ABSTRACT: Based on performance of feedlot cattle, steam flaking increases the value of corn by 18%, considerably more than is suggested by tabular values. Tabular values underestimate the energy availability of flaked corn by failing to account for digestibility of the nonstarch OM that is increased by flaking by the same magnitude (10%) as starch. Correcting for improvement in digestibility of nonstarch OM increases the NEg value of steam-flaked corn to 1.70 Mcal/kg, a value very close to values calculated from cattle performance trials. Digestibility of starch from corn grain is limited by the protein matrix that encapsulates starch granules, and by the compact nature of the starch itself. Disruption of the protein matrix (by shear forces on hot grain during flaking) is the first limiting step toward optimizing starch digestion. Five critical production factors influence the quality of steam-flaked corn: steam chest temperature, steaming time, roll corrugation, roll gap, and roll tension. For optimal shear, it is important that rolls be hot and that kernels be hot when flaked. Steam chests should be designed to allow a steaming time of at least 30 min at maximum roller mill capacity producing a flake of 0.31 kg/L (24 lb/bushel). As little as 5% moisture uptake during steaming appears adequate. The rate of flaking and distribution of kernels across the rolls also are critical. Quality standards for steam-flaked corn include measurements of flake thickness, flake density, starch solubility, and enzyme reactivity. Flake density, the most common quality standard, closely associated with starch solubility ($r^2 = 0.87$) and enzyme reactivity ($r^2 = 0.79$), still explains only 63% of the variability in percentage fecal starch and 52% of the variability in starch digestibility. Direct determination of fecal starch can explain 91% of the variability in starch digestion. The NEg value of corn can be predicted from fecal starch: \(\text{NEg} = 1.78 - 0.0184\text{FS}\).

Starch digestion is a Kappa Curve function of hot flake density, reaching a maximum at a flake density of approximately 0.31 kg/L. Flaking to a density of less than 0.31 kg/L, though increasing starch solubility, may reduce DMI, increase variability of weight gain among animals within a pen, and predispose cattle to acidosis and bloat without increasing starch digestion. We recommend that the steam-flaking process be optimized on the basis of fecal starch analysis.

Key Words: Cattle, Maize, Protein, Processing, Protein

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Introduction

Although steam flaking is known to increase the feeding value of corn above that of whole or dry-rolled corn, the magnitude of this improvement is rarely recognized. Effects of substituting steam-flaked corn for whole or rolled corn in several studies are summarized in Table 1. Net energy values for each diet were calculated from estimates of energy gain (\(\text{EG}, \text{Mcal/d}\)) based on growth performance (NRC, 1984; i.e., \(\text{EG}_{\text{medium frame yearling steer}} = \left[0.0493\text{BW}^{0.75}\right]\text{ADG}^{1.097}\), where BW is the mean shrunken body weight [full weight \(\times 0.96\)]) and maintenance energy expended (\(\text{Mcal/d}, \text{EM}; \text{EM} = 0.077\text{BW}^{0.75}, \text{NRC, 1984}\)). The NE values of the diet for maintenance and gain can be estimated from performance and feed intake using the quadratic formula \(x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\), where \(\begin{align*}
a &= -0.877\text{DMI}, \\
b &= 0.877\text{EM} + 0.41\text{DMI} + \text{EG}, \\
c &= -0.41\text{EM}, \text{ and NEg} &= 0.877\text{NEm} - 0.41 \quad (\text{Zinn and Shen, 1998}).
\end{align*}\)

Diet ME values were calculated based on the equation \(\text{ME} = (\text{NEm} + 0.696)/0.91\) (derived from NRC, 1996). The ME values for steam-flaked corn were estimated using the replacement technique: steam-flaked corn \(\text{ME} = (\text{ME of test diet} - \text{ME of control diet})/\%\text{ corn in diets} + 3.25\). The 3.25 is the NRC (1996) estimate for ME concentration of cracked corn grain. Thereafter, \(\text{NEm} \text{ and NEg values for the steam-flaked corn were calculated from ME. Based on these calculations, flaked corn had an average of 14\% more NEm and 19\% more...
Table 1. Performance and net energy advantage (%) of steam-flaked corn grain over dry-processed corn grain

<table>
<thead>
<tr>
<th>Item</th>
<th>Corn</th>
<th>ADG, %</th>
<th>DMI, %</th>
<th>ADG/DMI</th>
<th>NE&lt;sub&gt;m&lt;/sub&gt;</th>
<th>NE&lt;sub&gt;g&lt;/sub&gt;</th>
<th>NE&lt;sub&gt;m&lt;/sub&gt;</th>
<th>NE&lt;sub&gt;g&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matsushima and Montgomery (1967)</td>
<td>Ground</td>
<td>6.7</td>
<td>-5.0</td>
<td>12.2</td>
<td>2.41</td>
<td>1.70</td>
<td>12.2</td>
<td>17.3</td>
</tr>
<tr>
<td>Lee et al. (1982) Trial 1</td>
<td>Whole</td>
<td>-11.0</td>
<td>-12.5</td>
<td>1.7</td>
<td>2.53</td>
<td>1.81</td>
<td>6.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Lee et al. (1982) Trial 2</td>
<td>Whole</td>
<td>15.1</td>
<td>2.0</td>
<td>12.8</td>
<td>2.35</td>
<td>1.65</td>
<td>12.4</td>
<td>17.1</td>
</tr>
<tr>
<td>Ramirez et al. (1985)</td>
<td>Whole</td>
<td>6.4</td>
<td>-4.3</td>
<td>11.2</td>
<td>2.42</td>
<td>1.71</td>
<td>14.1</td>
<td>18.8</td>
</tr>
<tr>
<td>Zinn (1987)</td>
<td>Dry-rolled</td>
<td>1.7</td>
<td>-3.3</td>
<td>7.4</td>
<td>2.47</td>
<td>1.75</td>
<td>11.7</td>
<td>15.9</td>
</tr>
<tr>
<td>Barajas and Zinn (1998) Urea</td>
<td>Dry-rolled</td>
<td>7.6</td>
<td>-6.1</td>
<td>19.6</td>
<td>2.42</td>
<td>1.71</td>
<td>20.2</td>
<td>27.2</td>
</tr>
<tr>
<td>Barajas and Zinn (1998) Cottonseed</td>
<td>Dry-rolled</td>
<td>10.1</td>
<td>-6.6</td>
<td>17.9</td>
<td>2.56</td>
<td>1.84</td>
<td>19.2</td>
<td>25.9</td>
</tr>
<tr>
<td>Ward et al. (2000)</td>
<td>Dry-rolled</td>
<td>7.0</td>
<td>-7.0</td>
<td>15.0</td>
<td>2.54</td>
<td>1.82</td>
<td>15.6</td>
<td>20.0</td>
</tr>
<tr>
<td>Trials average</td>
<td></td>
<td>5.4</td>
<td>-6.1</td>
<td>12.2</td>
<td>2.46</td>
<td>1.75</td>
<td>14.0</td>
<td>18.8</td>
</tr>
<tr>
<td>NRC (1984) for beef cattle</td>
<td>Grain</td>
<td>2.38</td>
<td>1.67</td>
<td>6.2</td>
<td>2.38</td>
<td>1.67</td>
<td>6.2</td>
<td>7.7</td>
</tr>
<tr>
<td>NRC (1996) for beef cattle</td>
<td>Cracked</td>
<td>2.33</td>
<td>1.62</td>
<td>4.0</td>
<td>2.33</td>
<td>1.62</td>
<td>4.0</td>
<td>4.5</td>
</tr>
<tr>
<td>NRC (2000) for dairy at 3× maint.</td>
<td>Cracked</td>
<td>2.24</td>
<td>1.55</td>
<td>9.3</td>
<td>2.24</td>
<td>1.55</td>
<td>9.3</td>
<td>11.5</td>
</tr>
</tbody>
</table>

NE<sub>m</sub> than dry-rolled corn or whole-corn grain. These increases in NE are more than triple the benefits proposed for flaking (4 and 4.5% for NE<sub>m</sub> and NE<sub>g</sub>, respectively) for beef cattle (NRC, 1996) and considerably greater than the 9.3 and 11.5% increases proposed for dairy cattle (NRC, 2000).

The objective of this review is to outline some of the many mechanical factors that can influence the flaking process, discuss why feeding values observed for steam-flaked corn usually exceed the tabular values, and examine various techniques and measurements that can be used to appraise the efficacy of flaking and consistency of the flakes.

Background and Discussion

Steam flaking consistently increases energy availability of corn grain, but are the NE values (2.46 and 1.75 Mcal/kg, respectively) derived for steam-flaked corn using the replacement technique unrealistically high? One limitation of the replacement technique is that derived NE values depend on accurate estimates of the NE values of feedstuffs. Associative interactions of feed ingredients on dietary NE might differ slightly depending on grain processing, but remain undefined. However, the tabular NE values for dry-rolled corn probably have been overestimated. If the NE<sub>m</sub> of steam-flaked corn were, indeed, 2.47 Mcal/kg, the corresponding DE value for steam-flaked corn would be 4.25 Mcal/kg (DE = [0.6612 + NE<sub>m</sub>/0.7364; NRC, 1984), 95% the GE value of corn.

The NE value of a feedstuff also can be estimated by subtracting tabular (NRC, 1996) ME contributions of the other dietary ingredients from the ME value of the complete diet estimated on the basis of growth performance. A summary of NE estimates for dry-rolled and steam-flaked corn reported by Owens et al. (1997) is presented in Table 2. Across the 183 trials in which dry-rolled corn comprised more than 70% of diet DM, the estimated NE<sub>m</sub> and NE<sub>g</sub> values for dry-rolled corn averaged 2.24 and 1.56 Mcal/kg, respectively. These estimates are 2.8 and 4.0% greater than current tabular values for dry corn grain or ground corn (2.18 and 1.50 Mcal/kg, respectively; NRC, 1996) but are similar to tabular values for cracked corn (2.24 and 1.55 Mcal/kg, respectively; NRC, 1996). Across 53 trials in which steam-flaked corn comprised more than 70% of diet DM, the estimated NE<sub>m</sub> and NE<sub>g</sub> values for steam-flaked corn averaged 2.62 and 1.88 Mcal/kg, respectively. These estimates are 12.4 and 16% greater than current tabular values (2.33 and 1.62 Mcal/kg; NRC, 1996). Based on this summary, steam flaking resulted in grain containing 14.2 and 17.3% more NE<sub>m</sub> and NE<sub>g</sub> than dry-rolled corn. Note that although the absolute values differ slightly by the two systems of calculation, the improvements associated with flaking corn grain were very similar.

Why Does Steam-Flaked Corn Have Greater NE Than Tables Indicate?

Most tabular energy values have been calculated from measured TDN value (NE<sub>m</sub> = 0.0305TDN − 0.5058) or from estimated digestibility of individual components (NRC, 1996, 2000). The NRC (1996) indicates that steam flaking increases the TDN value of corn by 5.7% (93 vs 88%). This improvement appears to be based on the assumption that all of the increase in energy value of corn with flaking is due solely to increased starch digestion.

Starch concentration of corn grain for 46 modern yellow dent corn grain hybrids from test plots across the United States averaged 71.0 ± 0.4% of DM (range of 70.3 to 71.9% for different Pioneer hybrids produced in 2000; F. N. Owens, personal communication), though individual samples of corn grain from throughout the Midwest had a much wider range in starch content (61 to 78%; White and Pollak, 1995) despite having a similar mean (71.7%). Starch concentration decreases as protein or oil concentration of a hybrid increases (Figure 1), partly by replacement of germ by endosperm.
Flaking corn

Table 2. Literature summary of energy values of dry-rolled and steam-flaked corn grain

<table>
<thead>
<tr>
<th>Item</th>
<th>No. of trials</th>
<th>ME, Mcal/kg</th>
<th>SD</th>
<th>NE, Mcal/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn form</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry-rolled</td>
<td>183</td>
<td>3.26</td>
<td>0.21</td>
<td>2.24</td>
</tr>
<tr>
<td>Steam-flaked</td>
<td>53</td>
<td>3.73</td>
<td>0.38</td>
<td>2.62</td>
</tr>
<tr>
<td>Advantage, %</td>
<td>—</td>
<td>12.6</td>
<td>—</td>
<td>14.2</td>
</tr>
</tbody>
</table>

*Owens et al. (1997).

Hybrids with a longer growing season generally have greater grain DM yields ($r^2 = 0.82$ among 46 Pioneer hybrids) and potentially a greater endosperm:germ ratio (Sauber and Owens, 2001).

In a 9-yr summary of published trials with corn grain, Huntington (1995) reported that steam flaking increased starch digestion an average of 7 percentage units (99 vs 92%). Accordingly, if all the improvement in TDN with steam flaking were due solely to increased starch digestion, then the expected increase in TDN would be 5.7% [(0.99–0.92)/0.714/0.88, where 0.714 is the percentage starch and 0.88 is the TDN value (NRC, 1996) for dry corn grain], precisely the value indicated by NRC (1996). However, flaking also increases exposure of other constituents of the kernel (e.g., protein) and thereby may increase digestibility of those constituents. Zinn et al. (1995) observed that steam flaking increased starch digestion by 10% (99 vs 90%), corresponding to an increase in OM digestion of 6.4 percentage units, while increasing total OM digestion by 8.6 percentage units (92.6 vs 84%). This means that the digestibility of nonstarch OM was increased from 73 to 80.6% by steam flaking the corn. Thus, digestibility of nonstarch OM was increased by flaking to the same degree (10%) that starch digestibility was increased. This improvement in nonstarch digestibility would give steam-flaked corn a TDN of 95.5%, corresponding to NE$_m$ and NE$_g$ values of 2.41 and 1.70 Mcal/kg, respectively.

In addition to improving the digestibility of corn, steam flaking also reduces methane energy loss by as much as 30% (Johnson et al., 1968; Zinn, 1987; Zinn et al., 1995). However, this favorable effect of steam flaking on methane energy losses may be offset by a lower energy recovery from starch digested in the rumen vs the small intestine.

Why Does Steam Flaking Enhance Digestibility of Corn or Corn-Based Diets?

Most of the starch in corn grain is within endosperm of the kernel in a granular form. With typical yellow dent corn, these starch granules are composed of roughly 27% amylose (α 1-4 glucosidic linkages) and 73% amylopectin (α 1-4 glucosidic linked chains connected to α 1-6 glucosidic linked chains). The linear nature of amylose allows the starch to form very compact crystalline micelles when dried. In contrast, the bush-like structure of amylopectin restricts intermolecular bonding and prevents compaction of micelles. Compared to the diameter of raw corn starch granules (1 to 30 μm with an average of about 8 μm; Campbell et al., 1996), individual starch molecules are quite short (0.03 to 0.12 μm; Fishman et al., 1995).

Tight intermolecular bonding between starch molecules, along with the compact nature of the starch granule, impedes rapid moisture uptake (rehydration), but under normal atmospheric conditions corn starch will absorb 10 to 17% moisture. The first 8 to 11 percentage points is tightly bound and is considered water of constitution. Under water saturation conditions and temperatures below 60°C, raw corn starch will absorb a maximum of 40% water, resulting in a reversible swelling of the starch granule by about 9% (Leach, 1965).

Gelatinization refers to the irreversible swelling of the starch granule. In practice, gelatinization is defined by how it is measured: loss of birefringence; swelling power; solubility; enzymatic reactivity. Raw starch exhibits a maltese cross birefringence when observed microscopically with plane polarized light. Because of differences among starch granules in the degree of association of their starch micelles, individual granules swell and melt within a narrow temperature range, but the
total population of granules will lose their polarization cross over a 7-to-10°C range in temperature, called the gelatinization temperature range (GTR; Table 3). At the low point of this range, loss begins, whereas at the apex of the GTR, the birefringence end point temperature (BEPT), 98% of the granules in the population have lost their birefringence.

The GTR varies with maize genotype (Table 3) and environmental factors related to crop production. The GTR of “regular” cornstarch is 62 to 72°C, though this can differ slightly depending on the method of measurement. At 62°C moisture uptake by starch granules does not exceed 1:2 (33% moisture). At BEPT (72°C) moisture uptake by the granule can reach 10:1 (91% moisture). Thus, moisture uptake by cornstarch is 20-fold greater at the BEPT than at the lowest point of the GTR. If cornstarch is heated further in a saturated vapor at 95°C, the granule will continue to swell to a moisture concentration of 24:1 (96% moisture; Leach, 1965). Although waxy corn hybrids contain much less amylose than regular corn, they have similar GTR and starch solubility at 95°C. However, the swelling power (g water uptake/g starch at 95°C for 30 min) of waxy cornstarch is 267% greater than that of regular cornstarch. During gelatinization, amylopectin granules (from waxy hybrids) will swell by up to 200%, whereas high-amylose granules (from high-amylose hybrids) may not swell at all with exposure to moist heat (Atkin et al., 1998).

High-amylose cornstarch does not have a characteristic GTR. Even after heating with saturated vapor at 95°C for 30 min, moisture uptake by high-amylose starch is only 6 g/g starch, a value only 25% that of starch from typical corn (Table 3). A familiar example that illustrates the challenge in gelatinizing high-amylose starch is evident from the inability to cook dry beans. The starch present in pulses, including peas and beans, is characterized rich in amylose; this is the reason they resist swelling, even after prolonged boiling in water.

In addition to corn variety, environmental factors can alter starch gelatinization. Freeman et al. (1968) reported that the BEPT was 3°C (78 vs 75°C) higher for waxy corn grown in Texas than for the same hybrid grown in Illinois. The BEPT also was 4°C higher for “regular” corn grown in Coastal Texas than for the same hybrid grown in the High Plains. Starch characteristics can be affected by environmental temperature, soil type, planting date, year, and location, as summarized by Krieger et al. (1998). For example, ears exposed to higher temperature during grain filling will have smaller starch granules with less amylose even though the amylose molecules are longer (Lu et al., 1996).

Although various indices of gelatinization have received primary emphasis in the qualitative evaluation of steam-flaked corn, extent of starch digestion is not dependent on gelatinization alone. Gelatinization is one method of increasing solubility in water. Yet digestibility and solubility do not appear to be related. For example, even though industrial cornstarch (99% starch, less than 0.25% protein) has a very low solubility (less than 3%), it has a very high (>90%) extent of digestion in the rumen (derived from Zinn and Owens, 1986). Osman et al. (1970) observed that degradation of starch by pancreatin was similar (17.8, 12.9, and 16.0%, respectively) for untreated, steamed (but not flaked), and coarsely flaked sorghum grain. However, when steamed sorghum was flaked to a medium or to a thin flake thickness, enzymatic starch degradation increased markedly (to 221 and 293% of untreated milo, respectively). This effect was not brought about by grinding; all of the treatments were finely ground before analysis of starch reactivity. Similarly, Trei et al. (1966) noted that steaming or pressure cooking milo grain without flaking had very limited impact on in vitro gas production (a 26% decrease to 4% increase), whereas moist heat combined with flaking increased in vitro gas production at 3 h by 30 to 87% over untreated grain. Thus, steaming alone, though it influences water absorption and swelling of the starch granule, by itself appears insufficient to markedly increase starch digestibility. Alternatively, reducing particle size alone without moist heat is inadequate; fine grinding of milo increased in vivo digestibility of DM and energy from rolled milo by only 2.5% compared to a 10.5% increase with steam flaking (Mehen et al., 1966). To enhance rate of starch digestion, moist heat must be combined with shear or rupture of starch granules. Perhaps the shear involved with flaking permits a greater proportion of the starch granule population to be exposed to the moist heat treatment; indeed, loss of birefringence is much greater with flatter, thinner flakes (Trei et al., 1966).

Little research has been published regarding the interaction of degree of moisture absorption and flaking pressure on degree of shear and on starch utilization.

### Table 3. Starch species affects gelatinization

<table>
<thead>
<tr>
<th>Corn species</th>
<th>GTR</th>
<th>Swelling power, g/g starch</th>
<th>Solubility, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>62–72</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>Waxy</td>
<td>63–72</td>
<td>64</td>
<td>23</td>
</tr>
<tr>
<td>High-amylose</td>
<td>—</td>
<td>6</td>
<td>12</td>
</tr>
</tbody>
</table>

*a* Leach, 1965.  
*b* Gelatinization temperature range.  
*c* Water uptake, g/g starch.
in cattle. Zinn (1990a) observed that when corn was steamed for a constant time (34 min at 105°C), increasing the pressure on the rolls to produce flake densities of 0.41, 0.36, and 0.31 kg/L (32, 28, and 24 lb/bushel, respectively) linearly increased extent of starch digestion both in the rumen and in the total digestive tract. In contrast, although doubling the steaming time (67 vs 34 min) at 105°C before flaking to a density of 0.31 kg/L increased both kernel moisture (18%) and enzymatic starch reactivity (225%), it failed to increase either ruminal or total tract starch digestion; these averaged 85.4 and 99.6%, respectively (Zinn, 1990b). Nevertheless, steam flaking increased ruminal and total tract starch digestion by 25 and 9%, respectively, over that of dry-rolled corn, in close agreement with summary values (Huntington, 1995). Moisture uptake during steaming for 34 min was only 5 percentage points, but this appeared adequate to optimize the feeding value of corn when flaked to a density of 0.31 kg/L (24 lb/bushel). Because gelatinization should increase at higher moisture levels, the results support the concept that extent of gelatinization did not limit the feeding value of the grain.

Whether moisture concentration of the grain at flaking alters the ideal roll pressure (and flake weight) for feeding is not known. Longer steaming time may reduce the roll pressure necessary to obtain an optimal shear. That is, starch digestibility of corn steamed for 34 min and flaked to a density of 0.31 kg/L might have a starch digestibility similar to that of corn steamed for 68 min but flaked to a density of 0.36 kg/L (28 lb/bushel). In a recent study (Zinn et al., 2000), regular steam-flaked and tempered steam-flaked corn were compared at two flake densities (0.31 vs 0.39 kg/L). In all cases corn was steamed for 34 min before flaking. Tempering corn consisted of adding 7.5% water in combination with a surfactant approximately 1.5 h before steaming. Moisture concentration (immediately following flaking) of regular- and tempered-flaked corn averaged 17.3 and 21.0%, respectively. There were no interactions between moisture concentration of the grain and flake density on the NE value of steam-flaked corn. Consistent with results reported by Zinn (1990b), moisture concentration of steam-flaked corn did not influence either growth performance or the NE value of the corn. However, flake density remained important: decreasing flake density from 0.39 to 0.31 kg/L increased ADG (4.5%), feed efficiency (3.0%), and the NE\textsubscript{ADG} and NE\textsubscript{EE} values of steam-flaked corn by 3.4 and 4.2 Mcal/kg, respectively. The magnitude of these improvements in NE value of corn from decreasing flake density was in close agreement with those reported by Zinn (1990a). Apparently, starch digestibility is less dependent on moisture concentration at flaking than on flake density.

Due to the compact nature of starch molecules within the starch granules, particularly in the hard endosperm portion of kernels, penetration by comparatively large amylolytic enzymes is restricted (McAllister et al., 1990). Although it has been proposed that digestion of cornstarch granules must proceed inward from the outside (French, 1973), partially digested cornstarch granules appear hollow (McAllister et al., 1990). Indeed, starch granules of the soft or floury corn endosperm have pores on their orange-peel-like surface; in contrast, the compressed spheres of starch in the vitreous or hard endosperm, besides being densely packed and glued together by alcohol-soluble zeins, have no pores for enzyme entry (Dombrink-Kurtzman and Knutson, 1997) and thereby resist digestion. Because the time for penetration of starch granules of the hard endosperm of corn grain is thought to be too slow for optimal starch utilization, most efforts to improve starch digestion have focused on enhancing starch solubility. However, as mentioned above, the primary barrier to digestion of native cornstarch appears to be the protein matrix that encapsulates the starch granules. With wheat, the protein matrix consists largely of glutenins; these are soluble in weak acid and base and are readily degraded in the rumen. Consequently, extent of ruminal digestion of wheat starch is high (> 80%) and it is not increased by steam flaking (Zinn, 1994). In contrast, the protein matrix surrounding the cornstarch granule is composed primarily of the prolamin, zein. Several types of zein (alpha, beta, gamma, and delta) are found in corn grain. Although zein proteins are insoluble in alcohol, they are insoluble within the ruminal environment. Consequently, zein proteins are fermented slowly in the rumen (NRC, 1985). Disruption of this protein matrix is essential for optimizing starch digestion. The feasibility of disrupting the protein matrix will vary with the amount of protein associated with the starch granule. Some starch granules are surrounded by a thick protein matrix. These comprise the vitreous or horny endosperm, so named because of its hard or flinty nature. The vitreous endosperm is found on the lateral sides of the dent corn kernel. In contrast, the more floury endosperm has starch granules surrounded by a thinner protein matrix. Starch granules within the floury endosperm are more open or loosely packed, giving the starch an opaque, floury appearance.

The close association of the protein-rich horny endosperm to the outer surface of the kernel is fortuitous for grain processing. Being near the kernel surface, the hard starch of the endosperm is directly exposed to the shear forces during flaking of corn grain. Merely increasing starch solubility by 5 to 10 percentage units (i.e., 13 vs 20%) will increase total tract starch digestibility from 90 to over 99% (Zinn et al., 1998).

As discussed later, improvements in total tract starch digestion with steam flaking are the result of increases in both ruminal and postruminal starch digestibility. Of these two, the latter appears to be of greater economic importance. Shear, particularly of the protein-rich horny endosperm, will expose more of the corn protein to the postruminal proteolytic process; this, in turn, increases the exposure of associated starch to the amylolytic process. Hence, a linkage between postruminal protein and starch digestibility would be expected. In-
deed, increased postruminal protein digestibility is a consistent effect of steam flaking corn (Zinn, 1990a; Zinn et al., 1998; Barajas and Zinn, 1998). The marked increase observed in postruminal starch digestibility due to steam flaking corn (53 ± 26%) is associated with an appreciable increase (13 ± 6%) in postruminal N digestibility.

Steam flaking corn also may exert a positive associative effect with fermentable fiber through increasing the potential for postruminal fermentation. Generally, pH of feces is inversely correlated with fecal starch concentration, though other factors (dietary buffers and protein) can influence fecal pH. Starch that reaches the large intestine reduces pH considerably below the optimum for bacterial fermentation of cellulose. Through decreasing the amount of starch that reaches the large intestine to be fermented there, flaked corn helps maintain a cecal pH that is high enough to be suitable for microbial fermentation of NDF and ADF. Consequently, one of the advantages of flaking grain is to increase digestibility of fiber, both from the NDF inherent in corn grain (6 to 10% of DM) and digestible NDF from roughage included in the diet. Compensatory fiber digestion in the large intestine will not be fully realized when either substrate (very low digestibility roughage) or retention time (high amounts of dietary roughage) may limit fermentation in the large intestine.

Retrogradation

If granule shear is the primary factor affecting starch availability, then how important is starch retrogradation that occurs as flaked corn dries? Retrogradation refers to the re-association of dispersed starch molecules. The stability of gelatinized starch is directly proportional to the degree of dispersion of starch molecules but inversely proportional to amylose concentration. Retrogradation causes a glue-like hardening of affected segments of starch; this decreases porosity of the internal starch matrix and limits rehydration and enzyme penetration. Ward and Galyean (1999) observed that enzymatic starch availability was 40% lower for steam-flaked corn that was sampled after storage in a holding bin than for the same corn sampled from directly beneath the flaking rolls. Enzyme reactivities were 33 vs 55%, respectively. Nevertheless, in vitro digestion (measured in 4-h intervals) was not different for the fresh and the bin-stored samples.

Allowing steam-flaked corn to dry is not synonymous with retrogradation. Zinn and Barajas (1997) observed that starch solubility, one measure correlated with starch gelatinization, was similar (26.0 vs 26.6) for freshly prepared steam-flaked corn and steam-flaked corn that had been allowed to air-dry on a concrete pad for 5 d. Furthermore, no differences were detected between fresh and air-dry steam-flaked corn in ruminal or total tract starch digestion.

Figure 2. Steam flaker component illustration.

Optimizing Flake Quality

A component illustration of a steam flaker is presented in Figure 2. Five critical factors that influence the quality of steam flaked corn are 1) steam chest temperature, 2) steaming time, 3) roll corrugation, 4) roll gap, and 5) roll tension. For extermination of viable weed seed, local ordinances may require that grain in the steam chest be exposed to a temperature of greater than 96°C for a minimum of 3.75 min (CDFA, 1984).

Very little research has evaluated the minimal steaming time necessary to produce an optimal flake. Zinn (1990b) demonstrated that steaming for more than 30 min did not enhance either starch digestibility (already over 99%) or the NE value of corn flaked to a density of 0.31 kg/L. Typically, the minimum steaming time is a function of maximum roller mill capacity at a given flake density and the size of the steam chest. Because flaker mills are usually operated at or near their maximum capacity, steam chests should be designed so that their capacity is sufficient to allow for a steaming time of 30 min at maximum roller mill capacity producing a flake of 0.31 kg/L.

Steaming time is regulated by a feeder bar at the base of the steam chest (Figure 2). Small changes in velocity of the feeder bar can make a dramatic difference in the appearance of the flake. The effect is due only partly to changes in steaming time, because appearance of flakes changes immediately when the velo-
ity of the feeder bar is changed. This may be a result of an alteration in the gap between the flaking rolls. The rate of feeding and distribution of kernels along the rolls also can alter the gap between the flaking rolls. Uneven feeding of kernels along the rolls can widen the roll gap; a widened gap will permit more whole or poorly processed kernels to pass between the rolls. This problem can be reduced by proper regulation of the initial roll gap (Figure 2), the tension between rolls, and by “pin feeders” to help maintain even distribution of kernels across the full width of the flaking rolls.

In practice, flaking rolls are adjusted before flaking by one of two methods. One method is to set the rolls to have zero tolerance (zero initial roll gap) and apply a moderately lower ram pressure or tension on the rolls (usually about 3,500 kPa) so that grain passing between the rolls will force a gap to be formed. The other method is to set the gap between rolls at a fixed distance (0.8 to 1.0 mm) and apply a higher ram pressure (usually about 6,000 kPa) so that grain cannot markedly increase the gap between the flaking rolls. In either case, the ram pressure applied to the rolls will depend on the desired flake density.

An advantage of setting the rolls at zero tolerance with less ram pressure is that this will allow a hard rock or bolt to pass between the rolls with minimal damage to the flaking rolls. However, at zero tolerance, the flaking rolls may wear against each other should the flow of corn to the rolls stop or be otherwise impeded. Furthermore, setting a minimal roll gap (0.8 to 1.0 mm) with high ram pressure, the flakes produced will have a more uniform and consistent thickness.

The influence of initial roll gap (zero tolerance vs 1 mm) on fecal starch excretion in steers fed corn flaked to densities of 0.26 to 0.41 kg/L is presented in Table 4. Flake densities were achieved by altering ram pressure. At all flake densities, fecal starch was lower for corn flaked through rolls set with an initial gap of 1.0 mm, presumably because this setting allowed fewer poorly processed kernels to pass through the flaking rolls. At the higher flake density (0.41 kg/L) the percentage of fecal starch was decreased 25% for 1.00 vs 0 mm roll gap.

In an effort to conserve steam, some mill operators reduce or completely stop the flow of steam to the lowest section of the steam chest. However, for optimal shear effect, it is important that the rolls be hot and that kernels do not cool before being flaked. If the steam chest does not have a thermometer in its lowest section, then the steam line to the lowermost section should be opened to about 80% of the minimum that will cause corn to be “blown” by the feeder bar.

Assessing Adequacy of Processing

Quality standards for steam-flaked corn usually are based on some physical measurement such as flake thickness (mm; taken as the average thickness of 10 whole flakes, selected at random), flake density (kg/L), starch solubility (amyloglucosidase-reactive starch), and enzyme reactivity (porcine-pancreatin-amylase-reactive starch). One advantage of flake thickness as a measure of flake quality is that this measurement is independent of time, conditions, or location (i.e., at the holding bin, at the feed bunk, in a sample of complete mixed feed). Other measurements, such as flake density, will change with freshness of the flakes, weighing bucket size, moisture loss, and abrasion during handling of grain, but flake thickness remains constant. The relationship between flake thickness (FT, mm) and flake density (FD, kg/L) is moderately close ($r^2 = 0.74$; $FD = 0.042 + 0.14FT$), but flake density can vary with degree of fines present with the flakes (Zinn, 1990b).

 Flake density is the quality standard used most commonly for steam-flaked corn. Because it can be measured directly as corn exits the rolls, the flaking process can be adjusted immediately based on flake density. Furthermore, flake density is closely associated with changes in starch solubility ($r^2 = 0.87$) and enzyme reactivity ($r^2 = 0.79$). Unfortunately, however, flake density appears less reliable as an index of in vivo starch digestibility. In a summary of 64 trials involving steam-flaked corn (Figures 3 and 4), flake density explained only 22% of the variation in ruminal starch digestion and 52% of the variation in total tract starch digestion. Timing also can alter flake density value, because hot flakes rapidly settle as they cool. Flake density should be measured consistently, either within a few seconds after the grain is flaked or after the sample has been allowed to cool. Measurements with a container larger than that typically used for determining density of whole grain are more repeatable and reliable due to reduced friction of flakes with the sides of the bucket. Live animal measurements are the ideal indicator of the adequacy of the steam flaking process. Such measurements include percentage fecal starch and fecal pH. In the 64-trial summary mentioned previously, changes in flake density explained 63% of the variation in fecal starch ($FS = -12.6 + 47.3FD$). However, direct determination of fecal starch explained 68% of the variation in ruminal starch digestion, and 91% of the variation in total tract starch digestion ($TSD$; Figure 5). Because of the very close and direct relationship between fecal starch and starch digestion, and because starch digestion, alone, can explain most of the variation in the NE value of corn ($Corn NE_m = -0.70 + 0.032TSD$; $r^2 = 0.88$), analysis

<table>
<thead>
<tr>
<th>Item</th>
<th>Flake density, kg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.26</td>
</tr>
<tr>
<td>Roll gap, mm</td>
<td>0</td>
</tr>
<tr>
<td>Difference, %</td>
<td>−2.9</td>
</tr>
</tbody>
</table>

Table 4. Influence of roll gap and flake density on percentage fecal starch

$FD = 0.70 + 0.032TSD$; $r^2 = 0.88$.
of fecal starch can be used to directly assess the NE value of corn: \( \text{NE}_m = 2.50 - 0.021\text{FS}, \ \text{NE}_g = 0.877\text{NE}_m - 0.41 \).

Acid production in the cecum and large intestine increases with increasing postruminal fermentation of starch. Hence, fecal pH and fecal starch are inversely related (Zinn and Owens, 1980). Barajas and Zinn (1998) observed that in cattle consuming dry-rolled and steam-flaked corn-based finishing diets, fecal pH (FpH) explained 26% of the variation in fecal starch (FS = 114.2 - 17.0FpH; n = 80). The regression equation for dry-rolled corn, alone, was: FS = 100.0 - 13.4FpH (n = 40; \( r^2 = 0.34 \)). The regression equation for steam-flaked corn, alone, was FS = 28.1 - 3.88FpH (n = 40; \( r^2 = 0.15 \)). This limited association between FpH and percentage FS suggests that other factors (e.g., dietary buffers) can limit the practicality of fecal pH as a measurement for assessing efficiency of corn processing.

Does Steam Flaking to Increase Extent of Ruminal Digestion Reduce the Quantity of Cornstarch That Is Digested in the Small Intestine?

Feeding a combination of dry-rolled (or whole shelled) corn along with steam-flaked corn has been suggested to augment both ruminal and postruminal starch diges-
tion. This speculation is due, in part, to the concept that the brief retention time of starch particles in the small intestine (under 4 h) along with enzyme insufficiencies might limit the amount of starch that can be digested postruminally (Karr et al., 1966). One might speculate that flaking the majority of the corn in the diet would reduce starch flow to the small intestine and permit a greater amount of starch from dry-rolled corn to be digested postruminally. The primary weakness of this “retention time-enzymatic capacity limitation” theory is that postruminal starch digestibility is much lower for dry-rolled than for steam-flaked corn; furthermore, postruminal digestibility increases as starch flow to the small intestine increases (Figure 6). With dry-rolled corn, ruminal starch digestion as a percentage of starch intake ($\text{RSD}_\text{I}$, 59 ± 12%) and postruminal starch digestion as a percentage of starch entering the small intestine ($\text{PSD}_\text{I}$, 63 ± 10%) are inversely related ($\text{PSD}_\text{I}$, % $\text{RSD}_\text{I} = 280 - 2.86\text{RSD}; r^2 = 0.76$; Zinn, 1990b; Zinn et al., 1995, 1998; Barajas and Zinn, 1998). Likewise, with steam-flaked corn, ruminal starch digestion (80 ± 6%) and postruminal starch digestion (95 ± 2%) are also inversely related ($\text{PSD}_\text{I}$, % $\text{RSD}_\text{I} = 247 - 1.60\text{RSD}; r^2 = 0.94$; Zinn, 1990a,b; Zinn et al., 1995, 1998; Barajas and Zinn, 1998). This supports the concept that the most readily fermented starch will be digested in the rumen, leaving a less digestible residue to flow to the small intestine. However, both ruminal and postruminal starch digestion are greater for steam-flaked than for dry-rolled corn, and the depression in postruminal digestibility with increased ruminal starch digestibility is considerably less with flaked than with dry-rolled corn grain.

In order to directly test the “retention time-enzymatic capacity limitation” theory, Zinn et al. (1995) fed steers dry-rolled and steam-flaked corn-based diets at two levels of DMI (1.6 vs 2.4% of BW). With dry-rolled corn, increasing DMI (and hence, starch intake) by 50% did not influence the percentage of starch that was digested either in the rumen (as a percentage of intake), postru-

![Figure 5](image1.png)

**Figure 5.** Relationship between fecal starch concentration and total tract starch digestion (64-trial summary).

![Figure 6](image2.png)

**Figure 6.** Relationship between ruminal and postruminal starch digestion of dry-rolled and steam-flaked corn (64-trial summary).
Flaxseed meal and corn processing on starch utilization. In practical growing-finishing trials as well as metabolism trials, Barajas and Zinn (1998) observed the interaction of undegradable protein supply needed for fermentation of starch in the rumen or large intestine. In support of this theory, Veira et al. (1980) observed an inverse relationship between sperm fraction of the kernel and whole shelled corn, the amount of starch disappearing in the intestines (g/d) can be greater for steam-flaked corn than for dry-rolled corn (Zinn, 1990a; Zinn et al., 1995; Barajas and Zinn, 1998). This may be the result of an effect of steam flaking on postruminal digestibility of zein proteins. Coincident with increases in postruminal starch digestibility, steam flaking also increases postruminal protein digestibility. For example, Barajas and Zinn (1998) observed that steam flaking corn increased postruminal digestibility of starch and protein by 41 and 17%, respectively. The marked increase in postruminal starch digestibility with steam flaking corn may be due to shear effects on the protein, and hence, on starch availability, particularly starch from the horny endosperm fraction of the kernel.

Can Protein Supplementation Enhance Postruminal Starch Digestion?

Walker and Harmon (1995) observed that abomasal infusion of starch hydrolyzate in steers decreased the pH and amylase concentration of pancreatic fluid and amylase secretion by the pancreas. Magee (1961) hypothesized that increasing the intestinal protein supply might increase starch utilization by enhancing enzyme secretions. In their studies the quantity and activity of pancreatic amylase increased when casein hydrolyzate was infused into the duodenum of sheep. Taniguchi et al. (1995) observed a slight increase (3%) in digestibility of starch when casein was infused into the abomasum instead of the rumen. In support of this theory, Veira et al. (1980) observed an inverse relationship between dietary CP (9.9 to 16.2%) and fecal starch (28.4 to 22.1%), although low levels of dietary CP might limit ammonia supply needed for fermentation of starch in the rumen or large intestine. In practical growing-finishing trials as well as metabolism trials, Barajas and Zinn (1998) evaluated the interaction of undegradable intake protein supplementation (urea vs cottonseed meal) and corn processing on starch utilization. Increasing protein flow to the small intestine by 13% did not influence the NE value of dry-rolled and steam-flaked corn, as determined in the growth performance trial, nor did it influence site and extent of starch digestion. These findings are consistent with conclusions of Owens et al. (1986) and Zinn et al. (1995) that the physicochemical form of the particulate matter containing starch is the primary factor limiting the amylolytic process, rather than the abundance or activity of enzymes. Postruminal starch digestion appears to be limited by accessibility of the amylolytic process.

Steam Flaking and Ruminal Acid Production: Can Grain Be Excessively Processed?

During the first 4 h after feeding, ruminal pH typically is lower for cattle fed diets containing steam-flaked corn than for cattle fed diets containing dry-rolled or whole shelled corn (Lee et al., 1982; Zinn et al., 1995; Barajas and Zinn, 1998). The extent of this depression in ruminal pH is affected by flake density (Zinn, 1990a). As flake density of corn decreases, starch solubility increases (Zinn, 1990a; Theurer et al., 1999). Starch solubility, alone, explains 67% of the variation in extent of ruminal starch digestion. Thus, extent of ruminal starch digestion also increases with degree of processing. However, as indicated previously, total tract starch digestibility is a Kappa Curve function of degree of processing, reaching a maximum with a flake density of 0.31 kg/L. If grain is processed by steam-flaking beyond this point, rate and extent of ruminal starch digestion can be excessive, causing decreased DMI and increased variation in ADG among animals within a pen and can predispose cattle to acidosis and bloat (Zinn, 1990a). Because multiple factors are involved, definitive studies on optimal starch solubility are limited. At present, it seems prudent to optimize degree of processing on the basis of fecal starch analysis (optimal = 2 to 3% fecal starch).

Steam flaking corn decreases the ruminal acetate:propionate ratio (Lee et al., 1982; Zinn, 1987; Barajas and Zinn, 1998). A reduction in the acetate:propionate ratio reflects a decrease in methane energy loss during ruminal fermentation (Wolin, 1960); this conversion of energy can accentuate the beneficial effect of steam flaking on the NE value of corn. However, more extensive processing did not enhance effects on ruminal VFA ratios (Zinn, 1990a). Hence, decreasing flake thickness may not further augment the favorable effects of steam flaking on methane energy loss and related increases in NE value of corn.

Implications

Proper steam flaking will increase the NE\textsubscript{m} and NE\textsubscript{g} values of normal yellow corn grain by 15 and 18%, respectively. Current feeding standards underestimate the NE\textsubscript{g} value of steam-flaked corn by 3.8% and overestimate the NE\textsubscript{g} value of dry-rolled corn by 5.5%. The increase in digestibility depends on disruption of the protective protein matrix surrounding the starch granules.
ules, rather than simply increasing starch solubility. Flaking of corn increases extent of digestion of starch both in the rumen and in the small intestine; this can largely explain the increased net energy value of the grain. Though availability of starch can be estimated from various measures of gelatinization (flake density, flake thickness, starch solubility, and nutrient release during incubation with amylase), adequacy of steam flaking can be predicted most reliably and directly by measuring the starch concentration of feces.

**Literature Cited**


