-1.7
95 5	52	586	HPE	22	15940	38349	54.9	15890	- 974	92.1	13.1
96 2	50	538	HPE	22	15915	36635	52.7	12952	2466	102.0	13.6
96 6	53	544	HPE	25	14054	34777	56.4	13986	1174	100.2	6.4
97 1	49	559	HPE	24	14419	35592	56.4	11312	2338	104.8	17.4
94 2	50	550	HPL	21	16886	36059	49.6	16066	-2473	78.2	-0.9
94 6	53	543	HPL	23	15276	35574	53.8	16555	-3606	104.5	-3.2
95 1	49	553	HPL	23	15405	36093	54.0	14919	- 225	100.4	7.2
96 3	51	550	HPL	20	17709	37046	43.3	12089	2377	90.9	13.7
96 4	38	507	HPL	21	16680	41026	56.4	17554	1550	113.8	17.5
97 5	52	583	HPL	21	16228	36570	52.5	9889	2650	100.1	7.9
95 4	38	530	SP	20	17826	37408	48.2	17235	- 380	56.1	9.8
95 3	51	545	SP	21	16564	30544	42.3	11408	-1267	59.3	.2
94 1	49	569	SP	21	16866	33816	46.2	15218	-3697	58.9	2.3
96 5	52	556	SP	25	14047	33075	54.1	12078	- 360	79.4	16.9
97 2	50	546	SP	21	16863	34866	47.7	11593	2462	71.9	7.6
97 6	53	578	SP	20	17485	34626	45.7	12124	977	75.0	2.8
94 5	52	553	CONC	27	13208	35867	62.5	17189	-2694	102.8	12.8
95 2	50	502	CONC	29	12372	33419	62.0	14447	568	97.3	10.1
95 6	53	527	CONC	29	12380	33499	62.1	14412	- 54	99.2	11.1
96 1	49	539	CONC	26	13146	34625	60.3	12885	1702	104.7	16.2
97 3	51	493	CONC	30	11498	30551	61.4	10345	2115	107.1	8.2
97 4	38	489	CONC	26	13238	34719	60.6	15727	- 356	110.2	3.7
104 1	46	537	HPE	21	16550	35863	49.6	12870	498	167.8	-7.5
104 4	48	557	HPE	24	14593	35206	55.3	12922	773	139.2	7.9
105 2	52	577	HPE	20	17034	37895	50.7	13200	- 67	129.9	1.2
106 .3	60	598	HPE	21	16652	36536	50.0	12630	746	145.0	5.5
106 6	36	563	HPE	24	14372	34956	55.4	13008	1150	142.3	3.2
107 5	61	579	HPE	21	16483	39935	55.4	15614	- 99	154.4	10.7
104 3	60	604	HPL	19	18598	38697	48.2	15942	-1107	103.5	-0.7
104 6	36	559	HPL	22	15704	37656	55.3	15677	184	119.2	7.4
105 5	58	549	HPL	26	13225	30867	53.6	9311	2611	99.1	8.7
106 1	46	539	HPL	23	15331	31899	48.1	9033	2694	95.6	5.1
106 4	48	572	HPL	28	12520	29614	54.2	6406	4110	104.0	14.4

107 2	*52*	*562*	*HPL*	*23*	*14930*	*32200*	*49.7*	*8691*	*1335*	*71.0*	*14.8*
104 5	*58*	*572*	*SP*	*23*	*15298*	*30400*	*45.3*	*10135*	*908*	*68.5*	*-4.1*
106 2	52	571	SP	24	14551	31543	49.4	10130	- 530	89.3	4.5
105 4	48	562	SP	28	12311	27979	51.7	8955	- 136	82.0	2.4
105 1	46	545	SP	22	15930	32794	46.9	11309	1528	85.8	-0.3
107 3	60	615	SP	22	15799	33164	47.8	9487	2387	85.2	10.5
107 6	36	566	SP	26	13602	30968	51.9	10440	1216	97.8	1.8
104 2	57	482	CONC	34	10402	27567	60.8	9222	942	93.9	13.1
105 3	60	571	CONC	27	12991	34909	61.6	14366	- 256	130.6	-2.6
105 6	36	534	CONC	27	12991	35215	62.1	13809	1646	128.9	15.0
106 5	61	548	CONC	26	13174	35038	61.6	17361	-4597	108.3	8.5
107 1	46	514	CONC	35	10012	26466	60.5	8359	2122	108.6	10.2
107 4	48	568	CONC	36	9600	25199	60.0	5094	3501	127.7	5.0
117 1	65	530	LPOF	15	16804	36319	49.1	12817	39	199.4	-0.8
117 2	66	572	LPOF	15	16813	37163	50.2	15053	-1746	181.4	15.9
118 3	70	564	LPOF	15	16789	36360	49.2	14907	-1139	173.5	15.5
118 6	69	539	LPOF	15	16778	37771	51.1	14330	1501	197.9	16.1
117 3	70	566	LP2F	15	15777	34767	49.3	17897	-7188	159.4	17.6
117 4	61	578	LP2F	15	16168	37015	51.2	17184	-3373	183.1	15.9
118 2	66	567	LP2F	16	16211	37376	51.5	15033	- 163	172.7	23.8
118 5	68	505	LP2F	16	16102	34737	48.2	12966	595	172.4	14.2
117 5	68	507	LP4F	17	15503	35903	51.1	14787	269	153.0	10.3
117 6	69	526	LP4F	16	15315	36216	52.2	14263	- 126	152.1	21.0
118 1	65	522	LP4F	17	15497	35386	50.3	11639	1024	182.6	21.6
118 4	61	576	LP4F	17	15482	36013	51.2	14449	79	168.6	15.4
124 1	77	525	GPE	18	16811	37244	52.5	14675	- 401	122.0	1.7
124 2	67	623	GPE	20	17710	39924	53.5	13704	1305	143.1	11.1
125 3	78	481	GPE	20	17319	38237	52.4	14553	1189	122.7	7.6
125 4	79	574	GPE	19	17630	38826	52.4	13588	2212	149.9	-2.6
126 5	68	516	GPE	20	17339	38298	52.3	13560	2323	131.2	4.5
126 6	61	610	GPE	19	17498	39834	54.2	11708	3256	158.8	-3.9
124 3	78	479	LPE	20	16889	38159	51.4	15046	- 341	200.6	5.3
124 4	79	565	LPE	20	16683	36974	50.4	13716	-1004	216.2	-5.9
125 5	68	505	LPE	20	17343	39172	51.8	13998	1902	197.8	16.0
125 6	61	608	LPE	19	17510	41311	54.0	13318	2192	244.9	-3.3
126 1	77	511	LPE	19	17722	39171	51.4	13471	873	223.4	-4.2
126 2	67	641	LPE	20	17779	40152	52.5	10904	4230	242.1	-4.0
124 5	68	490	LPL	24	14768	30948	48.4	13908	-3416	123.6	10.0
124 6	61	602	LPL	20	17074	34521	46.8	12226	-2794	189.3	-7.6
125 1	77	527	LPL	19	17709	35678	46.8	13564	-1782	165.7	6.3
125 2	67	634	LPL	19	17699	35505	46.6	12044	- 505	168.3	1.4
126 3	78	498	LPL	19	17587	35706	47.0	13159	848	172.5	-0.1

Appendix B. (continued)

Exp. and Cow No	Cow Code	W (kg)	Ration code	P_L (%)	I_T (g)	M_E (kcal)	q (%)	L_E (kcal)	R_E (kcal)	L_N (g)	R_N (g)
126 4	79	594	LPL	19	17714	35303	46.2	12574	- 194	184.3	- 5.2
HR1 8	81	470	G	66	12636	28798	53.4	9532	-1096	182.3	5.0
HR2 9	82	498	G	67	13206	29709	51.9	9726	554	196.1	-13.3
HR3 7	65	548	G	62	15991	36980	53.7	11446	1417	237.1	- 7.4
HR3 10	70	586	G	66	15193	34928	53.6	10556	1621	207.2	4.8
HR1 10	70	578	GW	67	15849	35477	53.0	13780	- 692	210.8	7.8
HR2 7	65	533	GW	61	15556	34306	52.0	12929	-2220	207.0	- 6.2
HR2 8	81	462	GW	61	11136	25622	54.0	9036	- 316	148.6	- 1.9
HR3 9	82	489	GW	70	14514	31355	51.0	9546	2364	175.6	8.2
HR1 7	65	541	GC	15	16896	36034	51.6	15208	-1956	216.5	3.3
HR1 9	82	477	GC	17	15114	30338	48.9	11921	- 743	199.9	-11.9
HR2 10	70	570	GC	16	16050	34907	52.3	12942	863	210.6	3.1
HR3 8	81	457	GC	18	12926	28752	53.4	8647	1273	161.5	8.6
131 1	87	479	H	53	15311	40124	60.0	17795	-1646	156.6	- 5.6
131 2	78	517	H	64	14785	38060	59.0	14852	- 150	157.1	- 0.6
132 3	77	568	H	62	15808	41163	59.6	14578	1164	184.5	7.2
132 4	79	593	H	55	17608	46915	61.1	20028	821	203.4	2.2
133 5	88	513	H	55	15790	41576	60.0	17000	-1347	159.1	12.3
133 6	89	550	H	60	15544	41025	60.2	16727	437	178.1	2.5
131 3	77	562	G	61	16080	41144	58.7	16830	- 149	147.7	5.6
131 4	79	587	G	55	17875	46720	60.0	21484	100	158.7	14.8
132 5	88	521	G	57	16442	42695	59.3	18630	-2163	156.1	4.1
132 6	89	539	G	60	15478	40051	59.1	18857	-2967	147.4	-15.9
133 1	87	490	G	57	16716	42510	58.0	16467	1638	149.5	- 1.9
133 2	78	523	G	65	15204	39050	58.5	13563	2778	137.2	8.3
131 5	88	510	GP	18	14916	37309	57.0	19786	-6182	122.2	15.2
132 1	87	480	GP	17	16385	39687	55.4	16931	55	158.1	3.4
133 3	77	564	GP	17	16193	41032	58.4	12915	4029	199.6	8.1
131 6	89	529	GP	18	14329	36192	57.6	20208	-6431	120.2	17.0
132 2	78	505	GP	17	15273	37251	55.8	14666	758	169.4	9.3
133 4	79	586	GP	14	17920	45017	57.9	19521	689	215.9	1.1
134 7	79	553	GPOF	10	14425	32524	53.8	15115	-2697	152.1	-14.1
134 8	88	470	GPOF	31	12786	27953	51.4	12683	-4623	121.8	11.2
135 9	89	512	GPOF	41	14818	31887	50.4	12399	595	156.0	1.7
135 0	78	477	GPOF	20	10173	23106	53.8	8695	- 606	102.0	- 2.5
135 7	79	554	GP3F	17	14960	34888	54.3	14132	140	129.4	16.9
135 8	88	459	GP3F	21	13703	29348	49.5	11343	-2769	123.7	11.2

134	9	89	505	GP3F	49	12267	27031	50.9	14335	-5466	133.8	- 1.7
134	0	78	482	GP3F	55	11057	26472	55.9	10954	-1011	113.5	2.4
136	1	71	488	HP4S	35	14824	38196	58.5	21006	-7891	147.5	10.2
136	2	84	604	HP4S	38	17358	44605	58.3	21953	-6029	205.4	9.4
136	3	94	566	HP4S	33	15346	40050	59.3	14817	9	207.5	4.4
137	1	71	483	HP8S	19	17379	43350	56.7	18928	-1108	198.0	19.8
137	2	84	598	HP8S	18	18795	46942	56.7	20829	-1855	222.4	18.1
137	3	94	562	HP8S	20	15480	39706	58.2	13270	1757	219.1	14.2
136	4	95	567	HP4A	34	16373	39867	55.3	16618	-2420	198.7	21.6
136	5	96	542	HP4A	34	16312	39570	55.0	18570	-5409	194.1	12.5
136	6	97	524	HP4A	30	15385	37779	55.8	17238	-3416	182.8	13.9
137	4	80	498	HP8A	17	16305	37703	52.6	17796	-3212	196.8	5.5
137	5	96	538	HP8A	19	17743	41020	52.6	16376	- 740	238.0	9.1
137	6	97	529	HP8A	20	16857	40220	54.2	16239	- 337	221.6	13.7
138	1	102	512	LPEI	14	16506	37203	51.5	17828	-4407	176.2	30.6
138	2	103	538	LPEI	17	17052	35909	48.0	15728	-3516	216.6	- 3.4
139	4	105	501	LPEI	19	16361	35656	49.8	13720	- 586	193.8	15.0
139	5	106	539	LPEI	21	16371	36567	51.1	19686	-8829	220.5	- 2.4
140	3	104	569	LPEI	20	17664	40760	52.8	14885	1709	191.0	33.5
140	6	107	563	LPEI	21	16785	37110	50.6	12208	2193	229.1	9.2
138	3	104	542	LPLI	19	17726	37404	47.9	16359	-3253	153.3	37.0
138	4	105	507	LPLI	12	15627	32914	47.8	14338	-3010	163.1	.5
139	1	102	512	LPLI	19	17666	37213	47.8	16403	-2900	169.2	3.9
139	6	107	553	LPLI	21	16871	35428	47.7	14649	-1715	186.8	- 5.9
140	2	103	534	LPLI	19	17691	36525	46.8	13991	- 873	194.0	- 1.7
140	5	106	531	LPLI	21	16720	35621	48.3	17437	-4789	202.0	-11.2
138	5	106	565	LPII	16	14534	31139	49.6	18899	-12043	174.5	-13.2
138	6	107	556	LPII	17	15777	32851	48.2	14813	-4976	176.8	- 4.8
139	2	103	532	LPII	19	17416	34350	46.1	13986	-2635	202.6	- 5.2
139	3	104	547	LPII	20	17582	36847	49.0	15819	-2444	171.7	16.3
140	1	102	494	LPII	18	16762	34980	48.9	12150	128	202.2	- 8.7
140	4	105	506	LPII	18	16060	33328	48.4	12115	166	183.3	1.4
142	1	79	594	HP4S	41	16573	41168	57.5	15286	253	233.4	13.9
141	2	108	504	HP4S	39	16081	40997	59.0	18466	-1967	210.0	16.8
141	1	79	608	HP8S	20	16807	39933	55.3	22088	-7137	220.5	- 5.5
142	2	108	494	HP8S	18	16379	39754	56.4	13970	1929	222.6	23.8
142	3	94	586	HP4A	38	15800	40435	58.2	16657	-1385	234.7	- 1.7
142	4	109	460	HP4A	42	15342	38665	57.2	13381	2287	233.1	16.5
141	5	106	536	HP4A	44	15747	40424	58.2	13343	2752	248.5	19.5
141	6	100	556	HP4A	42	16729	41784	56.8	16561	-1382	266.1	- 1.4
141	3	94	606	HP8A	19	16422	41830	58.0	19434	-2266	245.8	- 2.2
141	4	109	454	HP8A	22	15921	39335	56.2	14148	2555	245.6	10.9
142	5	106	528	HP8A	22	15881	40695	57.9	13106	3953	257.0	22.4
142	6	100	544	HP8A	21	16855	40854	55.2	15602	- 278	261.8	5.6

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