Energy Consumption During Flour Milling: Description of Two Measuring Systems and the Influence of Wheat Hardness on Energy Requirements[1]

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ABSTRACT

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Two instruments are described, one that employs a strain gauge transducer with instrumentation to measure energy requirements during milling for any selected roll stand in the Grain Research Laboratory (GRL) pilot mill, and another that employs a watt transducer to measure energy requirements for the roll stands in either the GRL 6-in. or GRL 10-in. laboratory experimental mill. Reproducibility of both instruments was excellent. Both instruments were sufficiently sensitive to detect relatively subtle differences within a series of hard red spring wheats of varying protein content and quality. When compared to results for break flour release and flour starch damage, the energy readings gave an accurate estimate of kernel hardness.

In recent years, as energy has become increasingly expensive, power costs have assumed much greater importance in the economics of flour mill operations. In a recent article, Zwingelberg (1980) estimated that as much as 75% of the energy used in a modern flour mill was associated with the actual milling process. The remaining 25% was for processes such as grain cleaning, storage, flour blending, shipping and packaging, and preparation of mill feed.

One factor expected to significantly influence power consumption during flour milling is kernel hardness. In fact, several hardness tests have been described that are based on the energy required (Anderson et al 1966, Blum et al 1960, Greenaway 1969) or the time required to grind wheat kernels (Kosmolak 1978, Stenvert and Kingswood 1977). The prominent role of wheat species and environment on kernel hardness is widely recognized (Irvine 1970), yet the influence of protein content on kernel hardness has not been established conclusively. Some workers have reported that increased protein content causes increased kernel hardness (Greenaway 1969, Stenvert and Kingswood 1977), whereas others have reported that increased protein content produces softer kernels (Irvine 1970, Moss 1978). This discrepancy may exist because of differences in the types of grain-hardness tests employed (Moss 1978, Obuchowski and Bushuk 1980) or because of the particular qualities of the samples examined.

Recent articles have provided detailed descriptions of two versatile Grain Research Laboratory (GRL) research mills (Black et al 1980a) and a pilot flour mill (Black 1980). These mills were part of an extensive research program into factors that affect the milling operation. The two GRL research mills were equipped with an instrument to measure the power and energy consumed by the mill-drive motors on each roll stand. A direct-current (DC) output directly proportional to power was used for recording. Energy consumed was accumulated by a digital counter. The pilot mill was equipped with an instrument to measure motor reaction torque of any individual stand of rolls. The design provided for the integration of motor speed and torque to give a power readout and recorder trace. A voltage-to-frequency converter integrated time and power to obtain energy readings accumulated in digital form.

The energy-monitoring devices are described in this article. The reproducibility and sensitivity of the equipment are illustrated by presenting results from a comparative study of the energy requirements during roller milling for some wheats of varying hardness.

INSTRUMENTATION

Pilot Mill

The general concept of the instrument used for obtaining measurements of motor reaction torque and their conversion to power and energy values is shown in Fig. 1. This system, with its

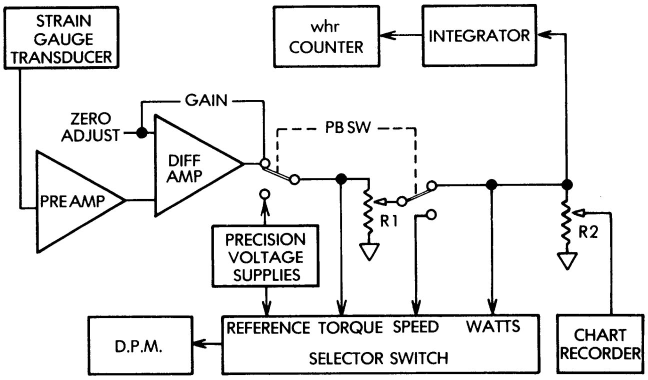

Fig. 1. Concept for obtaining torque, power, and energy values from the reaction force generated by the motor of a given roll stand on the Grain Research Laboratory pilot mill. PBSW = push-button switch, D.P.M. = digit panel meter.

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options of torque, power, and energy readout, was flexible enough to investigate which factors might be most useful in studying the milling characteristics of wheats. Furthermore, this system allowed for compact instrumentation so that, if studies were to be extended to the simultaneous measurement of all roll stand motors, location and space availability would not be a problem.

The strain-gauge transducer consists of four strain gauges bonded to a beam made of hardened tool steel. The 2-HP DC motor used to drive a pair of rolls is mounted in a cradle similar to that shown by Voisey and Kilborn (1974). One end of the beam is clamped to a base plate supporting the motor cradle; the other end is connected through a universal link and lever to the motor housing, which is prevented from rotating by the strain-gauge beam. Therefore, the strain gauges detect the reaction of the motor housing to the torque required to drive the rolls. The lever to the motor is extended past the link connection and has a hole drilled 250 mm from the motor centerline for use with weights in calibrating the strain-gauge signal.

The preamplifier is contained in a relatively small (150 × 150 × 100-mm) dust-tight box and located close to the strain-gauge transducer. It is used to boost strain-gauge signals and thereby minimize electrical-noise interference in the transmission of the signals to the main instrument located about 5–10 m from the motor.

All other components except the chart recorder are contained in a sloped panel box (Fig. 2) measuring 330 × 205 × 235 mm. The differential amplifier provides two functions. The gain control is used to calibrate the strain-gauge signal from the preamplifier in terms of torque. The zero-adjust control is used to null the output of the differential amplifier as the mill runs empty of stock. Torque is monitored through a selector switch by an analogic 3½-digit panel meter (DPM) and/or a Riken Denshi SP-G5V chart recorder by adjusting R2 to provide the desired relationship between torque as read on the meter and recorder response.

To monitor power and energy, speed of the DC motor must be applied as a factor to the torque value. This is accomplished by setting the selector switch to SPEED, holding in the push-botton switch, and adjusting R1 (ten-turn potentiometer) to produce a DPM readout equal to the rpm of the motor. The push-button switch disconnects the amplifier from R1 and applies in its place a precision-regulated voltage of 1.998 ± 0.001 V. With R1 in one extreme position, this voltage appears at the DPM and is read as 1,998 rpm. With R1 in the other extreme position, the voltage appearing at the DPM is 0. Therefore, a speed setting of 0–1,998 may be dialed in directly. This will proportion torque values at the slider of R1 according to speed when the push-button switch is released.

In converting torque and speed measurements to the electrical equivalent (watts), the following formula was used:

$$\frac{2\pi\,Tn}{611.7} = \text{electrical equivalent (watts)},$$

where T = torque in kg-cm, n = rpm of motor, and 611.7 = equivalent in kg-cm of 1 W.

For any given torque level, n is directly proportional to watts. Conversely, for any given speed, T is directly proportional to watts. Therefore, by proportioning T (using R1) according to n, a value representing the product of each is obtained when the push-button switch is released and may be read with the selector switch in the watts position.

This corrected signal voltage appears at both R2 (and hence the recorder) and also at the integrator, a voltage-to-frequency converter made by North Hills Electronics, model IV 110. The integrator is calibrated to drive an electromechanical counter in increments representing 0.1 watt-hours (WH) as derived from the signal representing watts. As long as the push-button switch is in the normally closed position (released), moving the selector switch does not interfere with signals appearing at the recorder or integrator.

Other features of the instrument include a reference voltage that may be switched into the system for rapid checking of the performance of the integrator and for calibrating the recorder level using R2.

Experimental Mills

The instrumentation used for the experimental mills is based on an AC watt transducer and provides readouts of power and energy. Space and drive unit configuration precluded the use of strain gauges with the drive units of the pilot mill. Also, the AC measuring system can be simply electrically switched to measure individual stands of rolls on either the 6- or 10-in. mills with a much lower component count than is possible with a strain-gauge system. The general concept of the instrumentation is shown in Fig. 3.

The single-phase AC mains power may be applied either directly or through a 230-V 5KVA Sola voltage regulator and a watt transducer to the individual motors driving the mill by selecting with switches (SW) 3–6. The voltage regulator compensates for line and load variation and provides a stable power source when monitoring energy. The watt transducer is an Exceltronic model XL 5C5A2 (Scientific Columbus) having a DC signal output of 0–1 mA, which is directly proportional to power passing through it and corresponds to a range of 0–2,000 W. The DC voltage produced from this signal appears across R1 and the GROSS terminal of SW1. The slider of the potentiometer R1 may be used to correct for mechanical efficiency of the drive system by reducing the signal voltage in proportion to mechanical losses (as applied to dough mixers by Kilborn and Tipples 1973). In this study, only gross values were used. The common terminal of SW1 passes the signal voltage to the input of the differential amplifier. The gain control of the amplifier is used to raise the signal voltage to the desired level for driving the integrator, and the zero control for zeroing out the signal produced by the mill running empty of stock. R2, integrator, counter, and chart recorder are used as described for the pilot mill. A reference voltage allows the daily checking of these components, using SW2. The power panel and monitoring system are shown in Fig. 4.

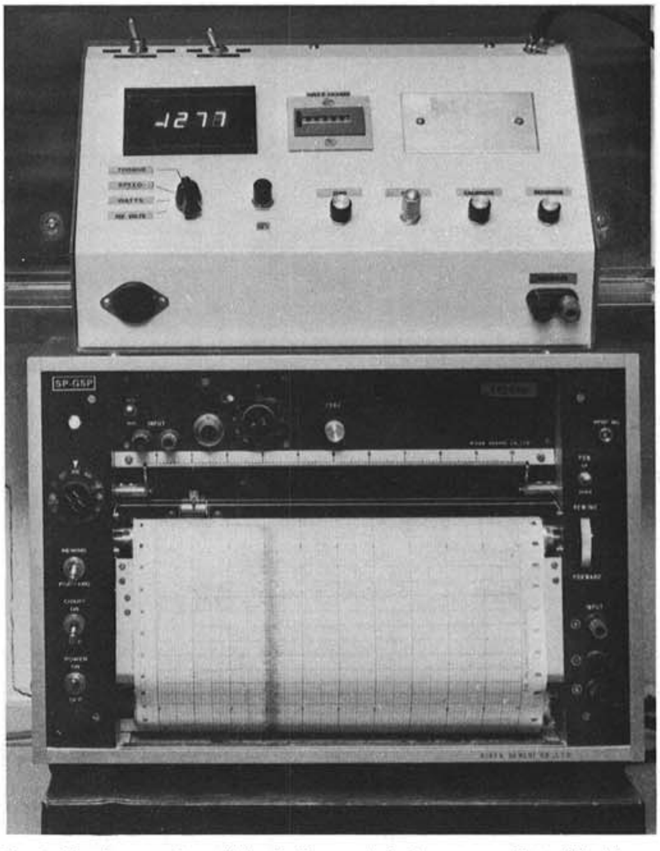

Fig. 2. Monitor station of Grain Research Laboratory pilot mill. **Above**, sloped panel box containing instrumentation; **below**, chart recorder.

MATERIALS AND METHODS

Wheat

Four samples of No. 1 Canada Western red spring (CWRS) wheat of varying protein content (RS 15.0, RS 13.7, RS 13.2, RS 12.4) were obtained from an export terminal elevator in the fall of 1980. Other samples included a composite sample of Canadian hard red spring wheat from the 1980 crop degraded to Canada Feed (CFD) because of light test weight and damage, two composite samples of No. 1 Canada Western amber durum (AD) of different protein levels (12.3 and 14.6) from the 1980 crop, and an English soft wheat (ESW). Some quality characteristics are listed in Table I.

Milling

For optimum sifting properties and flow of stock during milling, the ESW was milled untempered (wheat moisture 14.3%). All other samples were tempered to 16.5% moisture for 18 hr. Although energy measurements can be made on the GRL 6-in. experimental mill, only the 10-in. experimental mill and the pilot mill were used in this study.

Each wheat sample was milled four times in 2-kg portions in the 10-in. GRL experimental mill (Black et al 1980a) using a previously described mill flow (Black et al 1980b). Power consumption was monitored at each stage of grinding, individual mill streams collected, and a portion of each used to prepare straight-grade flour. Break flour release was computed from the total combined weight of flour produced by the four breaks expressed as the proportion of wheat passing through the first break rolls.

Sufficient material remained to study the ESW, the four CWRS samples of varying protein content and AD 12.3, using the pilot mill (Black 1980). Preliminary studies found no significant differences in power consumption among any of the wheats during grinding in the first break rolls at several roll-gap settings. Therefore, power consumption was monitored at another phase of the milling process. The most convenient approach was to convey stock from the first break directly to the third break rolls, bypassing the first break sifter. Energy consumption during grinding on the third break rolls was measured three times for 2-kg portions of each wheat. After passage through the third break rolls, stock was sifted on a box sifter and break flour release expressed as the proportion of material which passed through an 8 XX sieve. A portion of the flour was retained for analyses.

Starch Damage

Starch damage was determined on individual mill streams and straight-grade flour by the method of Farrand (1964).

RESULTS AND DISCUSSION

Reproducibility of Energy Readings

As a preliminary study, the reproducibility of the energy readings was determined at each stage of grinding for the 10-in. experimental mill. A sample of CWRS wheat from 1978 was milled 10 times in 2-kg portions on separate days. As shown in Table II,

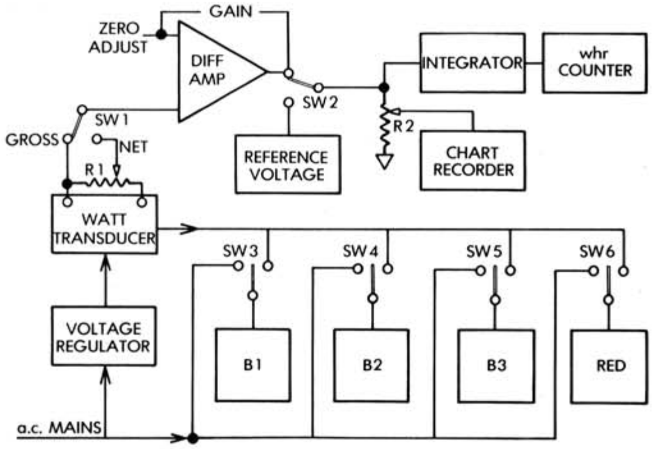

Fig. 3. Concept for obtaining power and energy measurements from a watt transducer connected to the drive motor of a given roll stand on the Grain Research Laboratory experimental mills. SW = switch, B = break roll stand, RED = reduction roll stand.

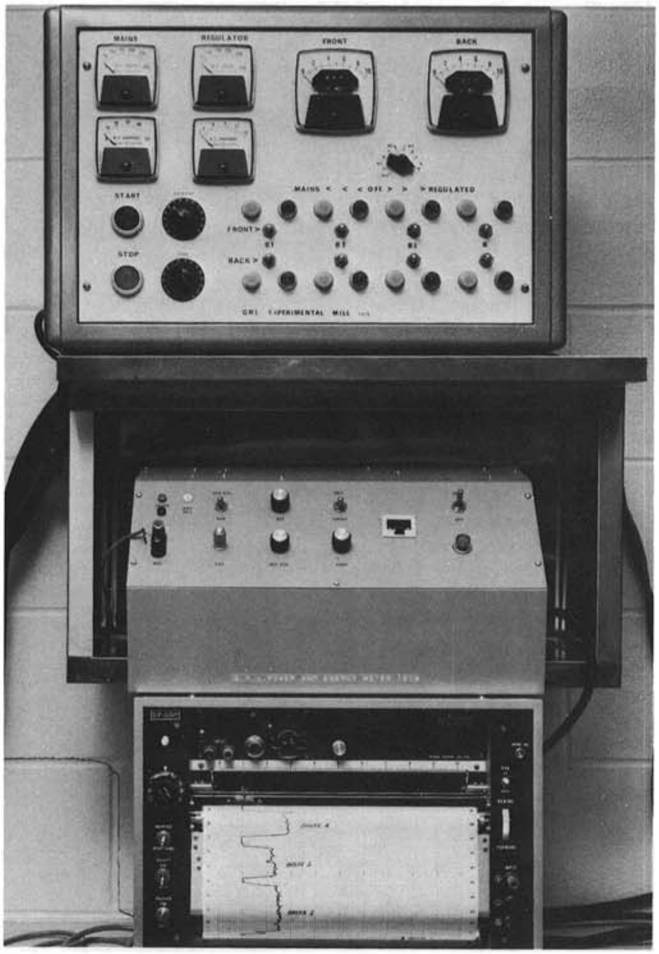

Fig. 4. Control and monitor station of Grain Research Laboratory experimental mills. **Top**, power control panel; **middle**, sloped panel box containing monitoring instrumentation; and **bottom**, chart recorder.

TABLE I
Some Quality Characteristics for Wheat Samples[a]

	Wheat Samples							
Property	**ESW**	**RS 15.0**	**RS 13.7**	**RS 13.2**	**RS 12.4**	**CFD**	**AD 12.3**	**AD 14.6**
Hectoliter weight, kg	77.8	80.3	80.9	81.5	80.9	74.9	82.7	82.1
Protein, %	11.4	15.0	13.7	13.2	12.4	12.9	12.3	14.6
Ash, %	1.58	1.57	1.49	1.50	1.66	1.61	1.46	1.45
Flour yield,[b] %	74.0	77.1	76.8	76.5	76.3	73.0	75.8	75.4

[a] ESW = English soft wheat, RS = red spring, CFD = Canada Feed, AD = amber durum.
[b] Milled in a 10-in. experimental mill.

reproducibility was excellent at all stages of milling. The coefficient of variation for total energy consumption was lower than that for any individual roll stand despite the expectation of cumulative error in summing the results. This was probably due to slight variations in the amount and character of stock being fed to the various rolls. This, in turn, may have been caused by such factors as slight differences in tempering, feed rate, and sieving efficiency, which tended to partly cancel out over the course of the milling.

Reproducibility for energy readings on the third roll stand when serving as the second break was also very good (Table II), based on 10 separate determinations for 2-kg portions of a CWRS wheat from 1979. A major source of error when examining 2-kg samples on the pilot mill was caused by accumulation of stocks in the spouting above the roll stand, which made it necessary to clean the mill between readings. Wheat is normally milled in the pilot mill in quantities of 20 kg or greater, and under those circumstances reproducibility would be expected to improve.

TABLE II
Reproducibility of Energy Readings[a]

Roll stand	Energy Consumption[b] Mean	Energy Consumption[b] Standard Deviation	Coefficient of Variation (%)
Experimental mill			
B1	1.8	0.064	3.57
B2	6.4	0.131	2.05
B3	1.8	0.061	3.49
B4	2.1	0.086	4.11
M1	0.7	0.058	8.47
M2	3.2	0.081	2.55
M3	1.1	0.067	6.25
M4	3.2	0.075	2.38
M5	1.3	0.104	8.03
M6	0.4	0.026	7.03
All breaks	12.1	0.184	1.52
All reductions	9.8	0.198	2.02
Total energy	21.9	0.399	1.37
Pilot mill			
B2[c]	3.7	0.125	3.36

[a] At each stage of grinding on the Grain Research Laboratory 10-in. research mill and during grinding in a selected roll in the Grain Research Laboratory pilot mill for a representative Canadian hard red spring wheat sample.

[b] Watt hr/kg of wheat going to B1.

[c] Third break roll stand used as second break.

Energy Requirements During Milling and Wheat Hardness

Large differences were observed in the energy requirements between the eight wheats milled in the 10-in. experimental mill and for the six wheats milled in the pilot mill (Table III). Energy readings taken on the pilot mill were in complete agreement with the trends established with the 10-in. experimental mill. As expected, the ESW exhibited a very low energy requirement, whereas the two AD samples exhibited a very high energy requirement. Of particular interest was the trend established for the four CWRS samples of varying protein content and the CFD sample. An inverse relationship existed between energy requirement during milling and protein content for the CWRS samples. The CFD sample, in turn, when milled in the 10-in. experimental mill, exhibited a 20% greater energy requirement than the CWRS samples of comparable protein (RS 13.2 and RS 12.4). These data were in complete agreement with the report of Irvine (1970) that the hardness of RS wheat, as measured by flour starch damage, was inversely related to both protein content and grain quality. In contrast to the CWRS samples, the two durum wheats appeared to show the opposite trend; the low-protein sample exhibited a slightly lower energy requirement than the higher-protein sample. Definite conclusions could not be drawn from the limited number of samples included in the current study, but parts of the discrepancy in the literature concerning the relationship between wheat hardness and protein content (Greenaway 1969, Irvine 1970, Moss 1978, Stenvert and Kingswood 1977) may be caused by different behavior by different wheat classes.

The various wheats exhibited similar rankings in energy requirements at almost all stages of milling in the 10-in. experimental mill (Table III). However, variations between wheats generally were much greater during the reduction process than in the break process. In particular, a definite trend could not be established among the wheats during passage through the first break rolls. A similar result was found during a preliminary study in the pilot mill. A comparison of ESW and AD 12.3 demonstrated only a very slight difference in energy requirements during passage through the first break rolls (results not shown). However, as shown in Table III, when energy requirements were monitored during a second break, a definite trend between samples was established. These results are in agreement with a recent report by Obuchowski and Bushuk (1980), who found that, although hardness values for debranned grain ranked wheat cultivars in the same order as for values determined on whole wheat, bran had a definite influence on results for grain hardness evaluation.

TABLE III
Energy Consumption[a] During Milling for Some Widely Differing Wheats

Roll stand	Wheat Sample[b] ESW	RS 15.0	RS 13.7	RS 13.2	RS 12.4	CFD	AD 12.3	AD 14.6
Experimental mill[c]								
B1	1.4	1.5	1.5	1.4	1.5	1.7	1.3	1.5
B2	4.1	5.7	5.8	6.1	6.4	7.0	7.3	7.3
B3	1.8	1.5	1.5	1.6	1.7	2.3	2.3	2.3
B4	0.7	1.7	1.7	1.9	1.8	2.2	3.2	3.2
M1	0.4	0.6	0.6	0.7	0.7	1.0	1.7	1.9
M2	1.5	2.8	3.0	3.2	3.2	3.5	5.6	5.5
M3	0.3	0.9	0.9	0.9	0.8	0.9	1.3	1.3
M4	1.8	2.5	2.5	3.0	2.9	3.7	6.5	6.4
M5	0.6	0.9	0.9	1.1	1.1	1.6	2.9	3.9
M6	0.3	0.2	0.2	0.3	0.3	0.6	1.0	1.2
All breaks	8.0	10.4	10.5	11.0	11.4	13.3	14.1	14.3
All reductions	4.9	7.9	8.1	9.2	9.0	11.3	19.0	20.2
Total energy	12.9	18.3	18.6	20.2	20.4	24.6	33.1	34.5
Pilot mill[d]								
B2	3.2	3.5	3.7	3.8	4.0	ND	4.4	ND

[a] Watt hr/kg of wheat going to B1.

[b] ESW = English soft wheat, RS = red spring, CFD = Canada Feed, AD = amber durum, ND = not determined.

[c] Results are average of four separate determinations.

[d] Results are average of three separate determinations.

TABLE IV
Break Flour Release and Flour Starch Damage for Some Widely Differing Wheats

	Wheat Sample[a]							
	ESW	RS 15.0	RS 13.7	RS 13.2	RS 12.4	CFD	AD 12.3	AD 14.6
Experimental mill[b]								
Break flour release, %	32.9	25.1	24.2	23.1	22.6	19.2	12.7	12.0
Starch damage, Farrand units								
B1 + B2	7	18	17	21	22	30	58	51
B3	9	14	16	16	19	28	46	41
B4	5	21	21	23	23	34	57	50
Bran flour	15	18	19	20	24	32	42	35
M1 + M2	7	26	25	28	28	40	62	56
M3	9	26	25	27	27	37	58	53
M4	7	31	30	35	34	48	67	62
M5	9	35	33	36	35	53	71	65
M6	10	39	39	42	42	57	78	70
Straight-grade	7	27	26	30	30	42	63	60
Pilot mill[c]								
Break flour release, %	36.0	28.4	27.6	25.0	25.6	ND	16.0	ND
Starch damage, Farrand units								
B1 + B2	8	18	19	21	23	ND	35	ND

[a] ESW = English soft wheat, RS = red spring, CFD = Canada Feed, AD = amber durum, ND = not determined.
[b] Average of four millings.
[c] Average of three millings.

Obuchowski and Bushuk (1980) also observed that hardness indices for a debranned RS wheat cultivar exhibited no relationship between protein content and endosperm hardness. In contrast, in the current study (Table III) an inverse relationship appeared to exist between protein content and energy requirements throughout the reduction process for the four CWRS wheats of various protein content.

Flour starch damage (Irvine 1970, Williams 1967) and break flour release (Stenvert 1972) are two widely used measures of wheat hardness. In the current study, break flour release (Table IV) in the 10-in. experimental mill was very highly correlated to energy requirements (Table III) for all breaks ($r = -0.98$), all reductions ($r = -0.96$), and total work ($r = -0.98$). A similar high correlation ($r = -0.97$) was observed between samples for energy requirements and flour release during passage through the second break in the pilot mill.

Starch damage values for the various flour streams and straight-grade flours (Table IV) were generally in excellent agreement with both energy requirements (Table III) and break flour release (Table IV). With a few exceptions, the wheats could be ranked in the same order of hardness based on starch damage results at all stages of milling.

A slight anomoly appeared to exist in the relative flour starch damages for the two AD samples. Based on energy requirements (Table III) and break release (Table IV), AD 12.4 was slightly softer than AD 14.6. However, based on starch damage results (Table IV), AD 12.4 was slightly harder than AD 14.6.

Kernel hardness is only one factor that would be expected to affect energy requirements during milling. Other factors such as feed rate, roll gap, roll speed, roll differential, and tempering procedure also play a significant role. Research into the effect of these and other factors on energy requirements during flour milling is continuing.

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