EXTENSION CIRCULAR 422

From Feed to Milk:

Understanding Rumen Function

CONTENTS

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Tables

PART I: BACKGROUND IN BASIC NUTRITION OF DAIRY CATTLE

Feed costs represent 45 to 60 percent of the total cost of producing milk. The key to maximizing dairy farm profitability is to maintain nutrient levels while carefully managing feed costs. When optimal nutrition is achieved, cows will produce better quality and larger quantities of milk. Overall health should improve, resulting in cost savings in veterinary fees, breeding, and treatment with drugs.

A basic understanding of animal nutrition as it applies to dairy cattle is essential to good herd management. Proper feeding of the dairy cow is complicated and requires a combination of scientific knowledge, creativity, and good management skills to balance the needs of the rumen microorganisms and the needs of the animal.

Rumen physiology

What makes ruminant animals unique is their four stomach compartments: the reticulum, the rumen, the omasum, and the abomasum. The reticulum and the rumen are often discussed together because they are adjoining compartments. The reticulum is actually the largest of the various sacs of the rumen. Digestion of feedstuffs by microorganisms takes place in both stomach compartments.

The reticulum, often called "the blind pouch," is the first stomach compartment. If the cow consumes metal or other large indigestible items, the honeycomb structure of the stomach wall acts as a sieve and prohibits any hardware from moving further into the digestive tract. Feed that enters the reticulum is later regurgitated and remasticated as part of the cud. The reticulum can contain up to 2.5 gallons of undigested feed and feed being digested (digesta).

The rumen is a large, hollow muscular organ. The rumen develops anatomically in size, structure, and microbial activity as the calf's diet is changed from liquid milk or replacer to dry feed or silages. In the mature ruminant, the rumen nearly fills the entire left side of the abdominal cavity.

The rumen is a fermentation vat that can hold 40 to 60 gallons of material and is the site of microbial activity. An estimated 150 billion microorganisms per teaspoon are present in its contents. They consist of bacteria, protozoa, and fungi. Bacteria require a warm, moist, oxygen-free environment for optimum growth. This type of environment is naturally maintained in the rumen with a temperature range of 100 to 108°F. If cows are fed a proper balance of forages and grain, the pH should range between 5.8 and 6.4, which allows the growth of many species of bacteria.

The omasum is sometimes referred to as the "manyplies" because of its many layers of muscular tissue. In the omasum, the particle size of digesta is reduced, and any excess water is removed before the digesta enters the abomasum. The omasum can contain up to 4 gallons of digesta.

The fourth compartment is the abomasum or "true stomach," where acids and enzymes further digest the cow's digesta. It is the first true glandular portion of the gastrointestinal tract where the stomach walls secrete enzymes. It functions very similarly to the stomach of many simple stomached animals such as the pig. This stomach compartment can hold approximately 5 gallons of material. The time that digesta remains in the abomasum is very short compared to the retention time of feeds in the rumen. The turnover rate of feedstuffs in the rumen and total retention time in the digestive tract, for lactating and dry cows, are shown in Table 1.

The presence of food in the abomasum stimulates hydrochloric acid production. Hydrochloric acid converts pepsinogen to pepsin, which breaks down protein to shorter molecular chain compounds such as peptides and amino acids for further digestion and absorption in the small intestine. The true stomach has a low pH of 2 to 4, due largely to this acid production. Some fat digestion also occurs in the true stomach.

Digesta flowing from the abomasum to the small intestines is composed of small particles suspended in liquid digesta. There is little sorting of particulate matter, and the flow of liquid and particles is rather similar. As digesta passes through the small intestine, the pH increases at a relatively slow rate. This has important implications for enzymatic activity in the intestine because enzymes secreted by the pancreas and intestinal mucosa generally have a pH optimum which is neutral to slightly alkaline.

Table 1. Rate of passage of feed for dry cows and lactating cows.

ITEM	DRY COWS[a]	MILK COWS[a]
Body weight, lb	1541	1381
Dry matter intake, lb/day	23.8	43.5
Milk production, lb/day	—	53.6
Ruminal mean retention time, hr		
Grain	25.6	19.4
Hay	30.0	30.3
Total mean retention time in the digestive tract, hr		
Grain	47.0	39.2
Hay	55.3	50.7

Source: Adapted from Hartnell, G. F. and L. D. Satter. 1979. Determination of rumen fill, retention time and ruminal turnover rates of ingesta at different stages of lactation in dairy cows. J. Anim. Sci. 48:381.

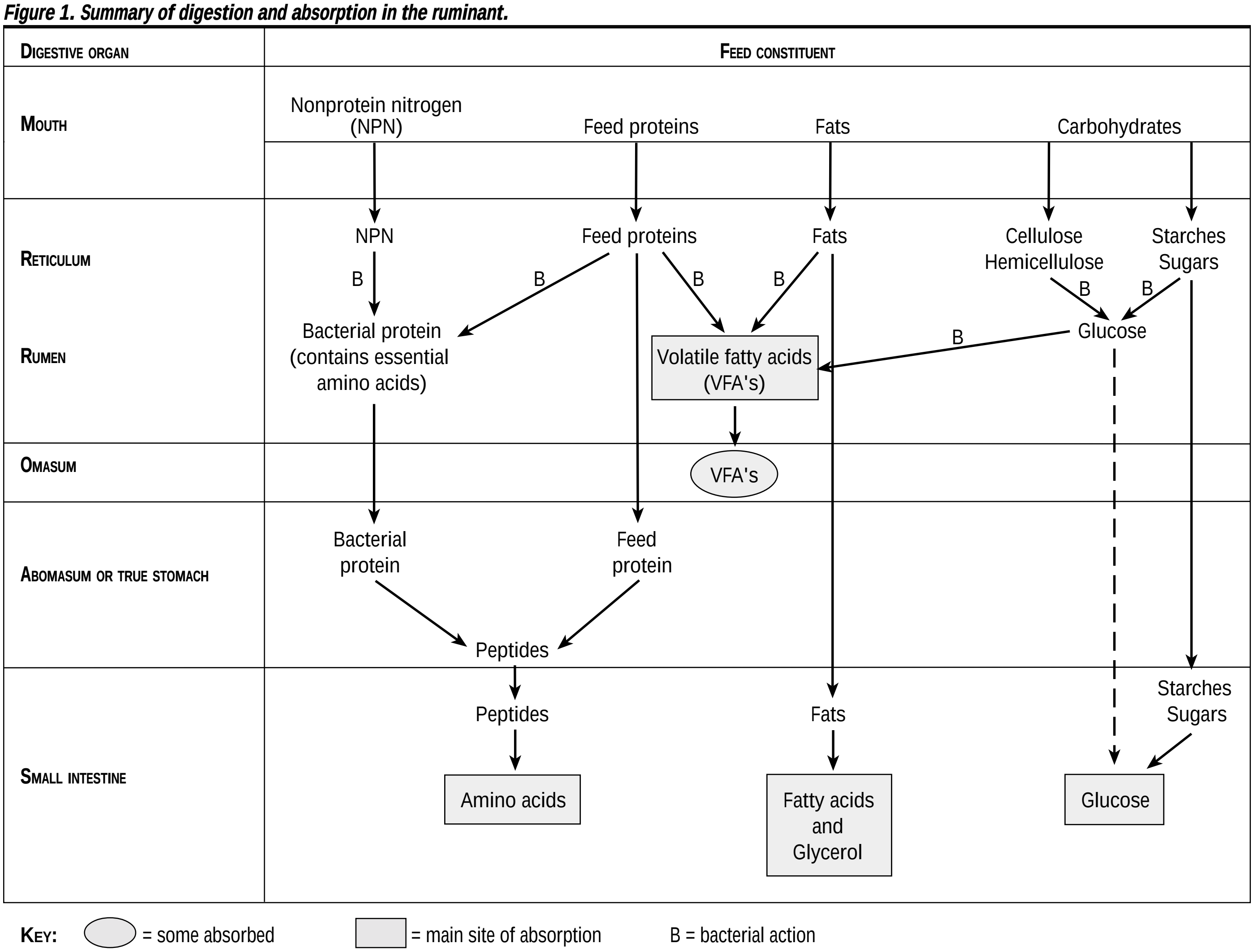
[a] Means reported in this table were taken from four dry cows and four lactating cows.

Bile salts, which are synthesized in the liver from cholesterol, aid in maintaining this alkaline pH in the small intestine. They also act as emulsifiers that separate fat globules and give lipase enzymes more surface area upon which to act. Both the biliary and the pancreatic secretions neutralize the gastric acids and provide enzymes for hydrolysis of starches, proteins, and lipids. The small intestine is the main absorption site for these breakdown products (Figure 1).

In adult ruminants fed high forage diets, virtually all of the soluble sugars as well as most of the starch in feeds are fermented by the rumen microbial population. However, animals fed high grain diets at high intake levels may have as much as 50 percent of the dietary starch escape ruminal fermentation and be presented in the lower tract for digestion. In these circumstances, substantial amounts of glucose may be absorbed from the small intestine.

Protein reaching the small intestine of the ruminant is derived from three sources: (a) dietary protein that has escaped breakdown by rumen microbes; (b) protein contained in bacterial and protozoal cells that flow out of the rumen; and (c) endogenous proteins contained in sloughed cells and secretions into the abomasum and intestine. Pancreatic and intestinal proteases break down these forms of protein so the amino acids and peptides can be absorbed in the small intestine.

Figure 1. Summary of digestion and absorption in the ruminant.



Lipids arriving in the small intestine are primarily esterified fatty acids and phospholipids. Triglycerides that escape ruminal breakdown and esterified fatty acids of microbial origin are readily hydrolyzed by pancreatic lipase to release free fatty acids. These are absorbed by the intestinal mucosal cells.

Any material that has not been utilized in the digestive tract to this point enters the large intestine. Absorption of water, minerals, nitrogen, and volatile fatty acids occurs in the large intestine. The homostatic functions of the large intestine involve electrolyte balance, some microbial fermentation, and temporary storage for excreta. Any products that have not been digested will pass out through the feces. Fecal material contains undigested feed, metabolic fecal nitrogen, and undigested fat and bacteria.

Rumination and saliva production

A ruminant animal has the ability to ingest feed rapidly and to complete the chewing at a later time. This process is known as rumination. The steps involved are regurgitation of the feed, remastication or rechewing, resalivation, and reswallowing of rumen digesta. The process of rumination reduces the particle size of feeds, which enhances microbial function and allows for easier passage out of the stomach compartments.

The regurgitated material is called a "bolus" or "cud" and consists primarily of chewed material coated with saliva. Saliva is a major secretion into the digestive tract, and its production is directly related to the amount of time a cow spends eating and ruminating (Table 2). Production of saliva in a mature ruminant can exceed 47.5 gallons per day when cows chew six to eight hours per day.

Saliva is rich in mineral ions, particularly sodium, phosphate, and bicarbonate, which serve as buffering agents in the digestive system (Table 3). Saliva neutralizes the acids produced during fermentation and helps to maintain an ideal environment for bacteria growth.

Production of saliva can be encouraged by controlling the ruminant's diet. The more a cow chews, the more saliva it produces. The amount of time a cow spends chewing is influenced by feeding management practices and the nature of the diet. The order in which feed ingredients are fed, the particle size of the feeds, the number of times during the day cows are fed, and the type of feed consumed can all directly affect saliva production. Long hay stimulates the greatest amount of chewing, rumination, and saliva production. Feeding forages high in cell wall content or neutral detergent fiber would tend to increase rumination time.

Table 2. Effect of ration on eating rate and on saliva production.

Feed	Eating rate pounds of feed/min	Salivary production teaspoons/pound of feed
Pelleted	.79	1.0
Fresh grass	.62	1.5
Silage	.55	2.0
Dried grass	.18	5.0
Hay	.15	6.0

Source: Bailey, C. B.1958. The role of secretion of mixed saliva in the cow. In: Proceedings of the Nutrition Society, p. xiii.

Table 3. Chemical composition of saliva from cattle.

Element	mEq/l[a]
Sodium	126
Potassium	6
Phosphate	26
Chloride	7
Bicarbonate	126

Source: Bailey, C. B. and C. C. Balch. 1961. Saliva secretion and its relation to feeding in cattle. British Journal of Nutrition 15:371.

[a] mEq/l is milliequivalents per liter.

Rumination may be significantly reduced, for example, by feeding high amounts of concentrates and finely chopped forages. High moisture feeds such as pasture or silage can reduce saliva produced per pound of dry matter intake by 50 percent. Grains or pelleted feeds can reduce the flow to 20 percent of that on a long-hay diet. Saliva production can drop dramatically if the cow does not receive adequate effective fiber, which is defined as a combination of forage particle size and forage neutral detergent fiber intake.

Function of the rumen

The rumen through its strong musculature allows mixing and churning of digesta. The movement of the rumen mixes the contents, promoting turnover and accessibility of the coarser forage particles for regurgitation, cud chewing, size reduction, and microbial digestion. Fine forage particles, dense concentrate particles, and materials which have become hydrated tend to congregate near the bottom. Particles tend to move out from the rumen as they are reduced in size through cud chewing and microbial action. The microbes also pass from the rumen for possible digestion in the lower gastrointestinal tract.

The structuring and composition of rumen contents is influenced by diet. Since the dairy cow consumes such a varied selection of feedstuffs and feed particle sizes, rumen contents do not have a uniform composition, and as a result there is stratification of feed particles. Long-hay diets produce contents with a large, less dense, floating layer beneath the gas dome with relatively liquid contents and suspended fiber beneath. Denser material sinks to the bottom of the rumen. The floating mat is composed of the more recently ingested forage. In diets where forage particle size is fine and forage neutral detergent fiber is low, the floating mat is diminished, but this occurs to a much greater extent when high levels of pelleted grain or concentrates are fed. The rumen contents with these types of diets are generally more viscous.

The function of the rumen as a fermentation vat and the presence of certain bacteria promote the development of gases. These gases are found in the upper part of the rumen with carbon dioxide and methane making up the largest portion (Table 4). The proportion of these gases is dependent on rumen ecology and fermentation balance. Ordinarily, the proportion of carbon dioxide is two to three times that of methane, although a large quantity of carbon dioxide is reduced to methane. Approximately 132 to 264 gallons of gas produced by fermentation are belched each day. The eructation of gases via belching is important in bloat prevention.

Table 4. Typical composition of rumen gases.

COMPONENT	AVERAGE PERCENT
Hydrogen	0.2
Oxygen	0.5
Nitrogen	7.0
Methane	26.8
Carbon dioxide	65.5

Source: Sniffen, C. J. and H. H. Herdt. The Veterinary Clinics of North America: Food Animal Practice, Vol 7, No 2. Philadelphia, Pa.: W. B. Saunders Company, 1991.

The mucosal surface of the rumen is characterized by ruminal papillae, the organs of absorption. Papillae distribution, size, and number are closely related to forage to concentrate ratio, feeding habits, forage availability, and digestibility.

If a ruminant's diet is significantly altered, as in moving from a high forage diet to a high grain diet or a dry cow ration to a lactating cow diet, this change should be implemented gradually to allow ruminal papillae time to adapt to nutritional changes. An adaptation period of two to three weeks is usually needed.

The development of the ruminal papillae is related to the production of certain acids from the fermentation of feeds. Increasing the proportions of butyric and propionic acids, as seen with high grain rations, increases blood flow to the ruminal epithelium, which stimulates vascular budding and epithelial cell proliferation. Papillae either grow in size and number or shorten in size, depending on the diet and the fermentation acids produced.

Rumen microbiology

The objective of feeding dairy cattle nutritionally balanced diets is to provide a rumen environment that maximizes microbial production and growth. When designing rations for ruminants, the needs of both the animal and the rumen microorganisms must be considered. In order to optimize animal performance, compromises in feeding the microbes or the cow may occur.

The microbial population in the rumen consists of bacteria, protozoa, and fungi. The majority of the concentration is as bacteria, which can number 10^{10} to 10^{11} cells/gram of rumen contents. Bacteria can be grouped according to their three main shapes (cocci, rods, and spirilla), according to their size (generally from 0.3 to 50 µm), and according to their different structures. They can also be grouped according to the type of substrate fermented and are categorized into eight distinct groups of rumen bacteria (Table 5). These species of bacteria degrade or utilize products such as cellulose, hemicellulose, starch, sugars, intermediate acids, protein, and lipids and produce methane. An expanded classification could include pectin utilizers and ammonia producers. Most species of bacteria are capable of fermenting more than one substrate.

The methane-producing bacteria are a special class of microorganisms responsible for regulating the overall fermentation in the rumen. They remove hydrogen gas by reducing carbon dioxide with hydrogen gas to form methane. Producing methane keeps the hydrogen concentration in the rumen low, which allows methanogenic bacteria to promote the growth of other bacterial species and provides for a more efficient fermentation. The effective removal of hydrogen by these methanogenic species encourages hydrogen-producing species to produce more hydrogen and thus alter their metabolism towards higher yielding pathways. These higher yielding pathways result in the synthesis of more microbial cells, which increases available protein to the ruminant.

The protozoa in the rumen number about 10^5 to 10^6 cells/gram of rumen contents and are influenced by feeding practices. Higher numbers of protozoa are generally found in the rumen when diets of high digestibility are fed. Different types of diets seem to encourage different protozoal genera. Some protozoa numbers are higher when diets contain large amounts of soluble sugars and other types predominate with high starch diets.

The protozoa actively ingest bacteria as a source of protein. They also appear to be a stabilizing factor for fermentation end products. Protozoa, like bacteria and fungi, contribute to fiber digestion. While the protozoa are an integral part of the microbial population and have a marked effect on the fermentation, their benefit to the ruminant is still controversial.

The anaerobic fungi are the most recently recognized group of rumen microbes. When animals are fed a high forage diet, rumen fungi may contribute up to 8 percent of the microbial mass. While it is still unclear whether these fungi are functionally significant, they have been shown to degrade cellulose and xylans, indicating some role in fiber digestion.

Table 5. Grouping of rumen bacterial species according to the type of substrates fermented.

Major Cellulolytic Species
Bacteroides succinogenes
Ruminococcus flavefaciens
Ruminococcus albus
Butyrivibrio fibrisolvens

Major Pectinolytic Species
Butyrivibrio fibrisolvens
Bacteroides ruminicola
Lachnospira multiparus
Succinivibrio dextrinosolvens
Treponema bryantii
Streptococcus bovis

Major Ureolytic Species
Succinivibrio dextrinosolvens
Selenomonas sp.
Bacteroides ruminicola
Ruminococcus bromii
Butyrivibrio sp.
Treponema sp.

Major Sugar-utilizing Species
Treponema bryantii
Lactobacillus vitulinus
Lactobacillus ruminus

Major Proteolytic Species
Bacteroides amylophilus
Bacteroides ruminicola
Butyrivibrio fibrisolvens
Streptococcus bovis

Major Lipid-utilizing Species
Anaerovibrio lipolytica
Butyrivibrio fibrisolvens
Treponema bryantii
Eubacterium sp.
Fusocillus sp.
Micrococcus sp.

Major Hemicellulolytic Species
Butyrivibrio fibrisolvens
Bacteroides ruminicola
Ruminococcus sp.

Major Amylolytic Species
Bacteroides amylophilus
Streptococcus bovis
Succinimonas amylolytica
Bacteroides ruminicola

Major Methane-producing Species
Methanobrevibacter ruminantium
Methanobacterium formicicum
Methanomicrobium mobile

Major Acid-utilizing Species
Megasphaera elsdenii
Selenomonas ruminantium

Major Ammonia-producing Species
Bacteroides ruminicola
Megasphera elsdenii
Selenomonas ruminantium

Source: Church, D. C., ed. The Ruminant Animal: Digestive Physiology and Nutrition. Englewood Cliffs, N.J.: Prentice Hall, 1988.

There are three interconnecting environments in which the microbes are located in the rumen. The first is the *liquid phase*, where free-living microbial groups in the rumen fluid feed on soluble carbohydrates and protein. This portion makes up 25 percent of the microbial mass. Next is the *solid phase*, where the microbial groups associated with or attached to food particles digest insoluble polysaccharides, such as starch and fiber, as well as the less soluble proteins. This can make up as much as 70 percent of the microbial mass. In the last phase, 5 percent of the microbes attach to the rumen epithelium cells or to the protozoa.

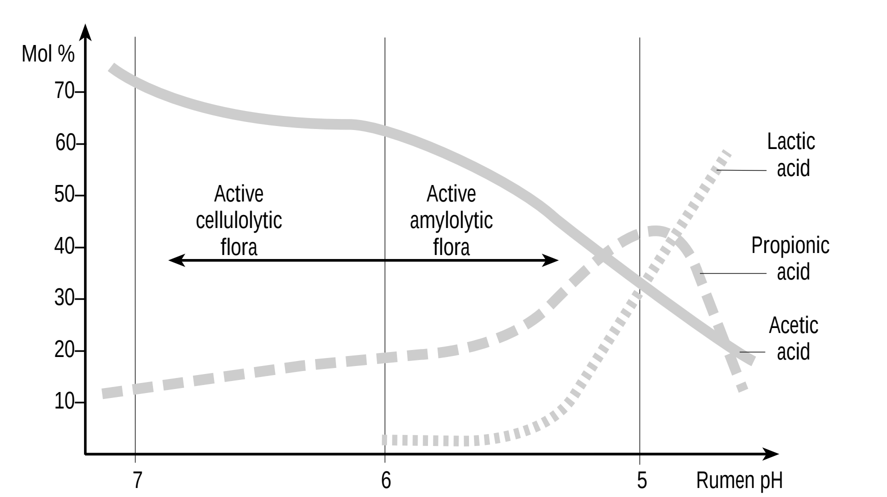
Microbial attachment in the rumen has numerous implications in the ruminant. In order for bacteria to maintain their numbers in the rumen, it is necessary that their reproduction time be shorter than the turnover rate of the rumen digesta. Since the passage rate of the particulate phase is much slower than that of the liquid phase in the rumen, slower-growing species attach to particle matter and are thereby prevented from being washed out of the rumen. The diet fed to the dairy cow influences the number and relative proportions of the different microbial species in the rumen.

Consideration of microbial reproduction rate is essential when making dietary changes in any ruminant. Major changes in the diet require a period of transition to allow for shifts in the populations of different microbial species. This adaptation may take several days. One of the most common problems encountered in nutrition management is sudden changes in the ruminant's diet to include large amounts of readily fermentable carbohydrates. Feeding diets of this type results in a succession of changes in the rumen microbial population during the adaptation period, specifically in those bacteria which produce and utilize lactate.

In this type of scenario, the acid-sensitive lactate utilizers are replaced by acid-tolerant lactate utilizers. Lactic acidosis arises from this abrupt shift to a high concentrate diet and keeps the effective lactate-utilizing species from increasing in sufficient numbers to prevent the accumulation of lactate. This results in decreasing the rumen pH to a very acidic level, less than 5.5.

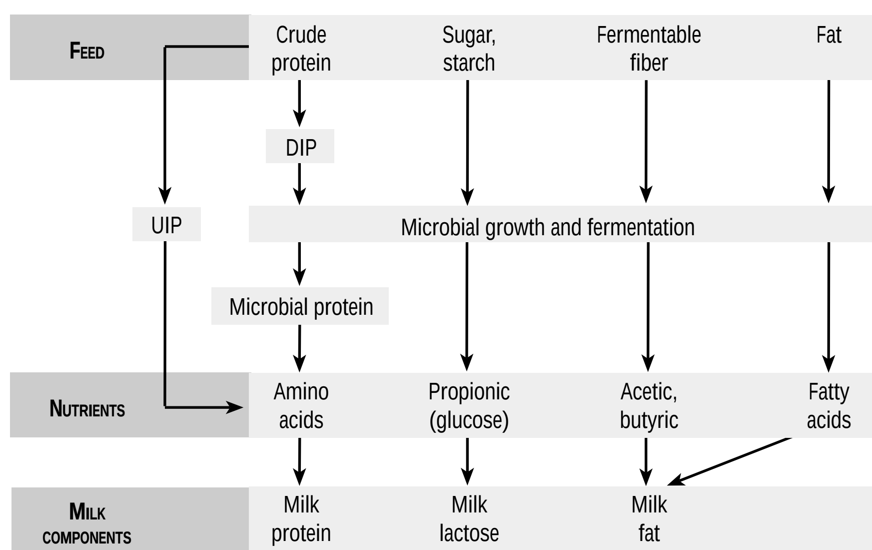
Rumen pH is one of the most variable factors which can influence the microbial population and the levels of volatile fatty acids produced (Figure 2). The rumen pH at which certain functions are optimized can differ. There are two basic groups of bacteria which function at various pH's. The fiber digesters are most active at a pH of 6.2 to 6.8. Cellulolytic bacteria and methanogenic bacteria can be reduced when the pH begins to fall below 6.0. The starch digesters prefer a more acidic environment, a pH of 5.2 to 6.0. Certain species of protozoa can be greatly depressed with a pH under 5.5. To accommodate all these needs, normal feeding practices should maintain a pH range between 5.8 to 6.4.

Figure 2. Ruminal fermentation as a consequence of adaptation due to pH regulation.



Kaufman, W., H. Hagemeister, and G. Durksen. Adaptation to changes in dietary composition level and frequency of feeding. In: Digestive Physiology and Metabolism in Ruminants, ed. Y. Ruckebusch and P. Thivend. Westport, Ct.: AVI Publishing, 1980, p. 587.

Figure 3. Feed, nutrient flow from the rumen, and milk components.



Source: Sniffen, C. J. and H. H. Herdt. The Veterinary Clinics of North America: Food Animal Practice, Vol 7, No 2. Philadelphia, Pa.: W. B. Saunders, 1991.

Note: UIP = undegradable intake protein; DIP = degradable intake protein.

Microbial digestion in the rumen

The rumen provides a site where the rumen microorganisms can digest carbohydrates, proteins, and fiber. Through this digestion process, energy or volatile fatty acids (VFA's) and microbial protein that can be utilized by the animal are produced (Figure 3).

Carbohydrates

When carbohydrates, both structural (neutral detergent fiber) and non-structural (sugars and starches), undergo microbial fermentation, they produce VFA's. The primary VFA's in descending order of abundance are acetic, propionic, butyric, isobutyric, valeric, isovaleric, and traces of various other acids. The VFA's can provide up to 80 percent of the energy needs of the animal.

Acetic acid can constitute 50 to 60 percent of the total VFA's. It predominates in a high forage diet. Acetate is used for fatty acid synthesis and is the main precursor for lipogenesis in adipose tissue. Some acetate is also used for muscle metabolism and body fat. Production of adequate levels of acetate in the rumen is essential to maintain adequate quantities of milk fat.

Acetic acid levels can drop if there is a lack of effective fiber in the ration. This can also occur when feeding a heavy concentrate diet or a diet high in heat-treated starch as in pelleting, steam crimping, or steam flaking. High intakes of oil can also depress acetic acid.

Propionic acid can make up 18 to 20 percent of the total VFA's. It reaches its highest concentration in a high grain diet. Propionic acid provides energy through conversion to blood glucose in the liver. It is also used in lactose or milk sugar synthesis.

Butyric acid provides energy to the rumen wall and makes up 12 to 18 percent of the total VFA's. It is largely converted to ketones during absorption through the rumen epithelium. B-hydroxybutric acid (B-HBA) accounts for more than 80 percent of the ketones. B-HBA is used for fatty acid synthesis in adipose and mammary gland tissues.

The proportion of VFA's are greatly influenced by diet and the status of the methanogenic population in the rumen. Despite wide swings in the microbial population and differences in feed intake, ruminal VFA proportions are fairly stable among diets with varying forage to concentrate ratios. However, the ruminal proportions of VFA's are largely pH dependent.

In general, as the forage to concentrate ratio decreases, the acetate to propionate ratio also decreases (Table 6). As cellulose and hemicellulose levels increase relative to soluble carbohydrate and starch levels, the acetate to propionate ratio also tends to increase. However, VFA production from a given substrate such as cellulose or starch varies with diet composition (Table 7). Although cellulose and hemicellulose are usually digested simultaneously in forages, the end-products produced may vary depending on diet.

The vast majority of VFA's are passively absorbed through the rumen wall. This continuous removal of VFA by absorption from the reticulo-rumen is important for maintaining a stable ruminal pH. Removal of acid products is also important for the continued growth of cellulolytic organisms. VFA's that remain in the digesta flow from the rumen to the lower tract and are absorbed by the omasum and abomasum.

Rate of VFA absorption from the rumen is influenced by the chain length of individual acids and ruminal pH. Increasing the chain length of the acid results in increased absorption rates in the following order: butyrate greater than propionate greater than acetate. Lower pH and the resultant increases in the proportion of the acids in the rumen favor more rapid absorption.

The net absorption of VFA's reaching the blood is dependent on the concentration in the rumen and the quantity used by the rumen wall. The rates of utilization by the rumen wall are for butyrate → propionate → acetate. As a result of the higher concentration in the rumen and the low rate of utilization by the rumen wall, acetate enters the blood in the greatest quantity, followed by propionate. Very little butyrate enters the blood due to the lesser amount in the rumen and greater amount metabolized by the rumen wall.

Lactic acid is important when starch is a part of the diet and is itself fermented to acetate, propionate, and butyrate. Lactate, when present, is absorbed directly through the rumen wall. Lactic acid does not accumulate to any large extent in dairy cattle that have been fed nutritionally sound rations that are managed properly. If gradual introduction of grains is practiced, the lactate-utilizing bacteria will develop and permit only a transient increase in lactic acid accumulation following ingestion of a diet high in readily fermentable carbohydrates. Problems arise when large amounts of starch or cereal concentrates are fed. Total lactate in severe cases may comprise 50 to 90 percent of the total rumen acids. The absorption of large amounts of lactic acid across the rumen wall to the blood produces systemic acidosis and results in animals going off feed, developing laminitis, and performing poorly overall.

Table 6. Effect of forage to concentrate ratio on the volatile fatty acid proportions in the lactating cow.

	Molar ratios, %		
Forage to concentrate ratio	Acetate	Propionate	Butyrate
100:00	71.4	16.0	7.9
75:25	68.2	18.1	8.0
50:50	65.3	18.4	10.4
40:60	59.8	25.9	10.2
20:80	53.6	30.6	10.7

Source: Physiology of Digestion and Metabolism in the Ruminant, ed. A.T. Phillipson. Newcastle-upon-Tyne, England: Oriel Press, 1970, p. 422.

Table 7. Estimated rumen fermentation characteristics.

		Proportion of carbohydrate converted to[b]		
Substrate	Diet[a]	Acetate	Propionate	Butyrate
Soluble carbohydrate[c]	F	0.69	0.20	0.10
	C	0.45	0.21	0.30
Starch	F	0.59	0.14	0.20
	C	0.40	0.30	0.20
Hemicellulose	F	0.57	0.18	0.21
	C	0.56	0.26	0.11
Cellulose	F	0.66	0.09	0.23
	C	0.79	0.06	0.06

Source: Murphy, M. R., R. L. Baldwin, and L. J. Koong. 1982. Estimation of stoichiometric parameters for rumen fermentation of roughage and concentrate diets. J. Animal Sci. 55:411-421.

[a] F codes forage diets; C codes diets containing more than 50 percent of a cereal-based concentrate diet.

[b] Ratios do not add up to 100 because the isoacids are not taken into account.

[c] Soluble carbohydrate fraction includes organic acids and pectin in this analysis.

Note: The acetate to propionate ratio resulting from fermentation of hemicellulose in a high forage diet was 3.2, but only 2.2 when fermented in a high grain diet. The acetate to propionate ratio from cellulose fermentation also varied with diet, 13.1 for a forage diet and 7.3 for a grain diet, both being much higher than that produced by hemicellulose.

Protein

Another critical function of the rumen microbes is synthesis of microbial protein. The biological value of microbial protein is 66 to 87 percent. Dietary protein may be improved or reduced in biological value by rumen microbes, depending on the quality of protein fed.

Most ruminal bacteria can use ammonia nitrogen as a source of nitrogen. Some species of bacteria require additional nitrogen compounds such as intact protein or carbon chains of certain amino acids for most efficient or rapid growth.

Ammonia is derived in the rumen through microbial degradation of dietary protein and dietary nonprotein nitrogen, from hydrolysis of recycled urea to the rumen, and from degradation of microbial crude protein. Rumen ammonia disappears from the rumen in different ways, such as incorporation of the nitrogen by the microbes, absorption through the rumen wall, and flushing to the omasum.

Ammonia not taken up by the microbes is absorbed directly through the rumen wall. The rate of absorption is dependent on the pH of the rumen environment and the concentration of ammonia. Absorption is rapid at a pH of 6.5 or higher. It declines to nearly zero at a pH of 4.5. Ammonia absorption increases as ruminal concentration increases. Indications of ammonia toxicity include ruminal ammonia concentration above 100 mg/dl, ruminal pH above 8, and blood plasma ammonia concentrations above 2 mg/dl.

Substitution of dietary nonprotein nitrogen, such as urea, for protein from plant and animal sources can reduce costs of protein supplementation. Urea is degraded by the microbes into ammonia, which can be used for microbial synthesis resulting in microbial protein. The microbes can also utilize nonprotein nitrogen in ensiled feeds and other feedstuffs. During the ensiling process, ammonia, amines, amides, and nitrates result from the degradation of protein and can be used as nitrogen sources by the rumen microbes.

The ruminant animal relies upon microbial crude protein synthesized in the rumen and dietary protein which escapes digestion in the rumen for its supply of amino acids. Microbial protein is very high in quality, rivaling animal protein and exceeding most vegetable proteins in essential amino acid content. However, the rumen microbes cannot produce all the essential amino acids required for animal growth and high levels of milk production.

The amino acids are absorbed and utilized in the small intestine. Most amino acids are used in the synthesis of body proteins, such as muscle and milk proteins. Some amino acids, especially those from protein reserves in the body tissue, may be used to maintain blood glucose levels and meet energy needs.

Lipids

Rumen microbes rapidly and extensively modify dietary lipids. Hydrolysis in the rumen proceeds rapidly after ingestion. The microbial metabolism of galactolipids (found in plant leaves) and triglycerides (found in seeds) starts with their hydrolysis. The glycerol and galactose portions are readily fermented to VFA's. Liberated fatty acids are neutralized at rumen pH and adhere to the surfaces of bacteria and feed particles. The rumen microbes cannot use fatty acids as an energy source, and their use is restricted to cell incorporation and synthetic purposes. Following the breakdown of lipids, the microbes are responsible for biohydrogenation, or the addition of hydrogen to fatty acids with double bonds. An example would be the microbial hydrogenation of oleic acid to stearic acid.

Vitamins

The rumen also functions in synthesizing B-complex vitamins and vitamin K. This makes the dairy cow less dependent on dietary sources. If cobalt intake is adequate, then vitamin B_{12} is generally not lacking. Additional supplementation of niacin or vitamin B_{12} may show a production response, though sometimes only in high-producing cows under stress.

Basic nutritional concepts behind feeding dairy cattle

Ruminants are excellent recyclers. They consume fibrous feeds and waste by-products that are not suitable for consumption by humans and single-stomached animals and convert them into nutritious feeds like meat and milk. Table 8 lists feed sources that are utilized by the ruminant.

Table 8. Feed ingredient sources that are utilized by ruminants.

Forage crops	Crop wastes	Food-processing wastes	Fiber-processing wastes	Protein substitutes	Animal wastes
Legumes	Straw	Corn factory	Wood fines	Urea	Blood meal
Grasses	Cornstalks	Apple pomace	Paper	Anhydrous-ammonia	Meat meal
Corn silage	Pea vines	Beet pulp	Cardboard		Bone meal
Small grain	Bean vines	Brewers grain	Cottonseed hulls		Feather meal
Sorghum-sudan		Distillers grain			Fish meal
		Soyhulls			
		Oil meals			
		Bakery waste			
		Mill by-products			

Land that is not suitable for growing food crops for human consumption can be utilized to grow forage for ruminants. Perennial and annual forages, such as alfalfa and corn silage, are low-cost and land-effective sources of nutrients.

In order for the ruminant to utilize these various sources of feedstuffs, certain basic rules for nutrition must be followed to ensure optimum performance. The main concepts are related to feed particle size, the structural and nonstructural carbohydrate fractions, and the protein fractions supplied from the various feeds.

Adequate effective fiber is necessary for proper rumen function. Rations fed with insufficient forage particle length result in cows spending less time chewing, which decreases the volume of saliva produced and leads to inadequate buffering and lower rumen pH.

When rumen pH falls below 6.0, the growth of the cellulolytic organisms can be reduced, allowing for an increase in the propionate-producing microbes. This can cause a decrease in the acetate to propionate ratio and potentially result in a lower milk fat percentage.

Particle size is important, especially for forage utilization and maintenance of a good fiber mat in the rumen. A fiber mat is essential to assure adequate growth and microbe activity and results in an increase of VFA's, especially acetate, and microbial protein yield. Table 9 illustrates the influence particle size can have on rumen function and production parameters.

Table 9. Eating, rumination behavior, rumen pH, volatile fatty acids (VFA's), average milk yield, and milk composition as influenced by particle size of the ration.

	Ration		
Item	Fine	Medium	Coarse
Eating, min./24 hr	195.3	204.4	204.7
Ruminating, min./24 hr	374.4[a]	466.3[b]	530.7[c]
Total chewing time, min./24 hr	569.7[a]	670.7[b]	735.4[c]
pH	5.3[a]	5.9[b]	6.0[b]
VFA, molar %			
Acetic	58.33[c]	61.24[d]	61.82[d]
Propionic	22.34[c]	20.16[c, d]	19.46[d]
Actual milk, lb/day	69.3	70.6	68.4
4% FCM, lb/day	60.5[a]	66.6[b, c]	64.9[a, c]
Milk fat, %	3.0[a]	3.6[b, c]	3.8[c]
Milk protein, %	3.0	3.0	3.1

Source: Grant et al. 1990. Milk fat depression in dairy cows: Role of silage particle size. J. Dairy Sci. 73:183442.

Note: Rations formulated on 55:45 silage to concentrate basis consisting of alfalfa silage, high moisture corn, and a mineral vitamin supplement. A field chopper with knives adjusted to a 3/16-inch theoretical cut length and fitted with a 3-inch recutter screen chopped the fine silage. A 3/8-inch theoretical cut length yielded coarsely chopped silage. A 1:1 mixture (dry weight) of the two silages provided the intermediate particle length in the medium ration.

[a, b, c, d] Means within rows with unlike superscripts differ significantly.

Feeding a ration with reduced forage particle size will increase dry matter intake, decrease digestibility, and result in lower rumen solid retention time. Rations that have a smaller initial forage particle size will enter the rumen at an even smaller size after initial chewing and swallowing, and therefore leave the rumen at a faster rate. The result is an increase in the rumen turnover rate allowing for an increase in dry matter intake, but because the rate of passage is faster, less time is available for microbes to digest the feeds.

In addition to the forage particle length, the fiber content in the diet is important. Fiber is necessary to provide adequate amounts of complex carbohydrates to slow digestibility and control the acidity in the rumen. Acid detergent fiber and neutral detergent fiber (ADF, NDF) are the main fiber fractions that are used in ration formulation. For high-producing, early lactation animals, recommendations are 18 to 20 percent of ADF and 28 to 30 percent of NDF in the total ration dry matter. The level of forage NDF and the forage particle length in the diet play an important role in determining effective fiber in the diet. However, not all fiber is of equal value in the ration. See Carbohydrates (p. **13**) for more in-depth information on forage NDF and on the nonstructural carbohydrates.

The digestibility of the fiber will vary depending on the source. For example, fiber in some by-product ingredients may be more digestible and more quickly digested than forage with the same fiber content. Fiber in low-quality forage may not be adequately digested. However, forages that are too immature may be lacking adequate fiber and may be digested too rapidly.

The manner in which grains are prepared can have a substantial effect on both the rumen environment and the cow. The particle size of the grains, such as fine ground, coarse, rolled, or steam flaked, can affect the digestibility of the grain and the total ration. The finer the grind of a cereal grain, the more exposed the endosperm of the grain, which allows for easier attack by rumen microbes. The type of heat processing influences availability of the starch (Table 10). This is associated with the gelatinization and rupture of the starch granules as seen, for example, in steam flaking. The method of grain processing, the amount of concentrate fed, and the level of nonstructural carbohydrates (NSC) in the total ration dry matter have a tremendous influence on animal performance.

There needs to be a balance between the cell wall (NDF) and the cell contents (NSC) to maximize production as well as maintain the health of the animal. Effective fiber is needed in the diet to provide a fiber mat and to slow down the availability of the carbohydrates to avoid low rumen pH. The NSC or sugars and starches are necessary to provide readily available energy for the rumen microbes and the animal. Balancing rations too far in one direction or the other can be detrimental to the dairy cow.

The main objective in balancing NDF and NSC is to control rumen pH. The optimum range in pH is 5.8 to 6.4 for synthesis of microbial protein and B-complex vitamins. This pH range may be somewhat higher or lower for short periods of time throughout the day, especially in conventional feeding systems. Ruminal pH normally fluctuates less when cows are fed a total mixed ration.

There are various ways to control the pH, such as providing adequate effective fiber and providing a balance of protein nitrogen, concentrate, fiber, and minerals in the rumen. Much of the final outcome of daily rumen pH level and fluctuation is determined by the feeding system and feeding management practice. In conventional feeding systems (those where grain and forage are fed separately), implementing a feeding strategy is essential to eliminate the peaks and valleys in rumen pH. Some common recommendations are feeding hay prior to concentrates, feeding high protein forages and concentrates close to feeding of high energy feeds, and feeding concentrates more than twice daily.

Table 10. Differences in extent of ruminal digestion of starches as affected by source and processing.

Processing	Percentage digestion in the rumen				
	Oats	Wheat	Barley	Corn	Milo
Ensiled, high moisture (fine grind)	99	99	98	85	—
Steam flaked (thin flake)	99	98	97	86	84
Ensiled, high moisture (coarse rolled)	—	—	—	82	80
Dry, fine grind	94	93	91	78	72
Dry, medium grind	89	88	87	74	68
Dry, coarse grind	79	78	77	65	61
Dry, whole	—	—	—	60	—

Source: H. H. Van Horn and C. J. Wilcox, ed. 1992. Nonstructural and structural carbohydrates. In: Large Dairy Herd Management. Management Services, American Dairy Science Association, Champaign, Ill., p 222.

Buffers can aid in controlling rumen pH. Sodium bicarbonate is the mostly widely used dietary buffer. Rations which benefit the most from buffers are rations containing a large percentage of corn silage and/or high moisture corn, and low fiber forages.

In addition to a good balance between the carbohydrate fractions, there needs to be a balance between rumen degradable and rumen bypass protein to meet the amino acid needs of high-producing cows. Bypass or undegradable intake protein (UIP) should range from 35 to 40 percent for early lactation and high milk production (over 80 pounds of milk per day). Paying close attention to the amino acid profile of bypass sources of protein will help supply the essential amino acids in the diet. However, balancing for UIP alone is not recommended. Adequate degradable protein is necessary so there are sufficient ammonia levels in the rumen to meet the nitrogen needs of the microbes.

In order for the ruminant to function properly, the nutritionist must know what substrates the rumen microbes are sensitive to so they can be avoided when formulating rations. The rumen microbes are sensitive to both excessive and deficient levels of protein, ammonia, urea, and the type and level of fat in the ration. Mineral levels, especially calcium, phosphorus, sulfur, magnesium, copper, zinc, and cobalt, can cause problems when either too high or too low.

Abnormally fermented material may alter the VFA's and lactic acid in the rumen. This is more apt to occur if pH or moisture contents of the material are out of the optimum range. Using feed spoiled by mold, putrefaction, and mycotoxins may decrease production and may increase the incidence of displaced abomasum.

Water can have an effect on the rumen microorganisms especially when there is heavy bacterial or metal contamination or high mineral concentrations such as chloride. Water that is extremely acidic or alkaline can also create problems. It may be necessary to send water samples out for analysis to check for abnormalities, especially when rations on paper appear balanced but cows are not responding accordingly.

Dry matter intake and its effect on the cow

The main objective in feeding management is to increase the dry matter intake of the cows. With this increase should come higher levels of milk production. In order for this to happen, close attention to energy, ration digestibility, rumen fill, palatability, temperature, body weight of the animal, feeding conditions, environment, ventilation, frequency of feeding, and water intake and quality are necessary. Establishing optimal standards in each category should result in optimal dry matter intake.

Most lactating cows will eat to satisfy energy needs if presented with a sound and balanced ration. Yet cows producing over 85 pounds of milk often cannot eat enough to meet their energy needs. They may utilize body energy reserves, mostly fat, to make up at least part of any energy deficiency. One pound of body fat may be utilized to effectively produce 7 to 9 pounds of milk, depending on the fat test.

High-producing cows should be in good body condition before they go dry. Table 11 gives the recommended range for body condition scores for the different stages of lactation. Each score change represents 120 to 150 pounds of body weight gain or loss. Obesity should be avoided because cows will be more susceptible to going off feed, ketosis, calving difficulties, and more infections such as mastitis. Low-producing and late-lactation animals will sometimes consume more feed than is necessary to meet energy needs; thus body condition should be monitored closely with these animals. Dry cows may consume double their needs if allowed to eat free choice.

Table 11. Target scores for stages of lactation using the 5-point body condition scale.

Stage of lactation	Target body condition score
Cows at calving	3+ to 4-
Early lactation	3- to 3
Mid-lactation	3
Late lactation	3 to 3+
Dry	3+ to 4-

Source: Body-condition Scoring as a Tool for Dairy Herd Management. Penn State Extension Circular 363.

When ration digestibility is too low, animals usually cannot eat enough to meet their nutrient needs. If the energy density in the diet is less than .66 Mcal NEL, then it may be impossible for high-producing cows to meet their energy requirements.

Some rations that are relatively high in digestibility may be consumed at lower levels since energy needs may be met with less intake. High-quality rations for high-producing dairy cattle should contain around .74 Mcal NEL. Rations containing too much concentrate and not enough forage and effective fiber may actually depress intakes, milk production, and fat test and may adversely affect health. Ration digestibility may also be depressed by an improper balance of nutrients. Low-quality forage is a more frequent cause of lowered intakes and performance than the lack of energy in the concentrate portion of the ration. Improper forage and grain preparation may depress digestibility, performance, and sometimes total ration dry matter intake.

When feeding rations with low digestibility, rumen fill is quickly achieved. These rations are digested slowly and, to a lesser extent, pass out of the rumen at a slower rate. When rumen fill occurs, a signal is sent to the brain stem to stop intake as part of the overall process of intake regulation.

The use of sodium bicarbonate or sesquicarbonate at .80 percent in the total ration dry matter can increase digestibility by raising the rumen pH. This can result in higher dry matter intakes. An increase in milk production and/or fat test may be noted when these additives are fed.

Palatability is also a concern, especially in conventional feeding systems. Certain feedstuffs and additives may depress intakes of concentrates when fed conventionally compared to a total mixed ration (TMR). For example, animal protein blends may have to be limited in the grain mix used on a conventional ration compared to higher levels that can be fed in a TMR. Some species and varieties of forage are less palatable than others and may have to be restricted.

Both feeding conditions and environmental climate can limit intake. When the climate exceeds 65°F and 65 percent humidity, dry matter intake and often milk production and fat test may decrease. A substantial decrease in total ration dry matter may occur at over 80°F and 80 percent humidity. Thus there is a seasonal effect on dry matter intake with higher consumption usually occurring during cool weather and depressed intakes occurring during hot, humid weather. Forage quality and the energy content of the concentrates as well as the density levels of protein, minerals, and effective fiber generally need to be increased during the summer months. Poorly ventilated feeding or housing areas can increase heat and humidity and allow strong odors, such as ammonia, to become concentrated, which can cause a decline in consumption because animals spend less time in those areas.

Dry matter intake can be depressed when heating, putrefaction, and mold occur in ensiled feeds or TMR's. This can be minimized by not removing ensiled feeds from the silo much in advance of feeding. Ensiled feeds that have undergone abnormal fermentation may depress intakes. The presence of certain toxins, such as mycotoxins, alkaloids, and tannin, can cause problems. In order to minimize their effects on low performance, feed more often throughout the day, especially during the summer, to keep feed fresh and from heating. Avoid using problem feeds for milk cows, especially early lactation or high-producing cows.

Increasing feeding frequency may not be necessary when feeding a balanced ration that is managed properly. However, feeding more frequently than one to three times daily may be necessary in many situations to attain expected total ration dry matter intakes, feed utilization, and production.

Water consumption and quality are often overlooked as important factors affecting dry matter intake. In order for animals to receive a plentiful and clean supply of water, watering devices should be functioning properly to allow adequate intake. The chemical and bacterial quality should be checked occasionally for possible contaminants.

A balanced ration will allow for proper digestibility, good dry matter intakes, and satisfactory feed utilization. A ration should be developed with profitable levels of milk production in mind. In addition to balancing for the many nutrients, do not overlook the physical aspects of the ration, such as minimum forage required, maximum levels of concentrate to feed, effective fiber, and palatability.

PART II: FEED AND FEED NUTRIENTS FOR DAIRY CATTLE

Many different feeds or combinations of feeds can be successfully used in rations for dairy cattle. Feed ingredients supply sources of nutrients, fiber, and particle size necessary for normal digestion, metabolism, and performance. Because feeds vary in cost and nutrient content, good judgment must be used in the selection process. The type, source, and level of forages, roughages, concentrates, minerals, vitamins, and other additives in the diet must be considered when trying to meet the cow's nutrient requirements.

Forages are perennial and annual crops grown for use as pasture, green chop, haylage, silage, or hay that have been harvested at the proper length. They contain significant levels of protein, fiber, energy, and vitamins A and E. If the crops have been sun-cured, the feed may also contain significant levels of vitamin D.

Roughages are crops or processing wastes of adequate particle size that are high in fiber, relatively low in energy content, and devoid of fat soluble vitamins A, D, and E. Cereal straw, cornstalks, cottonseed hulls, corn cobs, or apple pomace with hulls are common roughages.

Concentrates are cereal grains and by-product feedstuffs containing relatively high levels of energy. Generally, concentrates are finer in particle size than properly harvested forages. Table 12 shows the classification of commonly used feed ingredients.

A dairy cow's diet is usually composed of various feed ingredients which can help meet her nutrient requirements. However, no one nutrient is more important than another, and an excess or deficiency of one or more nutrients can limit performance. Knowing what nutrients feed ingredients supply to a ration will help optimize feed utilization. The main nutrient categories of importance in dairy cattle rations are carbohydrates, fats, proteins, minerals, vitamins, and water. While fiber is not a nutrient by strict definition, it plays a critical role in digestion and must be considered when formulating rations.

Carbohydrates

Carbohydrates are the primary energy source for the ruminant and can be divided into two main fractions, structural and nonstructural. The structural portion of the plant is the cell wall material and is analytically defined as neutral detergent fiber (NDF). NDF consists of cellulose, hemicellulose, lignin, and a portion of the pectin. Forage intakes can be set using NDF when formulating dairy rations.

Acid detergent fiber (ADF) is another fiber value reported which contains only cellulose and lignin. Ruminants are unable to digest lignin; thus the higher the lignin content of a feed, the lower its digestibility. These complex carbohydrates are more slowly digested and often less completely digested than the nonstructural carbohydrates.

The simple or nonstructural carbohydrates (NSC) consist of the cell contents, including sugars, starches, pectins, short chains of cellulose-like substances (β-glucans), and in ensiled products, the fermentation acids. NSC is not a chemically achieved value but rather is estimated as [100 - (CP + NDF + ether extract + ash)]. This type of

Table 12. Classification of concentrate ingredients.

CP[a] > 40%	UIP[a] > 45% of CP	SP[a] > 30% of CP
Corn gluten meal	Blood meal	Corn gluten feed
Urea	Corn gluten meal	Whole cottonseed
Raw soybeans	Fish meal	Wheat midds
Canola meal	Animal protein blends	Raw soybeans
Cottonseed meal	Brewers grains (wet and dry)	Urea
Heat-treated soybeans	Distillers grains	
Soybean meal (44% or 48%)	Heat-treated soybeans	
NSC[a] >55%	**Fat >18%**	**NDF[a] >35%**
Bakery product (i.e., bread)	Chocolate	Beet pulp
Barley	Bakery waste products	Corn gluten feed
Milo	Raw soybeans	Distillers grain
Rye	Whole cottonseed	Wheat midds
Corn	Candy waste products	Brewers grain (wet and dry)
Hominy	Tallow	Whole cottonseed
Oats	Heat-treated soybeans	Soyhulls
Wheat		

Source: Concentrates for Dairy Cattle. Penn State Dairy and Animal Science Extension Fact Sheet 94-06.

[a] CP = crude protein; UIP = undegradable intake protein; SP = soluble protein; NSC = nonstructural carbohydrates; NDF = neutral detergent fiber. All values are listed on a dry matter basis.

carbohydrate is highly digestible when compared to NDF. Even though pectins and β-glucans are part of the cell wall, they are included in the NSC fraction because they are rapidly fermented and easily digestible (Table 13).

The amount of structural and nonstructural carbohydrates in a ration can have a profound effect on production and health if not properly balanced in a ration. The partitioning of the carbohydrate fractions between plant species, especially legumes and grasses, is different and can affect the extent and rate of digestion.

Comparing legumes and grasses of similar maturities, legumes are generally higher in lignin and lower in NDF. Grasses tend to be higher in hemicellulose and NDF. The range for cellulose is fairly similar between the two types of forage (Table 14).

Since legumes tend to have a higher lignin content compared to grasses, less NDF is available for digestion. Legumes have a faster rate of digestion than grasses, and therefore intakes are higher with legume forages. The rate of digestion is slower for grasses because they remain in the rumen longer. Consequently, the total amount of digestion is greater for grasses. Forage dry matter intake of predominantly grass forages can be restricted while still maintaining adequate forage NDF intake (Table 15). These differences between legumes and grasses can influence how rations are formulated for forage NDF and forage dry matter intake.

The NSC fractions of forages can also influence digestion. Pectins are found in legumes but are negligible in grasses. Pectins can ferment in the rumen as rapidly as starch, but they form acetate rather than propionate. β-glucans, which are a major component of grasses, ferment more slowly.

The NDF found in most concentrate ingredients is less effective due to finer particle size, greater density, higher digestibility, and quicker passage from the rumen than forage NDF. Most concentrates are too fine in particle size to provide a sufficient rumen mat, maintain normal rumen epithelial tissue, and stimulate sufficient chewing and eructation of gases. For these reasons, it is generally recommended that most of the NDF in the diet be in the form of forage NDF.

Table 13. Carbohydrate fractions for some common forages and feed ingredients.

		% of nonstructural carbohydrates			
Ingredient	% DM basis NSC	Sugar	Starch	Pectins β-glucans	VFA
Alfalfa haylage	23.0	0.0	40.9	33.0	26.1
Grass hay	17.2	35.4	15.2	49.4	0.0
Corn silage	45.3	0.0	71.3	0.0	28.7
Barley	61.8	9.1	81.7	9.2	0.0
Corn	71.4	20.0	80.0	0.0	0.0
Hominy	59.9	8.9	80.4	10.7	0.0
Oats	42.4	4.4	95.6	0.0	0.0
Wheat	73.8	8.9	80.2	10.9	0.0
HMEC	70.8	0.0	94.8	0.0	5.2
HMSC	75.9	0.0	97.2	0.0	2.8
Canola	25.8	11.4	45.6	43.0	0.0
Distillers	10.3	0.0	100.0	0.0	0.0
Corn gluten feed	24.7	3.7	71.2	25.1	0.0
Corn gluten meal	17.3	0.0	69.4	30.6	0.0
Soyhulls	14.1	18.8	18.8	62.4	0.0
Soybean meal, 44%	34.4	25.0	25.0	50.0	0.0
Wheat midds	31.2	10.0	90.0	0.0	0.0

Source: Adapted from T. Miller, J. Grimmett, and W. Hoover, West Virginia University, 1993.

The NSC fractions of cereal grains usually contain over 80 percent starch. Most by-product feeds contain a larger portion of the NSC fractions as starch with the remainder as sugars and pectins. In concentrate ingredients, the availability and rate of digestion of the starch depend on the grain source and processing method.

A good balance between the carbohydrate fractions is necessary to maintain normal rumen function and metabolism (Table 16). Extremes in either direction can adversely affect animal performance and health. For example, if forages are chopped too fine, then the effectiveness of fiber present in furnishing a mat for microbial function and stimulating good rumen motility is reduced. Low digestibility of the forage also may reduce the effectiveness of the fiber present. In order to keep the rumen functioning normally, minimum forage levels and proper particle size length of ensiled forages must be ensured.

Low fiber, both ADF and NDF, in the ration can result from lack of forage and/or extremely high-quality forage (mainly early spring or late fall cuttings). Lack of fiber can lower milk fat test and production and cause metabolic problems, such as rumen acidosis and infectious diseases. These problems can be controlled by following sound guidelines for forage harvesting, forage particle size length, and forage NDF intake, and forage dry matter intake.

A proper intake of NSC is necessary to provide sufficient propionic acid production to help meet the animal's energy needs, allow for adequate

Table 14. Fiber partition in various forages.

FORAGE	% DM	% DM BASIS ADF	NDF	HEMICELLULOSE	CELLULOSE	LIGNIN
Legume haylage	56[a]	34	44	10	27	7.4
	51-62	30-38	36-51	5-14	23-30	5.7-9.0
Legume silage	37	39	47	8.9	31	7.7
	30-43	33-44	40-55	4.1-13.6	22-34	5.3-10.0
MM legume[b] haylage	55	37	48	11.5	29	7.8
	51-60	31-42	40-56	5.7-17.3	25-33	4.3-11.4
MM legume[b] silage	35	39	52	13.4	32	6.8
	27-42	35-42	45-59	7.8-18.9	29-35	5.4-8.3
MM grass[b] haylage	59	38	54	15.7	31	7.7
	52-65	34-43	46-62	10.8-21	27-34	5.5-9.9
MM grass[b] silage	36	39	56	17.0	33	6.9
	28-45	35-44	50-63	12-22	29-36	4.7-9.0
Grass silage	31	41	62	21	24	6.4
	21-41	37-44	55-68	15-27	31-37	4.9-7.8
Corn silage	33	26	45	19	23	2.8
	25-40	22-30	38-51	15-23	19-27	2.2-3.5

Note: Samples from NEDHIC Forage Testing Lab, Ithaca, N.Y. Analysis performed by J. B. Robertson, Department of Animal Science, Cornell University.

[a] Mean one standard deviation (range indicated by darker shading represents 67% of samples received) will fall within these values.

[b] MM legume refers to mixed mainly legume forage; MM grass refers to mixed mainly grass forage.

Table 15. Guidelines for forage neutral detergent fiber (NDF) and forage dry matter intakes.

FORAGE NDF AS % OF BODY WEIGHT[a]	INTAKE LEVEL
.75%[b]	Minimum if ration provides 1.3-1.4% total NDF by use of by-product feeds.
.85%[b]	Minimum if ration provides 1.0-1.2% total NDF by use of grains or starch feeds.
.90%	Moderately low
.95%	Average
1.00%	Moderately high
1.10%	Maximum

Source: Using Neutral Detergent Fiber to Set Forage Intakes for Dairy Cows. Penn State Dairy and Animal Science Extension Fact Sheet 93-2.

[a] Forage dry matter intake should range between 1.4 to 2.4 percent of body weight regardless of forage NDF intake parameters.

[b] Higher minimum may be necessary if forage is chopped too fine.

Example of intake parameters between grass and legume forage:
Average body weight: 1300 lb; desired forage NDF as % BW: 0.90%
Legume hay @ 48% NDF; grass hay @ 62% NDF; 1300 X .009 = 11.7 lb forage NDF
Intake of legume forage: 11.7 ÷ .48 = 24.3 lb ÷ 1300 x 100 = 1.9% BW forage dry matter intake
Intake of grass forage: 11.7 ÷ .62 = 18.8 lb ÷ 1300 x 100 = 1.45% BW forage dry matter intake

Table 16. Guide to carbohydrate composition in rations for high-producing dairy cows.

ITEM	STAGE OF LACTATION EARLY	MID	LATE
Forage NDF, % DM	21-24	25-26	27-28
Total NDF, % DM	28-32	33-35	36-38
NSC, % DM	32-38	32-38	32-38

Source: Use of Total Mixed Rations (TMR) for Dairy Cows. Penn State Dairy and Animal Science Extension Fact Sheet 94-25.

microbial protein synthesis, and maintain normal fiber digestion as well as other rumen functions.

Inadequate NSC may depress the energy available from propionic and lactic acid production, reduce microbial protein synthesis, and decrease fiber digestion. Excessive NSC may depress fiber digestibility, acetic acid production, and milk fat test, as well as cause abnormalities in rumen tissue, which may lead to ulcers and liver abscesses.

Fats

Fat or ether extract can be used as an energy source for the high-producing dairy cow. Fat is approximately 2.25 times more energy rich than protein or carbohydrates on a pound for pound basis. Yet rumen microorganisms cannot tolerate high levels of fat. The types and levels of fats used in dairy cattle rations should be scrutinized closely both nutritionally and economically.

The main lipid component of forages is galactolipid, which involves glycerol, galactose, and unsaturated fatty acids (primarily linoleic and linolenic acid). Their concentration declines with the age of the plant and will vary with the proportion of leaves to stems.

The main storage lipids found in both plant seeds and animal fats are triglycerides (three fatty acids attached to glycerol). Some of the specialty products labeled as rumen inert are comprised of either triglycerides, free-fatty acids, or calcium salts of fatty acids. The fatty acid profile of vegetable, animal, and specialty fats is an important characteristic because of how it relates to ruminal inertness and postruminal digestibility (Table 17).

Fatty acids can be either saturated or unsaturated. Common saturated fatty acids (myristic, palmitic, and stearic) are solid at room temperature and melt at above body temperature. Unsaturated fatty acids (palmitoleic, oleic, linoleic, and linolenic) vary in melting point but tend to be liquid at room temperature. Unsaturated fats are more likely to interfere with ruminal fermentation than saturated fatty acids.

The fatty acids in whole cottonseed and full-fat soybeans contain large amounts of unsaturated fatty acids. However, whole oilseeds are less likely to interfere with ruminal fermentation compared to free oils. Whole oilseeds are slowly digested, allowing for a slow release of the oil in the rumen and more extensive microbial hydrogenation.

Tallow is the most commonly fed animal fat. It is comprised of about 50 percent saturated fatty acids. Saturated fats are believed to be relatively inert in the rumen because of their high melting point and low solubility in rumen fluid. However, 40 percent of the fatty acids in tallow are oleic acid, which may impair rumen fermentation when added in large quantities.

Fatty acids in grease and animal-vegetable blends are highly unsaturated. Their fatty acid profiles can be quite variable, and therefore they are not generally recommended for lactating cow diets.

Specialty fats that completely bypass the rumen are highly saturated. Many of these products consist of tallow or hydrogenated tallow. Others have the fatty acids complexed with calcium, which is relatively insoluble in rumen fluid.

To meet the essential fatty acid needs of the dairy cow, relatively low intakes of fat are needed. In most cases, 2 to 3 percent fat in the basal diet is adequate. A recommended limit for cows producing between 70 and 90 pounds of 4 percent fat-corrected milk is an additional 1.0 to 1.5 pounds of added fat from unprotected sources, such as animal fats, oilseeds, or a combination of the two, can be fed. This should result in an additional 2 to 3 percent fat in the ration totaling 5 percent. Cows producing over 90 pounds of 4 percent fat-corrected milk can be fed an additional .50 to 1.0 pound of protected fat. This would increase the total dietary fat to 6 to 7 percent of the total ration dry matter.

When supplemental fat is added to dairy rations, certain minerals must be adjusted. Modifications to the levels of calcium, phosphorus, and magnesium are needed. It may also be necessary to increase selenium and vitamin E. (See Minerals, p. 23, and Vitamins, p. 25.)

Table 17. Fatty acid profile of various commodity and specialty fat sources.

Fatty acid weight, %	Commodity fat sources: Whole cottonseed	Whole soybeans	Tallow	Yellow grease	Animal-vegetable blend
Myristic	1	—	3	3	1
Palmitic	25	11	26	18	22
Palmitoleic	—	—	6	4	5
Stearic	3	4	19	12	5
Oleic	17	24	40	47	36
Linoleic	54	54	5	13	29
Linolenic	—	7	1	3	2
Saturated, %[a]	29	15	48	33	28
Unsaturated, %[b]	71	85	52	67	72

Fatty acid weight, %	Specialty fat sources: Alifet	Booster fat	Carolac	Dairy 80	Energy booster	Megalac
Myristic	3	3	2	4	2	2
Palmitic	27	25	24	28	49	51
Palmitoleic	1	3	3	2	—	—
Stearic	37	22	35	55	35	4
Oleic	31	45	33	11	13	35
Linoleic	1	2	2	—	1	8
Linolenic	—	—	1	—	—	—
Saturated, %[a]	67	50	61	87	86	57
Unsaturated, %[b]	33	50	39	13	14	43

Sources: Palmquist, D. L. 1988. The feeding value of fats. In: Feed Science, ed. E.R. Orskov. Amsterdam: Elsevier Science, 1988, pp. 293-311.
Palmquist, D. L., A. Kelbly, and D. Kinsey. 1989. Digestibility by lactating dairy cows of diets containing two levels of several commercial fats. J. Dairy Sci. 72:572 (Suppl. 1).
DePeters, E. J., S. J. Taylor, C. M. Finley, and T.R. Famula. 1987. Dietary fat and nitrogen composition of milk from lactating cows. J. Dairy Sci. 70:1192.

[a] Saturated fatty acids (Myristic, Palmitic, Stearic).

[b] Unsaturated fatty acids (Palmitoleic, Oleic, Linoleic, Linolenic).

Protein

Ruminant protein nutrition is complicated and requires examining protein quality, protein fractions, and total protein. Certain levels of degradable, soluble, and undegradable intake protein must be present in the dairy cow's diet to meet the needs of rumen microbes as well as provide essential amino acids to the small intestine.

Developing rations to meet the cow's requirement for protein entails much more than balancing rations for total crude protein. The crude protein value reported for forages and feeds is a measure of their nitrogen content only; it does not indicate whether the nitrogen is contained as amino acid or true protein nitrogen or some nonprotein nitrogen source. It also does not tell how degradable or available the nitrogen in the feed is for rumen microbes to synthesize, how much of the amino acid nitrogen in the feed escapes degradation in the rumen, or the quality of this bypass protein. All these items need to be considered when formulating rations.

The three protein fractions most commonly used in ration formulations are degradable, undegradable, and soluble intake protein. The rumen microbes require an adequate supply of ruminally available nitrogen which comes from degradable sources of nitrogen in feeds, including both protein and nonprotein nitrogen sources. In addition, the rumen microbes benefit from a limited amount of the protein readily dissolving in the rumen. This is referred to as soluble intake protein. Protein that escapes or bypasses the rumen is referred to as undegradable intake protein.

When formulating rations, knowing how feed ingredients will contribute to the various protein fractions in a dairy cow's ration can be helpful for better meeting her protein requirements. Table 18 lists some of the crude protein fractions in various feedstuffs commonly fed to dairy cows.

Table 18. Crude protein and protein fractions in various forages and feed ingredients.

		% DM basis	% of crude protein	
Feedstuff	% DM	Crude protein	Soluble protein	Undegradable intake protein
Grass hay	90.0	10.5	29.0	37.0
MM grass hay[a]	90.0	12.5	30.0	34.0
Legume hay	90.0	18.6	32.0	28.0
MM legume hay[a]	90.0	16.8	31.0	31.0
Grass silage[b]	<35	12.6	51.0	23.0
	35-50		47.0	29.0
	>55		41.0	45.0
MM grass silage[a]	<35	14.0	52.5	22.0
	35-50		50.0	27.0
	>55		42.0	42.0
Legume silage	<35	19.3	60.0	18.0
	35-50		54.0	23.0
	>55		48.0	36.0
MM legume silage[a]	<35	17.4	57.0	20.0
	35-50		52.0	25.0
	>55		46.0	39.0
Corn silage	33.0	8.8	48.0	31.0
Corn silage-urea	34.0	13.2	70.0	19.0
Corn silage-NH_3	34.0	12.0	57.0	27.0
Blood meal	91.0	93.0	7.5	82.0
Brewers grain, dry	92.0	27.1	7.4	49.0
Brewers grain, wet	22.0	28.0	10.0	45.0
Canola meal	92.5	40.8	28.0	23.0
Corn, ear (dry)	87.0	9.0	15.6	65.6
Corn, ear (high moisture)	69.0	8.8	36.0	35.0
Corn, shell (dry)	88.0	10.0	12.0	52.0
Corn, shell (high moisture)	74.4	9.5	33.0	35.0
Corn gluten feed	90.0	23.0	52.0	25.0
Corn gluten meal	90.0	67.2	5.0	55.0
Corn distillers, dark	91.0	29.0	15.0	47.0
Corn distillers, light	92.0	29.0	15.0	54.0
Cottonseed, whole	88.4	23.7	27.1	41.0
Soybeans, raw	90.0	41.8	40.0	26.0
Soybeans, cooked	90.0	41.8	17.0	50.0
Soybean meal, 44%	90.0	50.0	20.0	35.0
Soybean meal, 48%	90.0	54.5	20.0	35.0
Wheat midds	89.0	18.0	40.0	21.0

Note: The expectancies on crude protein and protein fractions are provided for use when analyses are not available. If feasible, test concentrate ingredients as well as forages. These best-fit data have been developed from Northeast DHI forage testing summaries and compilations by the National Research Council (NRC) and from the feed industry.

[a] MM grass refers to mixed mainly grass forage. MM legume refers to mixed mainly legume forage.

[b] Use the grass data for small grain silage.

A more detailed description of the protein fractions can be determined using the detergent system for analyses of carbohydrates along with the partitioning of protein by borate buffer. These protein fractions are identified as fraction A (ammonia, nitrates, amino acids, and peptides), fraction B1 (globulins and some albumins), fraction B2 (mostly albumins and glutelins), fraction B3 (prolamins), and fraction C (Maillard products bound to lignin).

Fraction A protein degrades in the rumen instantaneously with none reaching the small intestine. Small amounts of fraction B1 reach the lower digestive track with intestinal digestibility being complete. The undegradable protein fractions consist of variable amounts of B2 (30 to 70 percent), most of B3, and fraction C. Fraction C bypasses the entire digestion system. Heat added or generated during the processing of some grains and by-products increases the bypass protein because globulins and albumins in the B1 fraction are denatured and are now in the B2 or B3 fraction. Table 19 lists the distribution of protein and nitrogen fractions in some commonly used feedstuffs. Although it is important to be aware of the detail involved with the various protein fractions, at present most feed analysis reports and ration formulation programs deal with target numbers related only to soluble, degradable, and undegradable intake protein.

Balancing rations on protein quality tends to be more complex compared to meeting the animal's requirement for total protein and protein fractions. Attention to both microbial protein production and the amino acid profile of feeds is needed.

Protein quality refers to the balance and amount of essential amino acids that a particular feed contains. There are approximately 23 different amino acids; each has a unique structure and all contain nitrogen. Approximately

Table 19. Average distribution of protein and nitrogen fractions in some feedstuffs.

	% DM basis	% of crude protein				
Feedstuff	Crude protein	A	B1	B2	B3	C
Concentrates:						
Blood meal	91.7	0.2	4.7	93.9	0.0	1.2
Brewers grain, dry	25.4	2.9	1.2	55.5	28.4	12.0
Canola	42.3	21.1	11.3	57.0	4.2	6.4
Corn grain	10.1	7.7	3.3	74.0[a]	10.0	5.0
Corn grain (high moisture)	10.1	40.0	0.0	44.1[a]	10.6	5.3
Corn, ear (dry)	9.0	11.2	4.8	66.2[a]	10.0	7.8
Corn, ear (high moisture)	9.0	30.0	0.0	51.3[a]	10.4	8.3
Corn distillers, dry	29.5	17.0	5.0	14.9[a]	43.1	20.0
Corn gluten feed	25.6	49.0	0.0	43.2[a]	5.7	2.1
Corn gluten meal	65.9	3.0	1.2	84.8[a]	9.0	2.0
Cottonseed, whole	23.0	0.8	39.2	54.0	0.0	6.0
Cottonseed meal	44.8	8.0	12.0	48.4	2.4	7.6
Fish meal	66.6	0.0	12.0	87.0	0.1	0.9
Soybean meal, 44%	49.9	11.0	9.0	75	3.0	2.0
Soybean meal, 48%	55.1	11.0	9.0	75	3.0	2.0
Soybeans, raw	42.8	10.0	34.2	51.4	1.5	2.9
Soybeans, heated	42.8	5.7	0.0	70.7	16.3	7.3
Wheat midds	18.4	12.0	28.0	56.0	1.4	2.6
Forages:						
Alfalfa hay, prebloom	21.7	28.8	1.2	55.0	5.0	10.0
Alfalfa hay, early bloom	19.0	28.8	1.2	52.2	7.8	10.0
Alfalfa hay, mid bloom	17.0	26.9	1.1	46.8	11.2	14.0
Grass hay, late vegetative	16.0	24.0	1.0	44.0	25.3	5.7
Grass hay, mid bloom	9.1	24.0	1.0	44.0	24.9	6.1
Grass hay, mature	7.0	24.0	1.0	44.0	24.5	6.5
Alfalfa silage, early bloom	19.0	50.0	0.0	23.3	11.7	15.0
Alfalfa silage, mid bloom	17.0	45.0	0.0	23.0	14.0	18.0
Corn silage, 45% grain	9.0	45.0	0.0	38.6	8.5	7.9
Corn silage, 34% grain	8.6	50.0	0.0	34.0	8.0	8.0
Corn silage, 25% grain	8.3	55.0	0.0	29.0	7.5	8.5

Source: Russell, J. B., J. D. O'Connor, D. G. Fox, P. J. Van Soest, and C. J. Sniffen. A net carbohydrate and protein system for evaluating cattle diets: I. Ruminal fermentation. J. Animal Sci. 1992. 70:3551–3561.

[a] Corn products contain zein, a slow-degrading prolamine protein that is soluble in neutral detergent fiber.

Table 20. List of the essential and nonessential amino acids.

ESSENTIAL AMINO ACIDS	NONESSENTIAL AMINO ACIDS
Arginine (Arg)	Alanine
Histidine (His)	Aspartic acid
Isoleucine (Ile)	Citrulline
Leucine (Leu)	Cysteine
Lysine (Lys)	Cystine
Methionine (Met)	Glutamic acid
Phenylalanine (Phe)	Glycine
Threonine (Thr)	Hydroxyglutamic acid
Tryptophan (Trp)	Hydroxyproline
Valine (Val)	Norleucine
	Proline
	Serine
	Tyrosine

10 to 13 amino acids must be supplied in the ration and are designated as essential (Table 20). Some of the essential amino acids, such as lysine and methionine, are labeled as limiting amino acids. If the appropriate precursors, such as nitrogen and sulfur, are present in the rumen, then essential amino acids can be synthesized by the rumen microbes. This is one of the unique features of rumen microbes.

Microbial protein is high-quality protein because it has a good balance of the essential amino acids needed by the cow. Microbial protein contributes a large portion of protein for the ruminant animal to digest in the small intestine. As much as 3.0 to 3.5 pounds of microbial protein can be synthesized per day in the rumen of a mature Holstein dairy cow. However, all the needs of a high-producing cow for essential amino acids cannot be met by microbial protein synthesis alone. Certain essential amino acids need to be supplied in the ration, and a sufficient proportion of this source must escape or bypass rumen degradation.

Rations need to be balanced for those essential amino acids that are likely to be limiting under particular feeding situations. Feed ingredients can vary in their amino acid quality, and by incorporating various sources dairy producers can better meet the animal's requirement (Table 21). The most limiting amino acids for the high-producing dairy cow are lysine, methionine, and arginine.

Table 21. The essential amino acid profiles of milk, ruminal bacteria, and feeds.

	% OF TOTAL ESSENTIAL AMINO ACID									
ITEM	ARG	HIS	ILE	LEU	LYS	MET	PHE	THR	TRP	VAL
Milk	7.2	5.5	11.4	19.5	16.0	5.5	10.0	8.9	3.0	13.0
Bacteria	10.4	4.2	11.5	15.9	16.6	5.0	10.1	11.3	2.7	12.3
Corn silage	6.4	5.5	10.3	27.8	7.5	4.8	12.0	10.1	1.4	14.1
Hay crop silage	8.9	5.3	11.0	18.9	10.3	3.8	13.5	10.3	3.3	14.7
Barley	12.8	5.9	9.6	18.4	9.6	4.5	13.3	9.1	3.1	13.6
Blood meal	7.6	11.2	2.1	22.8	15.7	2.1	12.3	8.1	2.7	15.4
Brewer's grain, dry	8.9	6.4	10.6	17.6	11.4	4.8	10.3	11.4	3.0	15.6
Canola meal	14.0	6.7	9.3	16.9	13.1	4.8	9.5	10.5	3.0	12.4
Corn grain	10.8	7.0	8.2	29.1	7.0	5.0	11.3	8.4	1.7	11.5
Corn gluten meal	6.9	4.7	9.3	36.4	3.8	5.5	13.8	7.5	1.5	10.7
Corn distillers, dark	7.7	7.2	9.8	26.3	6.2	5.2	11.1	10.3	2.7	13.4
Cottonseed meal	25.4	6.0	7.7	13.9	9.6	3.8	12.2	7.7	2.9	10.8
Feather meal	14.7	1.1	10.0	29.3	3.9	2.1	10.0	10.5	1.5	17.1
Fish meal	13.1	5.7	9.3	16.5	17.0	6.3	8.8	9.5	2.4	11.3
Meat and bone meal	20.5	5.5	7.8	16.2	14.2	3.6	9.2	9.0	1.8	12.1
Sorghum grain	9.4	5.8	9.4	30.9	5.6	4.3	12.6	8.0	2.2	11.8
Soybean meal	16.3	5.7	10.8	17.0	13.7	3.1	11.0	8.6	3.0	10.6
Wheat middlings	15.2	6.6	9.7	18.9	8.0	4.6	12.6	8.3	3.4	12.6

Source: Schwab, C. Amino acid nutrition of the high performance ruminant. Rhône-Poulenc Animal Nutrition and Health Symposium, San Francisco, Calif. 1995, pp. 1-75.

Table 22. Guide to protein composition in rations for high-producing dairy cows.

	Stage of lactation		
	Early	Mid	Late
Crude protein, % DM	17-18	16-17	15-16
Soluble protein, % CP	30-34	32-36	32-38
Degradable protein, % CP	62-66	62-66	62-66
Undegradable protein, % CP	34-38	34-38	34-38

Source: Use of Total Mixed Rations (TMR) for Dairy Cows. Penn State Dairy and Animal Science Extension Fact Sheet 94-25.

In the past, problems in protein nutrition were specific to either excesses or deficiencies in total crude protein. Now attention to the protein fractions and protein quality and maintaining a good balance are considered critical. This is important not only for maximal milk production, but for economical and environmental concerns. Table 22 gives some guidelines for protein fractions in the total ration dry matter for dairy cattle.

Table 23. Regression equations for estimating energy values of various feeds.

Feed	Net energy for lactation NEL (Mcal /lb)	Total digestible nutrients (TDN), %
Legumes	NEL = 1.044 - (0.0119 x ADF) ex: NEL = 1.044 - (0.0119 x 40) NEL = 0.568 Mcal/lb	TDN = 4.898 + (NEL x 89.796) ex: TDN = 4.898 + (0.568 x 89.796) TDN = 55.9%
Legume-grass mixtures	NEL = 1.0876 - (0.0127 x ADF) ex: NEL = 1.0876 - (0.0127 x 40) NEL = 0.580 Mcal/lb	TDN = 4.898 + (NEL x 89.796) ex: TDN = 4.898 + (0.580 x 89.796) TDN = 57.0%
Grasses, small grains, sorghum, sudangrass forages	NEL = 1.085 - (0.0124 x ADF) ex: NEL = 1.085 - (0.0124 x 40) NEL = 0.589 Mcal/lb	TDN = 4.898 + (NEL x 89.796) ex: TDN = 4.898 + (0.589 x 89.796) TDN = 57.8%
Bermuda grass	NEL = [(0.0245 x TDN) - 0.12] x 0.454 ex: NEL = [(0.0245 x 50.4) - 0.12] x 0.454 NEL = 0.506 Mcal/lb	TDN = 95.679 - (1.224 x ADF) ex: TDN = 95.679 - (1.224 x 37) TDN = 50.4%
Corn silage, whole plant (unadjusted values)	NEL = 1.044 - (0.0124 x ADF) ex: NEL = 1.044 - (0.0124 x 30) NEL = 0.672 Mcal/lb	TDN = 31.4 + (53.1 x NEL) ex: TDN = 31.4 + (53.1 x 0.672) TDN = 67.1%
Corn silage, whole plant (adjusted values)[a]	Adj. NEL = (ATDN - 31.4) ÷ 53.1 ex: Adj. NEL = (66.4 - 31.4) ÷ 53.1 Adj. NEL = 0.659 Mcal/lb	Adj. TDN = 92.49 + (-0.6525 x DM) ex: Adj. TDN = 92.49 + (-0.6525 x 40) Adj. TDN = 66.4%
Total mixed rations[b] (forage + grain)	NEL = [(TDN x 0.0245) - 0.12] x 0.454 ex: NEL = [(72.9 x .0245) - 0.12] x 0.454 NEL = 0.756 Mcal/lb	TDN = 93.53 - (1.03 x ADF) ex: TDN = 93.53 - (1.03 x 20) TDN = 72.9%
Concentrate mixtures[c]	NEL = [(TDN x 0.0245) - 0.12] x 0.454 ex: NEL = [(77.2 x 0.0245) - 0.12] x 0.454 NEL = .804 Mcal/lb	TDN = 81.41 - (0.60 x CF[d]) ex: TDN = 81.41 - (0.60 x 7.0) TDN = 77.2%
Ear corn	NEL = 1.036 - (0.0203 x ADF) ex: NEL = 1.036 - (0.0203 x 16) NEL = 0.711 Mcal/lb	TDN = 99.72 - (1.927 x ADF) ex: TDN = 99.72 - (1.927 x 16) TDN = 68.9%
Shelled corn	NEL = .9050 - (0.0026 x ADF) ex: NEL = 0.9050 - (0.0026 x 4) NEL = 0.895 Mcal/lb	TDN = 92.22 - (1.535 x ADF) ex: TDN = 92.22 - (1.535 x 4) TDN = 86.1%
Small grains	NEL = .9265 - (0.00793 x ADF) ex: NEL = 0.9265 - (0.00793 x 12) NEL = 0.831 Mcal/lb	TDN = 4.898 + (NEL x 89.796) ex: TDN = 4.898 + (0.831 x 89.796) TDN = 79.5%

Source: Developed by R. S. Adams, Penn State professor emeritus of dairy science, for use in forage and feed-testing schemes. Revised 1994.

Note: All values are on a dry matter basis. ADF = acid detergent fiber.

[a] Adjusted values are to compensate for overmature or hard grain fed to cattle. If the adjusted TDN value is lower than the unadjusted value, then all adjusted values for various energy expressions are reported for corn silage. DM = dry matter.

[b] Based on use of normal Northeastern U.S. forages and low-fiber concentrates with no added fat, when fed at forage-to-concentrate ratios commonly used for milking cows. Use TDN and NEL values for individual feeds to estimate these values for a TMR with a known formula.

[c] Based on a USDA complication of values obtained for low-fat concentrate formulas using book values for individual ingredients. Use values for individual feeds to obtain TDN and NEL values for known formulas.

[d] CF = crude fiber. CF = (ADF x .83) - 1.30. Example: CF = (10 x .83) - 1.30 = 7.0.

Energy

Energy is the fuel needed to support all life activities. Animals require energy not only for maintenance, but also to support production including growth, gestation, and lactation. Some excess energy is stored as glycogen, which is found in muscle and liver, but most is stored as fat. Energy for the dairy cow can be expressed in several ways: total digestible nutrients (TDN), net energy of maintenance (NEM), net energy of gain (NEG), and net energy of lactation (NEL). By expressing energy values in these terms, feed energy losses through feces, urine, methane, and heat can be accounted for.

TDN is defined as follows: digestible crude protein + digestible crude fiber + digestible fat x 2.25 + digestible nitrogen-free extract. TDN accounts for fecal losses and some urinary losses. Most estimates or expected net energy values are based on TDN levels obtained at maintenance intakes. There is some bias in using TDN values compared to net energy values of certain feeds. For example, TDN values are close to NEL for average and good-quality forages, but higher than NEL for poor forages. TDN is lower than NEL for many concentrates.

Net energy should be the energy value expression used to balance rations. It takes into account energy losses from feces, urine, gases, and heat. Net energy is subdivided into maintenance, gain, and lactation. NEM and NEG are used in ration formulations for growing cattle and fattening animals. NEL can be used for ration formulations of milking animals and maintenance of open dry cows and for pregnancy needs during the last two months of gestation. Dairy cows can use energy about as well for maintenance as for milk production. That is why there is one value, NEL, for the mature cow.

Most TDN and energy estimates in forage and grain testing are based solely or primarily on regression equations using acid detergent fiber and sometimes neutral detergent fiber values as the indicator (Tables 23 and 24). Not all laboratories compute these estimates in the same manner. Estimates should be compatible with allowances for energy used in the ration balancing program.

Table 24. Calculation of cattle NEM and NEG values.

Step 1. Calculate digestible energy (DE)

DE = TDN x 0.04409

DE = 55.9 x 0.04409

DE = 2.465

Step 2. Calculate metabolizable energy (ME)

ME = DE x 0.82

ME = 2.465 x 0.82

ME = 2.021

Step 3. Calculate net energy of maintenance (NEM)

NEM = (1.37 x ME) - (1.12) - (0.138 x ME^2) + (0.0105 x ME^3) x 0.454

NEM = (2.769 - 1.12 - 0.564 + 0.087) x 0.454

NEM = 0.532

Step 4. Report as NEM Mcal/lb DM.

Step 5. Calculate net energy of gain (NEG)

NEG = (1.42 x ME) - (1.65) - (0.174 x ME^2) + (0.0122 x ME^3) x 0.454

NEG = 2.870 - 1.65 - 0.711 + 0.101 x 0.454

NEG = 0.277

Step 6. Report as NEG Mcal/lb DM.

Source: Developed by R. S. Adams, Penn State professor emeritus of dairy science, using equations mainly available in 1989 NRC for dairy cattle.

Note: The example above assumes values for legume forage with 40% ADF, 51% NDF, and 55.9% TDN

Formulating rations to meet the energy needs of dairy cattle is dependent upon production level, body condition scores, environmental stress, and deviations in dry matter intake. Some guidelines to follow for NEL Mcal/lb of dry matter for high-producing cows are early lactation, 0.76-0.80; mid lactation, 0.72-0.76; and late lactation, 0.68-0.72. These energy values should not be the sole means of balancing rations for energy. Energy is achieved in sound rations containing adequate levels of NSC and fat. Relying on NEL values only, with no regard to NSC and fat levels in the ration, can be highly detrimental to animal performance and health.

Low energy intake often is a problem with young stock and high-producing cows. Inadequate caloric intake can reduce growth, decrease milk production, depress milk protein test and sometimes fat test, and impair reproduction and health. Primary causes can be underfeeding concentrate and/or forage and ration imbalances that impair digestibility, feed utilization, and metabolism.

Excessive energy intake can be a problem for cows in mid to late lactation and for dry cows and can occur when overfeeding concentrates. This leads to animals becoming overconditioned or fat. Excess energy can occur in dry cows when they are provided forages free choice for most of the day and can stem from steaming-up or lead-feeding of dry cows by increasing the concentrate to levels greater than .5 percent of body weight daily prior to calving. Rations should be balanced for all animal groups and body condition observed closely so that ration adjustments can be made accordingly.

Table 25. Summarization of minerals in the dairy ration.

Mineral	Function	Deficiency symptoms, associated problems (levels lower than NRC, 1989)	Toxicity symptoms and problems
Calcium (Ca)	Bone and teeth formation; blood clotting; muscle contraction.	Rickets; slow growth and poor bone development; easily fractured bones; reduced milk yield; milk fever (a disturbance of normal calcium metabolism).	Calcium fed at levels more than .95 to 1.00% dry matter basis may reduce intake and lower performance.
Phosphorus (P)	Bone and teeth formation P is involved in energy metabolism, part of DNA and RNA.	Fragile bones; poor growth; low blood P: depraved appetite—chewing wood, hair, and bones; poor reproductive performance. Chronic deficiency may cause animals to have stiff joints.	Excessive phosphorus intakes may cause bone resorption, elevated plasma phosphorus levels, and urinary calculi.
Chlorine (Cl)	Acid-base balance, maintenance of osmotic pressure, manufacture of hydrochloric acid in abomasum.	Craving for salt; reduced appetite.	Excessive levels of chlorine without sodium or potassium can contribute to an acidosis condition.
Magnesium (Mg)	Enzyme activator; found in skeletal tissue and bone.	Irritability; tetany; increased excitability.	Not usually a problem.
Sulfur (S)	Needed for rumen microbial protein synthesis especially when nonprotein nitrogen is fed.	Slow growth; reduced milk production; reduced feed efficiency.	Sulfur levels exceeding .35% on a dry matter basis may reduce intake and overload the urinary excretion system. Sulfur can interfere with the metabolism of other minerals, especially selenium and copper.
Potassium (K)	Maintenance of electrolyte balance; enzyme activator; muscle function; nerve function.	Decreased feed intake; loss of hair glossiness; lower blood and milk potassium.	High levels found in young, very lush forages can interfere with magnesium metabolism and utilization.
Iodine (I)	Synthesis of thyroxine.	Big neck in calves; goitrogenic substances may cause deficiency.	Toxicity signs may appear at 50 to 200 ppm. Symptoms include excess salivation, watery nasal discharge, and coughing.
Iron (Fe)	Part of hemoglobin; part of many enzyme systems.	Nutritional anemia.	Iron concentration exceeding 1,000 ppm is characterized by diarrhea, hyperthermia, metabolic acidosis, and reduced feed intake and daily gain.
Copper (Cu)	Needed for the manufacture of hemoglobin; coenzyme.	Severe diarrhea; abnormal appetite; poor growth; coarse, bleached, or graying of hair coat; osteomalcia.	Toxicity symptoms include jaundice, liver damage, and death. Upper limit is considered 80 ppm.
Cobalt (Co)	Part of vitamin B_{12}; needed for growth of rumen microorganisms.	Reduced appetite; anemia; decreased milk production; rough hair coat.	Upper limit is 10 to 20 ppm. Signs of toxicity include reduced feed intake and body weight; emaciation; weakness; anemia.
Manganese (Mn)	Growth; bone formation; enzyme activator.	Delayed or decreased signs of estrus; poor conception.	Maximum safe level is 1000 ppm. Excess interferes with iron metabolism and induces hypomagnesia.
Zinc (Zn)	Enzyme activator; wound healing.	Decreased weight gains; lowered feed efficiency; skin problems; slow wound healing; listlessness.	Maximum safe level is not more than 500 ppm.

(continued next page)

Table 25. *(continued)*

MINERAL	FUNCTION	DEFICIENCY SYMPTOMS, ASSOCIATED PROBLEMS (LEVELS LOWER THAN NRC, 1989)	TOXICITY SYMPTOMS AND PROBLEMS
Selenium (Se)	Functions with certain enzymes; associated with vitamin E.	White muscle disease in calves; retained placenta.	Maximum safe level is 3 to 5 ppm. Toxicity shown by “alkali disease” or “blind staggers”; lameness; sloughed hooves.
Molybdenum (Mo)	Part of the enzyme xanthine oxidase.	Loss of weight; emaciation; diarrhea.	Maximum safe level is 6 ppm. Symptoms include emaciation; intense liquid diarrhea; weakness; stiffness; hair color changes.

Sources: Compiled from Jurgens, M. H. Animal Feeding and Nutrition, 5th ed. Dubuque, Iowa: Kendall/Hunt, 1982, and National Research Council (NRC), 1989.

Minerals

Minerals can be expressed on the basis of elemental content or total ash. They provide skeletal structure to bones and cells and are necessary in many chemical and enzymatic reactions in the body. An animal may draw upon its bones for limited amounts of calcium and phosphorus. Table 25 describes the main functions, deficiency and toxicity symptoms, and associated problems that can occur. Table 26 gives a guide to the mineral levels to use in ration formulation.

Calcium can have a pronounced effect on rumen metabolism, production, skeletal growth, and reproduction. Calcium is most likely to be deficient when using rations high in grass or whole-plant corn silage. Failure to supplement or balance rations, especially for young stock and dry cows, can result in poor production and infertility. Milk fever and retained placenta may also increase. Poor skeletal growth and fractures in legs of young stock may result.

Excessive calcium in the ration for dry cows and springing heifers can depress digestibility, reduce feed intake, and increase the incidence of milk fever, retained placenta, and uterine infection. The incidence of infertility, especially cystic problems, may increase when calcium is highly excessive. Frequent causes of excessive calcium intake are overfeeding high-calcium forage to dry cows and over-supplementation with calcium for any animal group.

Phosphorus is very important for normal rumen metabolism, reproduction, skeletal growth, and production. Low phosphorus intake frequently occurs in young stock and dry cows from lack of supplementation or concentrate feeding. Sometimes the problem can be due to poor availability of phosphorus sources. Bone growth and strength may become impaired if inadequate levels of phosphorus are supplied.

Excessive phosphorus intake is most often encountered in rations for milk cows. This generally results from over-supplementation, particularly when high levels of by-product feed ingredients are fed. Production and especially reproduction may be adversely affected. Prolonged consumption of high phosphorus diets may cause metabolic problems due to disorders associated with calcium absorption and metabolism.

Magnesium is necessary to maintain normal rumen fermentation, skeletal growth, production, reproduction, and health. Depressed fiber digestibility and impaired reproduction usually occur when rations are not balanced for this element or properly supplemented. Low magnesium intake may result in grass or winter tetany and complicated milk fever cases. Excessive magnesium may depress intake, digestibility, and production. This may result in nutritional scouring or diarrhea.

Sulfur is necessary for the synthesis of essential amino acids by rumen microbes. Sulfur supplementation is important in rations containing high levels of nonprotein nitrogen since several sulfur-containing amino acids must be made by rumen microbes, notably, cysteine, cystine, and methionine. Low sulfur intake results in an induced protein deficiency, and excessive intake damages liver tissue and function. Forages should be tested periodically and balanced for this nutrient.

Potassium is essential for maintaining acid-base balance relationships and allowing transmission of nerve impulses to muscle fibers. It activates or functions as a cofactor in several enzyme systems. Potassium deficiency most often occurs when using rations containing large amounts of wet or dried brewers grains or distillers grains without solubles (light grains). Low intake of potassium can result in reduced feed intake and depressed production and fat test. Inadequate potassium in the diet can also increase stress from heat and humidity and may result in paralysis of rear legs. Excessive intakes of potassium by springing cows and heifers may increase udder congestion and is a factor related to milk fever in anion-cation balance.

Sodium and chloride are elements provided by salt, but they are also found to some extent in most feeds. Low salt intake is one of the most common problems in the diet of dairy cattle. This can result from failure to supplement salt when using commercial protein concentrates that are low in salt to make them more palatable.

Some rations are balanced using only sodium levels and may result in low chlorine due to the use of buffers. Salt should be provided free choice as well as force fed for most animal groups. Salt should be limited somewhat for springing and dry cows when severe problems are encountered with udder congestion. Low intakes seriously reduce feed intakes and production and may increase the incidence of displaced abomasum. Lack of salt also impairs acid-base balance.

Trace elements play an important role in the diet of dairy cattle. A lack of these elements may adversely affect production and especially health to an extent equal to the deficiency of either protein or energy. Dairy producers at least should monitor levels of copper, zinc, and selenium by using suitable trace mineral premixes containing other elements such as manganese, iron, cobalt, and iodine in proper proportions.

Low intakes of trace minerals can be widespread in young stock and dry cows. Copper and zinc often are lacking in rations for milk cows because levels of the elements are low in homegrown feeds in many areas of the country. Induced copper deficiency may result from high sulfate, molybdenum, iron, and manganese intakes through polluted water or crops.

Selenium is deficient in feeds grown in certain areas of the country (e.g., the Northeast). In many of these deficient areas, selenium is often lacking in rations for young stock and dry cows, and about one-third of the herds still have low levels in milk cows. Low intakes greatly increase susceptibility to infections, including those of the udder, uterus, and foot.

Cobalt and iodine are most often lacking in young stock and dry cow rations. Lack of cobalt results in a deficiency of vitamin B_{12}, which is essential to animal health and metabolism. Appetite is reduced, and anemia may result when cobalt is lacking. Lack of iodine hampers thyroid function and endocrine or hormonal relationships. Excessive intake of iodine may result in too high values in the milk (over .5 ppm). Dairy producers should provide a trace mineral salt or other mineral-vitamin mixtures containing these trace elements to all groups.

Fluorine and molybdenum generally are not lacking in a diet. Excesses to the point of toxicity are more apt to occur. This may result from high fluorine in some phosphorus supplements or contamination of forage by air pollution near aluminum plants, foundries, and steel mills. Excessive fluorine, over 30 to 40 ppm in the total ration dry matter, causes foot and leg problems and poor production. High molybdenum may result from water contamination, especially in coal areas. This can lead to an induced copper deficiency.

Excessive intakes of trace elements may adversely affect production and health. This generally occurs from over-

Table 26. Guide to mineral composition in rations for high-producing cows.

Mineral	Stage of lactation: Early	Mid	Late
		% DM	
Calcium[a]	0.81-0.91	0.77-0.87	0.70-0.80
Phosphorus[a]	0.46-0.52	0.44-0.50	0.40-0.46
Magnesium[a]	0.28-0.34	0.25-0.31	0.22-0.28
Potassium[b]	1.20-1.50	1.20-1.50	1.20-1.50
Sulfur	0.23-0.24	0.21-0.23	0.20-0.21
Salt, or	0.45-0.50	0.45-0.50	0.45-0.50
Sodium	0.20-0.25	0.20-0.25	0.20-0.25
Chloride	0.25-0.30	0.25-0.30	0.25-0.30
		PPM	
Manganese	44	44	44
Copper[c]	11-25	11-25	11-25
Zinc	70-80	70-80	70-80
Iron	100	100	100
Added selenium	0.30	0.30	0.30
Added cobalt	0.20	0.20	0.20
Added iodine	0.50	0.50	0.50

Source: Use of Total Mixed Rations (TMR) for Dairy Cows. Penn State Dairy and Animal Science Extension Fact Sheet 94-25.

Note: Table refers to milk production equivalent to a DHI rolling herd average of 18,000 pounds of 4% fat-corrected milk or higher.

[a] Use these minerals at the higher levels indicated when fat content exceeds 4.0 percent in the total ration dry matter.

[b] Use the higher potassium level during hot, humid weather.

[c] Use the higher copper levels when low serum copper occurs on rations containing usual levels of 10-12 ppm. Induced copper deficiency may result from excessive intake of iron, manganese, molybdenum, and sulfur.

Table 27. Summarization of fat-soluble vitamins in the dairy ration.

Vitamin	Function	Deficiency symptoms and associated problems (levels lower than NRC, 1989)	Toxicity symptoms and problems
A	Essential for normal vision; cellular function; and maintenance of epithelial linings of respiratory, reproductive, and digestive tracts.	Night blindness; skin problems; blind, dead or weak calves; reproductive problems.	Toxicity is not considered a problem under most practical feeding programs.
D	Normal bone growth and development; absorption of calcium and phosphorus; mobilization of calcium and phosphorus.	Rickets; osteomalcia.	Maximum limit is 100,000 IU/head daily.
E	Antioxidant; associated with selenium.	Oxidized flavor in milk; muscle problems; white muscle disease; cardiac muscle abnormalities.	Toxicity is not considered a problem under most practical feeding programs.
K	Required for blood clotting.	Moldy sweet clover disease; hemorrhages.	

Sources: Compiled from Jurgens, M. H. Animal Feeding and Nutrition, 5th ed. 1Dubuque, Iowa: Kendall/Hunt, 1982, and National Research Council (NRC), 1989.

supplementation and sometimes from water and feed contamination. Intake levels can be ascertained through the use of blood and liver analyses.

Vitamins

Dairy cattle have a physiological requirement for the fat-soluble vitamins A, D, E, and K. Generally, dairy cattle of all ages require a dietary source of vitamins A and E. Vitamin D may be synthesized in the skin under the influence of ultraviolet radiation or may be included in the diet. Rumen microbes synthesize adequate amounts of vitamin K to meet the needs of most dairy cattle with the exception of young calves. Under most feeding situations, there should be few problems with deficiencies (Table 27). However, as dairy cattle are being fed more ensiled forages and exposed to less sunlight, additional vitamin supplementation will be needed to maintain health and high levels of production (Table 28).

Fat-soluble vitamins may not constitute a large part of the ration; nonetheless they are extremely important in the health and production of the dairy cow. Vitamin A and its pro-vitamin, beta carotene, are necessary for good health and reproduction. Low vitamin A status is most apt to occur when rations are high in hay and/or corn silage. Haylage rations also may be low in vitamin A if they do not have good green color. Use of pasture or green chop at a minimum of 50 percent of the forage dry matter for several months can replenish liver stores.

Vitamin D supplementation at proper levels may improve calcium and phosphorus utilization, metabolism, and reproductive performance. Low intakes of vitamin D may result in rickets and weak bones, as well as weak or silent heats, especially in young stock. Vitamin D should be included in the formulation of the ration to avoid excessive levels. Excessive intakes occur quite frequently. An intake of 80,000 units per head daily may depress production. An intake exceeding 100,000 units for an extended period may increase the incidence of milk fever as well as infertility, joint problems, lameness, and heart failure.

Vitamin E is most apt to be limiting with a ration high in hay or corn silage and haylage lacking green color. Both vitamin E and selenium are necessary for good resistance to disease. Low intake of vitamin E makes the animal more susceptible to infections and has a pronounced effect on the ability of white blood cells to kill organisms and on the production of antibodies. Low vitamin E intake may result in oxidized flavor, or milk that tastes like cardboard. Many commercial products contain relatively low amounts of this vitamin.

Table 28. Guide to vitamin composition in rations for high-producing dairy cows.

	Stage of lactation		
	Early	Mid	Late
Vitamin	IU/lb DM		
Vitamin A	3500	3500	3500
Vitamin D			
Minimum	750	750	750
Maximum	1100	1100	1100
Vitamin E	20	20	20

Source: Use of Total Mixed Rations (TMR) for Dairy Cows. Penn State Dairy and Animal Science Extension Fact Sheet 94-25.

Vitamin K generally is not lacking in the ration. It is synthesized by rumen microbes, unlike other fat-soluble vitamins, and affects blood clotting. Sweet clover poisoning is the syndrome most commonly associated with vitamin K deficiency. When sweet clover hay or silage becomes moldy or spoiled, dicoumarol, a fermentation product, develops. The hemorrhagic action of dicoumarol and related derivatives is due to specific antivitamin K activity.

Water

Adequate water intake is needed to provide for vital body functions. Water is required for maintaining body fluids and proper ion balance; for digesting, absorbing, and metabolizing nutrients; for eliminating waste materials and excess heat from the body; for providing a fluid environment for the developing fetus; and for transporting nutrients to and from body tissue. Adequate water intake of reasonable good chemical and bacteriological quality must be available to optimize dry matter intake. The amount of water consumed is influenced by the dry matter ingested, climatic conditions, composition of the diet, water quality, and the physiological state of the animal. Table 29 shows expected water intakes, and Table 30 provides some standards related to water quality.

Table 29. Water intake needs by various age groups of dairy cattle, drinking water only.

COW TYPE	AGE OR CONDITION	GALLONS PER DAY[a]
Holstein calves	1 mo	1.3-2.0
Holstein calves	2 mo	1.5-2.4
Holstein calves	3 mo	2.1-2.8
Holstein calves	4 mo	3.0-3.5
Holstein heifers	5 mo	3.8-4.6
Holstein heifers	15-18 mo	5.9-7.1
Holstein heifers	18-24 mo	7.3-9.6
Dry cows	Pregnant, 6-9 mo	7-13; average 10
Lactating cows[b]		Depends on production and other factors. Total water and drinking water intakes for lactating cows can be calculated using the equations and procedures given in footnote b.

Note: Generally, beef cattle consume water at the rate of 1% of body weight in gallons daily. One gallon of water weighs 8.34 pounds. A cubic foot of water weighs 62.4 pounds. Water intake will be higher for all cattle during hot weather.

When water is being metered for milk cows, make sure other livestock (i.e., heifers, dry cows, beef cattle, or a bull) that have access to the same watering source are properly discounted so a more accurate estimate of water intake can be achieved.

Water from ration usually runs 25 to 50 pounds daily on low- and high-silage rations respectively. Lower levels of water intake given apply to intake in winter; higher levels to hot, humid weather.

[a] At air temperatures between 50° and 80° Fahrenheit, intake depends upon the forage ration water content. Higher levels apply to an all-hay ration.

[b] Drinking water for lactating cows largely depends on the production level, dry matter intake, and ration water intake. It can be estimated using the modified Kertz Equation (A.F. Kertz, Ralston Purina Company): Total water and drinking water intakes for lactating cows may be calculated using the following equation and procedures:

Total water intake (lb/day) = (4 x dry matter intake) + pounds of 4% FCM + 25.6
Drinking water intake (lb/day) = total water intake - ration water intake
4% FCM (fat corrected milk) = (.4 x lb milk) + 15 x (lb milk x % fat as decimal)

Example: Determine the drinking water intake for a 1,350-pound Holstein cow producing 60 pounds of milk with a 3.7% milk fat test. The moisture content of the ration is 55 percent (45% dry matter). The 4% FCM is (.4 x 60) + 15 x (60 x .037) or 57.3 pounds. The estimated dry matter intake is 43 pounds.

Total expected water intake = (4 x 43) + 57.3 + 25.6
= 254.9 lb of total water daily *or*
= 30.6 gallons (254.9 ÷ 8.34) *or*
= 4.4 lb per lb of 4% FCM produced daily (254.9 ÷ 57.3)

Expected drinking water intake = 254.9 - 52.5*
= 202.4 lb of drinking water daily *or*
= 24.3 gallons *or*
= 3.6 lb per lb of 4% FCM produced daily

*Ration water is derived as follows:
43 ÷ 0.45 = 95.5 total as-fed pounds of feed
95.5 x 0.55 = 52.5 lb ration water

Additional references dealing with water intake in greater detail are J. Dairy Sci. 66 (1983):35 and J. Dairy Sci. 75 (1992):1,472.

Table 30. Interpretation of a water analysis report.

Item	Average[a]	Expected[b]	Possible cattle problems[c]
pH for cows	7.0	6.8-7.5	under 5.5 or over 8.5
pH for veal calves		6.0-6.4	
Stability index	8.5	6.0-7.5	
Saturation index	-0.68		
Turbidity (Jackson units)	5.5	0-30	
Color, PCU[d]	0.7	0-15	
Odor threshold	0.07		
		Parts per million	
Dissolved solids	368	500 or less	over 3,000
Phenothalein alkalinity	0.9	0-trace	
Total alkalinity	141	0-400	over 5,000
Bicarbonate alkalinity	139		
Carbon dioxide	46	0-50	
Chloride[e]	20.2	0-250	
Sulfate	35.5	0-250	over 2,000
Fluoride	0.23	0-1.2	over 2.4 (mottling)
Phosphate	1.4	0-1.0	
Total hardness	208	0-180	
Calcium	60.4	0-43	over 500
Magnesium	13.9	0-29	over 125
Sodium	21.8	0-3	over 20 for veal calves
Iron	0.8	0-0.3	over 0.3 (taste, veal)
Manganese	0.3	0-0.05	over 0.05 (taste)
Copper	0.1	0-0.6	over 0.6 to 1.0
Silica	8.7	0-10	
Potassium	9.1	0-20	
Arsenic	—	0.05	over 0.20
Cadmium	—	0-0.01	over 0.05
Chromium	—	0-0.05	
Mercury	—	0-0.005	over 0.01
Lead	—	0-0.05	over 0.10
Nitrate as NO_3[f]	33.8	0-44	over 100
Nitrite as NO_2	0.28	0-0.33	over 4.0-10.0
Hydrogen sulfide	—	0-2	over 0.1 (taste)
Barium	—	0-1	over 10 (health)
Zinc	—	0-5	over 25
Molybdenum	—	0-0.068	
Total bacteria/100 ml	336,300	under 200	over 1 million
Total coliform/100 ml	933	less than 1	over 1 for calves; over 15 -50 for cows
Fecal coliform/100 ml[g]	—	less than 1	over 1 for calves; over 10 for cows
Fecal strep/100 ml	—	less than 1	over 3 for calves; over 30 for cows

[a] For most parameters, averages are from approximately 350 samples. Most samples were taken from water supplies on farms with animal health or production problems.

[b] Based primarily on criteria for water fit for human consumption.

[c] Based primarily on research literature and field experiences.

[d] PCU = platinum cobalt unit.

[e] Free or residual chlorine levels up to .5 to 1 ppm have not adversely affected ruminants. Municipal supplies with .2 to .5 ppm have been successfully used. Swimming pool water with 1 ppm has no demonstrable effects on cattle. Levels of 3 to 5 ppm in farm systems with short contact time have caused no apparent problems.

[f] Should not be consumed by young human infants if over 44 ppm NO_3 or 10 ppm NO_3-N.

[g] If pollution is from human wastes, fecal coliform should exceed fecal strep by several times. If pollution is from an animal source, strep should exceed coliform in refrigerated samples run soon after taking.

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