

# Quality of Hard Red Winter Wheat Grown Under High Temperature Conditions During Maturation and Ripening<sup>1</sup>

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## ABSTRACT

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High temperature during grain filling has been identified as a major factor in the end-use properties of bread wheat (*Triticum aestivum* L.). Our objectives were to assess the effect of high temperature during maturation on the grain characteristics, milling quality, and flour quality of hard red winter wheat. In three separate experiments, plants of wheat cultivar Karl 92 were subjected to regimes (day-night) of 20-20, 25-20, 30-20, and 35-20°C from 10 and 15 days after anthesis (DAA) until ripeness, and 25-20, 30-20, and 35-20°C from 20 DAA until ripeness. In other experiments, plants of wheat cultivars Karl 92 and TAM 107 were dried at 20 and 40°C, and spikes of Karl 92 were dried at different temperature and humidity conditions to assess the effects on quality of high temperature and

drying rates during grain ripening. Flour yield correlated positively with kernel weight and diameter, test weight, and proportion of large kernels. Flour yield decreased as temperature increased and correlated negatively with hardness index and proportion of small grains. High growth temperatures and rapid grain desiccation decreased mixing time and tolerance of the flours. The greatest damage occurred when high temperature was maintained continuously from early grain filling until ripeness. Weakening of dough properties by rapid desiccation during ripening suggest that temperature, humidity, and possibly soil moisture all contribute to the final quality of bread wheat.

Hard wheat is produced primarily in areas of the world with continental climates, which are ideally suited for growing high-protein grain for bread but are also extremely variable. Wide fluctuations in precipitation and temperature among growing locations and seasons in the hard winter wheat production area of the United States have had major effects on milling and end-use quality (Johnson et al 1966, 1972; Bequette 1989; Peterson et al 1992).

Temperatures as great as 35°C are common in hard wheat regions and reduce yield by altering kernel characteristics that probably affect milling quality of the grain. Stress from high temperature during the critical grain-filling period reduced kernel weight (Paulsen 1994). Kernel weight decreased particularly when high temperature occurred continuously during maturation (Wardlaw et al 1980, 1989). However, high temperatures for periods as brief as three days during both early and late stages of maturation reduced kernel weight significantly (Stone and Nicolas 1994, 1995). Other detrimental effects, including shriveled, notched, split, and opaque kernels, also were induced by high temperature during grain development and early maturation (Tashiro and Wardlaw 1990).

High temperatures during maturation might alter functional quality of the grain because kernel characteristics that are affected most are important for milling. Flour yield (a widely used measure of milling quality) and kernel weight (a sensitive yield characteristic) generally correlated positively in ordinary samples (Dattaraj et al 1975, Satumbaga et al 1995, Gwirtz et al 1996), as did two related characteristics, kernel diameter (Shuey 1960, Satumbaga et al 1995) and kernel uniformity (Li and Posner 1987), suggesting the likelihood of a similar association under high growth temperature conditions. Shriveling of kernels from high temperature during maturation may also diminish test weight, another common criterion of milling quality that correlated positively with flour yield (Shuey 1960, Satumbaga et al 1995, Gwirtz et al 1996).

Field studies suggested that temperature is particularly important

in determining the flour quality of hard red winter wheat. Quality was enhanced by moderately high temperature during maturation and ripening (Johnson et al 1972), but normal high temperatures reduced dough mixing times and loaf volumes (Finney and Fryer 1958). Loaf volumes were highly variable and not always reduced by high temperature, however, suggesting that other climatic factors were involved. The other environmental factors had minor effects in the absence of high temperature.

The quality of hard white wheat in Australia is also reduced by high temperature stress. Randall and Moss (1990) found that daily mean temperatures up to 30°C increased dough strength, but higher temperatures, even for brief three-day periods, decreased dough strength. Reduction in dough strength was related to the number of hours >35°C during grain maturation (Blumenthal et al 1991a,b). The results suggested that heat stress increased synthesis of gliadin at the expense of glutenin, diminishing the dough strength. However, the increase in gliadin relative to glutenin in response to high temperature varied among cultivars and stage of kernel development when the stress occurred (Blumenthal et al 1991a, 1995; Stone and Nicholas 1994).

The importance of environmental conditions on milling quality of hard red winter wheat was demonstrated by the greater variation in kernel traits and flour yield among locations and seasons than among cultivars (Johnson et al 1966, Bequette 1989). The specific environmental factors that were responsible for the variation in milling quality are unclear, and the effects of different stress conditions have not been documented. However, the kernel characteristics that are affected by high temperature and the importance of these characteristics in milling quality of grain suggest that heat stress is a major environmental factor. Temperature >32°C during kernel ripening was important in reducing the breadmaking quality of hard red winter wheat, but atmospheric humidity and soil conditions may also be involved (Finney and Fryer 1958, Graybosch et al 1995). Our objectives were to ascertain the effect of high temperature during different stages of maturation and ripening on the kernel characteristics that determine milling and flour quality of hard red winter wheat. Knowledge of these effects will increase understanding of the influence of the environment on wheat and help improve the quality of this important commodity.

## MATERIALS AND METHODS

Five separate experiments were conducted to assess the effects of high temperature on the quality of hard red winter wheat. Three experiments were directed at determining the effects of the tem-

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perature range 20–35°C during maturation of wheat on milling and flour quality of the grain. Temperature treatments were initiated 10, 15, and 20 days after anthesis (DAA) and maintained during maturation and ripening of the grain. Two additional experiments were performed to assess the effects of the temperature range 20–40°C and drying rate during grain ripening on flour quality.

### Growth Conditions

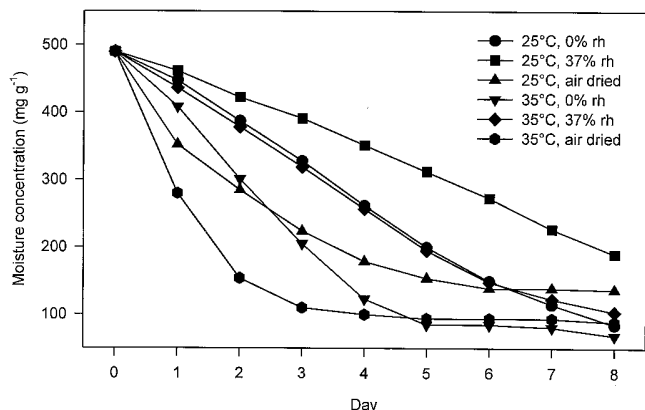
**10 DAA.** Seeds of the hard red winter wheat cultivar Karl 92 were germinated in vermiculite for five days and vernalized at 4°C for six weeks. Thirty-six seedlings were transplanted into 38-L (61 × 41 × 22-cm) plastic tubs containing equal parts of loam soil, sand, and peat moss, and placed in the greenhouse. Three rows of 12 seedlings each were planted for a final plant density of 144 plants/m<sup>2</sup> to simulate field conditions. Seedlings were planted on May 18, August 29, and November 11, 1994, for three replicates over time. The soil mixture in each tub was fertilized with 10 g of 20.0:8.7:16.6 (N-P-K) soluble fertilizer (Peters Professional, W. R. Grace and Co., Fogelsville, PA) at two, four, and six weeks after planting. High-intensity sodium light supplemented sunlight and maintained a 16-hr photoperiod. Temperatures in the greenhouse ranged from 20 to 30°C between night and day, and varied slightly among seasons.

Sixteen tubs containing the plants from each date were distributed randomly among four growth chambers (model PGW-36, Conviron, Pembina, ND) at 10 DAA (anthers extruded from 50% of main culm inflorescences). The chambers were set for temperature regimes of 20-20 (day-night), 25-20, 30-20, and 35-20°C. Daytime and nighttime temperatures were each held for 8 hr; a 4-hr transition period between them resulted in mean daily temperatures of 20.0, 22.5, 25.0, and 27.5°C, respectively.

Relative humidity in the chambers was set at 70%, the photoperiod was 16 hr, and the photon flux density (400–700 nm) was 980 μmol m<sup>-2</sup> sec<sup>-1</sup> at 15 cm from the lamps and 350 ± 50 μmol m<sup>-2</sup> sec<sup>-1</sup> at the plant canopy. Plants were watered as needed. The temperature treatments were maintained until the grain ripened.

Wheat spikes were hand-harvested when all plants reached harvest ripeness. Kernels were removed with a single-spike thresher (Lincoln Mfg. Co., Lincoln, NE), and the grain from plants in each tub was bulked and equilibrated with room temperature and humidity.

**15 DAA.** Growth conditions were similar to 10 DAA with several modifications. Vernalized seedlings were planted on February 7 and April 11, 1995, and June 5, 1996, and fertilized seven days after planting and at the boot stage. Plants were grown in the greenhouse until heading stage, when they were placed in chambers under a 20-20°C (day-night) regime. The same temperature treatments used for 10 DAA were imposed at 15 DAA until the grain was ripe. The latter two plantings were placed in growth chambers (model EG-15, Conviron) that had the same irradiance and photoperiod as before with no humidity control.



**Fig. 1.** Moisture loss from excised spikes of wheat cultivar Karl 92 under different temperature and humidity conditions during grain ripening.

**20 DAA.** Growth conditions were similar to those at 15 DAA. Vernalized seedlings were planted on October 9, 1995, and January 17 and March 7, 1996, and grown in the greenhouse until heading stage. The plants were placed in growth chambers at the heading stage under a 20-20°C (day-night) regime until 20 DAA, when temperature treatments of 25-20, 30-20, and 35-20°C were imposed until the grain ripened.

### Temperature During Ripening

The effect of temperature during grain desiccation on wheat quality was assessed. The top 30 cm of plants (culms and spikes) was cut from field plots of wheat cultivars Karl 92 and TAM 107 near Manhattan, KS, in the early afternoon on June 12, 1996 (early hard-dough stage) and on June 21, 1996 (late hard-dough stage). The culms and spikes were spread loosely in a 3-cm-deep layer on the floor of growth chambers (model E-15, Conviron) set at 20 or 40°C. Air was distributed past the plants through slots in the floor of the chambers, and the temperature was measured adjacent to the plants. Relative humidity, measured with a hygrometer (Micronta 63-844, Tandy Corp., Fort Worth, TX), was 63% rh at 20°C and 16% rh at 40°C. Treatments were replicated three times each date, and 1,700 and 1,300 g of cut plants (fresh weight) were collected per treatment for the June 12 and June 21 collections, respectively. A final harvest to determine quality of the field-ripened wheat was taken on July 11, 1996. Moisture content of the spikes when they were harvested was 54, 40, and 14%; mean dry weight per kernel was 24, 30, and 33 mg on June 12, June 21, and July 11, 1996, respectively. Kernels were removed with a single-spike thresher and the grain from each treatment was bulked and equilibrated with room temperature and humidity.

### Drying Rate During Ripening

The effects of temperature and humidity during ripening of grain were studied by drying wheat spikes at different rates. Spikes of Karl 92 were collected at the hard-dough stage from plots near Manhattan, KS, on June 13 and June 21, 1996, and from greenhouse-grown plants on February 19, 1997. Each sampling date was considered a replicate. Moisture content of the spikes was 49, 48, and 50% on each date, respectively. Samples (250 g) of spikes from each treatment were desiccated in controlled environment chambers (model E-8, Conviron) at 25 or 35°C above 50 (37% rh) or 100% (0% rh) (w/w) H<sub>2</sub>SO<sub>4</sub> solutions or over forced air (45% rh at 25°C and 25% rh at 35°C). H<sub>2</sub>SO<sub>4</sub>, which is strongly hygroscopic, was used to control the rate of water loss from the grain. For the H<sub>2</sub>SO<sub>4</sub> drying treatments, spikes were placed on a perforated, porcelain plate above 1 L of H<sub>2</sub>SO<sub>4</sub> (ACS grade) solution in enclosed 250-mm i.d. glass desiccators (Corning, Inc., Corning, NY). Spikes dried with forced air were placed in a tray on the chamber floor. Spikes from each treatment were weighed each day to determine the rate of moisture loss and dried until they reached moisture equilibrium (Fig. 1). Drying rates were calculated as the average moisture lost per day during the first three days of drying per unit of moisture originally present in the spikes. Naturally ripened grain of plants grown in the field and the greenhouse was harvested to compare with the artificially dried grain. Kernels were removed with a single-spike thresher, and the grain from each treatment was bulked and equilibrated with room temperature and humidity.

### Kernel Physical Characteristics

The kernel characteristics of grain produced under temperature treatments applied at 10, 15, and 20 DAA were determined to assess their influence on milling quality. Grain characteristics were determined with a single kernel characterization system (SKCS) (model 4100, Perten Instruments, Reno, NV). Mean values of kernel weight (equilibrium moisture basis), size characteristics, and hardness (crushing force) of 300 kernels at 180 kernels per minute were recorded. Test weight was measured by a micro procedure using a cup constructed to contain the gram equivalent of pounds per bushel.

Data were expressed as kilograms per hectoliter.

Kernel size distribution of the bulked wheat samples was determined with a Ro-tap sifter (W.S. Tyler, Inc., Mentor, OH) and U.S. standard testing sieves No. 7 (2.80-mm opening) and No. 10 (2.00-mm opening). The percentages of kernels remaining on top of the No. 7 and No. 10 sieves and passing through the No. 10 sieve were recorded.

### Laboratory Milling

The grain from all five experiments was milled to produce flour. Moisture content of the wheat from each treatment was determined by Approved Method 44-15A (AACC 1995). Wheat samples were tempered to 15.0% moisture for 24 hr before milling on a Brabender Quadramat Sr. laboratory flour mill (C. W. Brabender Instruments, Inc., Hackensack, NJ). The mill was stabilized at 30.6°C for ≈1 hr before milling. Four products: break flour, reduction flour, bran, and shorts, were obtained from each milling.

### Flour Analysis

Protein content ( $N \times 5.7$ ) of the flour was determined with a nitrogen analyzer (model FP-2000, Leco Corporation, St. Joseph, MI). Electronic mixographs were created using a 2-g mixograph and analyzed with MIXSMART software (National Mfg. Div., TCMCO, Lincoln, NE). Measurements used as indicators of dough quality were water absorption (percentage of full scale), time to peak (sec), peak height (percentage of full scale), peak width (percentage of full scale), width 2 min after peak (percentage of full scale), and the descending slope of the mixograph curve from the peak until 2 min after the peak (percentage of full scale per minute).

The relative proportion of gliadin to glutenin was determined by SE-HPLC (Batey et al 1991). Protein was extracted from flour in phosphate buffer containing SDS using a sonic dismembrator (model 60, Fisher Scientific, Pittsburgh, PA) and a 3-mm diameter probe at 22.5 kHz and power setting of 16 (10W average output). After centrifugation, supernatants of the flour extracts were analyzed (Waters Protein Pak 300sw column, Millipore Corp., Bedford, MA, and a Hewlett Packard series 1100 HPLC, Avondale, PA). The first major peak, which eluted from the column from 8.2 to 13.4 min, was considered glutenin; the second major peak, which eluted from 13.4 to 18.8 min, was regarded as gliadin.

### Statistical Analysis

The study consisted of five separate, completely randomized experiments, each with three replicates. Data were analyzed by general linear model procedures (SAS Institute, Cary, NC). Least significant differences were calculated at  $P > F = 0.10$ . The relationships between treatment means for flour yield and kernel characteristics

and between treatment means for dough mixing properties and drying rate were determined by regression procedures. Simple correlation coefficients between treatment means for kernel characteristics were determined using correlation procedures.

## RESULTS

### Milling Quality

Wheat plants were exposed to temperatures of 20–35°C during three growth phases: 10, 15, and 20 DAA until ripeness. The effects of the temperature treatments on kernel characteristics were determined as possible indicators of milling quality and flour yield. An SKCS was used to measure the influence of the temperature treatments on the size characteristics of the kernels produced. Both kernel weight (KW) and kernel diameter (KD) were greatest at the lower temperatures in treatments applied 10, 15, and 20 DAA until ripeness (Table I). Significant decreases in KW were observed when the plants were exposed to 30–20°C (day-night) from 10 or 20 DAA and 35–20°C from 15 or 20 DAA to ripeness. KD decreased when 30–20°C was applied from 20 DAA until ripeness and 35–20°C occurred from 15 and 20 DAA. Reductions in weight and diameter as a result of high temperature were relatively small (4–13%).

The hardness of the grain was also tested with the SKCS. Hardness index (HI) increased with higher temperatures when treatments were applied from 10, 15, and 20 DAA until ripeness. The greatest changes in hardness occurred as temperature increased from 25–20 to 30–20°C in all three growth phases. Further increase in temperature >30–20°C resulted in little further change in kernel hardness.

Grain test weight (TW), a commonly used indicator of potential flour yield, was high for most of the treatments and was >80 kg/hL at the low temperature in each of the three growth phases tested. Treatments that significantly reduced TW were 30–20°C from 10 DAA and 35–20°C from 15 and 20 DAA. The timing of the treatments had little effect on the response of TW to temperature, as indicated by similar responses to high temperatures at all three growth phases tested.

The high-temperature treatments had a greater affect on the kernel size distribution than on any other kernel characteristic measured. The proportion of large kernels, measured as grain remaining over the No. 7 sieve, was greatest at the low temperature in all growth phases. Conversely, the proportion of small kernels, which passed through the No. 7 sieve and remained over the No. 10 sieve, and very small kernels, which passed through the No. 10 sieve, were greatest at the high temperature. Kernel distribution was fairly similar at the low temperature for all experiments, but more small kernels resulted from high temperatures at 10 and 15 DAA than from high

TABLE I  
Kernel Characteristics of Wheat Cultivar Karl 92 Exposed to Different Temperatures from 10, 15, and 20 Days After Anthesis (DAA) Until Ripeness

DAA	Day-Night (°C)	Kernel Weight (mg)	Kernel Diameter (mm)	Hardness Index	Test Weight (kg/hL)	Kernel Size Distribution (%)		
						Over No. 7	Over No. 10	Through No. 10
10	20-20	31.2	2.30	71.5	81.5	68.2	31.3	0.5
	25-20	31.0	2.30	73.4	81.8	65.0	34.8	0.3
	30-20	29.2	2.23	80.8	79.9	45.8	53.8	0.4
	35-20	na <sup>a</sup>	na	na	na	18.2	79.0	2.6
LSD <sup>b</sup>	...	1.8	ns <sup>c</sup>	3.7	1.2	19.9	19.4	1.1
15	20-20	28.8	2.26	75.7	81.0	60.3	39.3	0.4
	25-20	27.7	2.21	76.8	79.3	42.3	56.5	1.3
	30-20	27.0	2.17	81.0	78.8	38.9	59.5	1.6
	35-20	25.2	2.07	82.0	77.0	25.8	72.3	2.1
LSD	...	2.9	0.15	4.2	2.3	15.0	15.2	0.8
20	25-20	29.7	2.26	74.5	80.1	57.2	42.0	0.8
	30-20	27.1	2.15	77.6	78.4	41.6	54.6	3.8
	35-20	27.4	2.17	80.4	77.4	37.6	60.5	2.0
	LSD	...	1.9	0.09	3.5	2.2	8.5	8.1

<sup>a</sup> Not available. Insufficient sample for analysis.

<sup>b</sup> Least significant difference ( $P < 0.10$ ).

<sup>c</sup> Not significant.

temperature at 20 DAA.

Ripe grain produced at the different temperatures and growth phases was experimentally milled to produce flour, bran, and shorts. Flour yield was greatest at the low temperature when treatments were applied from 10, 15, and 20 DAA until ripeness (Table II). Increasing temperature from 20-20 or 25-20 to 30-20°C produced insignificant reductions in flour yield, but reductions with further temperature increase to 35-20°C were significant. The timing and duration of the temperature stress were important in determining the magnitude of reductions in flour yield by high temperature. Reductions by 35-20°C from 15 and 20 DAA until ripeness were less severe than when the stress was imposed earlier.

Decreases in flour yield by high temperature were accompanied by increased amounts of bran, regardless of when the stress occurred. However, the amount of shorts only increased when high temperature occurred from 10 and 15 DAA until ripeness. Shorts also increased significantly when the temperature increased from 20-20 to 30-20°C from 10 DAA until ripeness.

Flour yield was related strongly to KW, HI, and TW in all three growth phases. Recovery of flour from milling was associated linearly and positively with KW (Fig. 2A). The relationship of flour yield with TW was similar and even slightly stronger (Fig. 2B). Flour yield and HI, on the other hand, were linked quadratically and negatively (Fig. 2C).

The yield of flour also depended greatly on the diameter and size distribution of the kernels. Flour yield was associated positively and linearly with KD (Fig. 2D) and positively and quadratically with the proportion of large kernels on a No. 7 sieve (Fig. 2E). Conversely, flour yield was related negatively and quadratically to the amount of small kernels on a No. 10 sieve (Fig. 2F). Regression coefficients for flour yield and kernel size distribution characteristics were higher than the coefficient for flour yield and KD.

Simple correlation coefficients between the kernel characteris-

tics that were measured were high, suggesting a common fundamental relationship (Table III). The coefficients indicated that heavier kernels had greater KD and TW and were less hard than lighter kernels. Heavier kernels formed typically under lower temperatures and lighter kernels under higher temperatures.

### Flour Quality

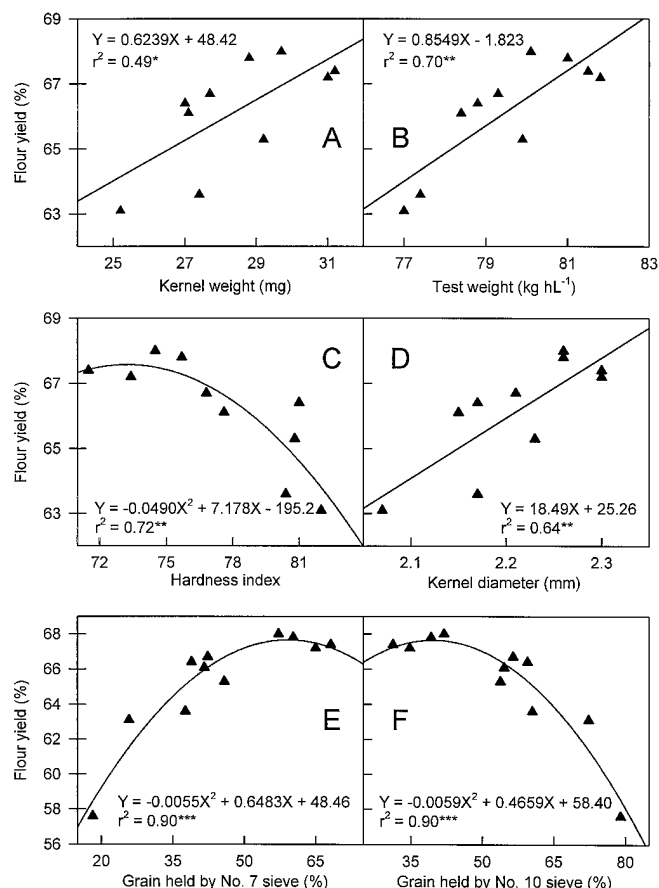
The effect of elevated temperature applied from 10, 15, and 20 DAA until ripeness on the flour quality of grain produced was assessed (Table IV). Two additional experiments were performed to determine the influence of temperature and grain drying rates during ripening on flour quality. In the first of these two experiments, spikes were excised from field-grown plants of Karl 92 and TAM 107 at the early- and hard-dough stages and dried (Table V). In the final experiment, the effects of drying rate during grain ripening were studied by desiccating excised spikes at different rates (Table VI); flour quality data was analyzed for treatment

**TABLE II**  
Flour Milling Characteristics of Wheat Cultivar Karl 92 Exposed to Different Temperatures at 10, 15, and 20 Days After Anthesis (DAA) Until Ripeness

DAA	Day-Night (°C)	Flour Yield (%)	Bran (%)	Shorts (%)
10	20-20	67.4	25.2	7.3
	25-20	67.2	25.1	7.8
	30-20	65.3	25.3	11.1
	35-20	57.6	31.0	11.4
LSD <sup>a</sup>	...	2.4	2.3	2.8
15	20-20	67.8	24.9	7.3
	25-20	66.7	25.8	7.7
	30-20	66.4	25.8	7.8
	35-20	63.1	28.0	9.2
LSD	...	4.2	2.7	1.5
20	25-20	68.0	25.0	6.9
	30-20	66.1	26.6	7.2
	35-20	63.6	28.3	8.1
	LSD	...	3.2	1.8

<sup>a</sup> Least significant difference ( $P < 0.10$ ).

<sup>b</sup> Not significant.



**Fig. 2.** Relationship between flour yield and quality of wheat cultivar Karl 92 exposed to different temperatures during kernel maturation and ripening. Kernel weight (A), test weight (B), hardness index (C), kernel diameter (D), grain held by a No. 7 sieve (E), and grain held by a No. 10 sieve (F). \*, \*\*, \*\*\* = significant at  $P \leq 0.05, 0.01,$  and  $0.001,$  respectively.

**TABLE III**  
Correlation Coefficients ( $r^2$ ) Among Kernel Characteristics of Wheat Cultivar Karl 92 Exposed to Different Temperatures from 10, 15, and 20 Days After Anthesis (DAA) Until Ripeness<sup>a</sup>

	Kernel Diameter	Hardness Index	Test Weight	Kernel Size Distribution	
				Over No. 7	Over No. 10
Kernel weight	0.97***	-0.83**	0.92***	0.95***	-0.94***
Kernel diameter		-0.83**	0.95***	0.96***	-0.95***
Hardness index			-0.83**	-0.91***	0.92***
Test weight				0.96***	-0.94***
Over No. 7					-1.00***

<sup>a</sup> \*\*, \*\*\* = significant at  $P \leq 0.01$  and  $0.001,$  respectively

effects, as well as the main effects of temperature and relative humidity. In all experiments, grain was harvested at ripeness, ground into flour, and analyzed.

Previous studies suggested that cultivars with long mixing times (Finney and Fryer 1958) and allele *Glu-D1d* coding for high molecular weight gluten subunit combinations 5+10 (Blumenthal et al 1995) were more tolerant of high temperature than those with shorter mixing times or allele *Glu-D1a*, which codes for subunits 2+12. Based on these previous findings, two cultivars were used in the current study when determining the effects of excised spikes dried at 20 or 40°C during grain desiccation. Karl 92 had a longer mixing time and subunits 5+10. TAM 107 had a shorter mix requirement and subunits 2+12. There were no cultivar by temperature interactions in this experiment, suggesting that the cultivars reacted similarly to the temperature treatments (data not shown). Therefore, the mean of the two cultivars was used to determine response to temperature (Table V).

Flour protein (FP) range was 14.0–18.5% when temperatures were applied from 10, 15, and 20 DAA (Table IV). The FP values were high when compared to typical values for flour from field-grown wheat; most likely because the plants grown in the growth chambers were well fertilized. FP concentration increased with temperature when treatments were applied 10 DAA until ripeness, but treatments from 15 and 20 DAA until ripeness did not affect FP. The FP content of flour from grain in spikes dried at 20 or 40°C varied with cultivar and date of cutting but was not affected by temperature treatment (data not shown). Flour of grain from spikes dried at controlled rates contained 11.3% protein, which did not vary with treatment.

Dough mixing properties were analyzed using a 2-g mixograph. The optimum water absorption (AB) was measured. Time to peak dough development (PT), height of the mixograph peak (PH), width of the mixograph curve at the peak (PW) were recorded as indicators of dough strength. Width of the mixograph curve at 2 min after the peak (PW+2) and the descending slope of the mixograph curve (DS) were taken as indicators of mixing tolerance.

The AB was closely associated with flour protein concentration. It increased with temperature when the treatments were imposed from 10 DAA until ripeness, but was unaffected by temperature treatments applied 15 and 20 DAA until ripeness (Table IV) and by the temperature and drying treatments during ripening (data not shown).

The PT decreased as temperature was increased from 30–20 to 35–20°C at 10 DAA until ripeness (Table IV). A decline in PT also occurred when excised spikes were dried at 40°C during the late-dough stage (Table V). When spikes were dried under controlled atmospheric conditions, PT was associated linearly and negatively

with the drying rate ( $Y = -0.0139X + 7.85, r^2 = 0.90, P \leq 0.01$ ).

The PH decreased as temperature increased from 30–20 to 35–20°C at 10 DAA until ripeness (Table IV). Temperature treatments applied 15 and 20 DAA and during grain ripening had no discernible effect on PH. When spikes were dried under various controlled rates during ripening, PH was greatest when spikes were dried in the open air (Table VI). The PW decreased when temperature was increased from 30–20 to 35–20°C applied 10 DAA until ripeness (Table IV).

Mixing tolerance was affected by temperature in all five experiments as indicated by PW+2, which was reduced at the highest temperature. The decline in PW+2 was greatest when temperature treatments occurred from 10 DAA until ripeness (Table IV). Reductions in PW+2 were similar under temperature treatments applied 15 and 20 DAA. Similar responses of PW+2 to temperature occurred at the two growth stages tested during grain desiccation; the two cultivars reacted alike to high temperature (Table V). When spikes were dried at different rates, the main effect of high temperature decreased PW+2 from 17.5 to 15.1 (LSD<sub>0.10</sub> = 1.6), but humidity had no effect. The decrease in PW+2 from high temperature treatments was greater than the reductions in curve width at the peak in all five experiments.

The DS was greatest when plants were grown or dried under high temperature in four of the five experiments. The exception occurred when plants were grown at different temperatures from 15 DAA until ripeness, which had no effect on the slope (Table IV). The largest reductions in slope occurred when high temperature

**TABLE V**  
Mean Values of Flour Quality and Mixograph Characteristics for Wheat Cultivars Karl 92 and TAM 107 Exposed to Different Temperatures During Grain Desiccation

Harvest Stage	Temp (°C)	Peak Time (min)	Peak Width (%)	Peak Width + 2 min (%)	Slope %/min	Gli/Glu <sup>a</sup> Ratio
Early hard dough	20	4.8	17.4	14.5	-0.2	1.00
	40	4.1	16.8	9.3	-2.4	0.91
LSD <sup>b</sup>	...	ns <sup>c</sup>	0.4	2.4	1.6	0.04
Late hard dough	20	4.4	20.7	14.7	-0.6	0.98
	40	3.8	18.1	10.7	-2.8	0.97
LSD	...	0.5	ns	2.0	0.3	ns
Ripeness <sup>d</sup>	...	4.9	17.9	13.1	-1.2	0.98

<sup>a</sup> Gliadin-to-glutenin ratio.

<sup>b</sup> Least significant difference ( $P < 0.10$ ).

<sup>c</sup> Not significant.

<sup>d</sup> Spikes excised from the field at harvest ripeness.

**TABLE IV**  
Flour Quality and Mixograph Characteristics of Wheat Cultivar Karl 92 Exposed to Different Temperatures from 10, 15, and 20 Days After Anthesis (DAA) Until Ripeness

DAA	Day-Night (°C)	Flour Protein (%)	Water Absorption (%)	Peak Time (min)	Peak Height (%)	Peak Width (%)	Peak Width + 2 min (%)	Slope (%/min)	Gli/Glu <sup>a</sup> Ratio
10	20-20	14.0	65.3	4.3	47.0	24.7	18.0	-0.4	0.95
	25-20	15.6	67.7	5.6	49.9	22.5	17.9	-0.4	0.96
	30-20	17.4	69.9	5.1	54.9	22.7	17.0	-2.1	1.00
	35-20	18.5	71.3	3.1	42.5	17.0	8.6	-5.2	1.04
LSD <sup>b</sup>	...	1.6	3.0	1.3	7.5	4.1	3.2	0.9	0.03
15	20-20	15.4	69.7	6.1	47.3	21.7	14.7	-2.9	1.00
	25-20	15.7	69.0	8.8	46.5	21.5	13.8	-2.6	0.99
	30-20	15.6	68.4	8.0	45.0	19.9	13.4	-1.6	1.00
	35-20	15.9	68.7	5.7	43.9	18.8	10.4	-2.6	0.99
LSD	...	ns <sup>c</sup>	ns	ns	ns	ns	4.1	ns	ns
20	25-20	15.3	70.5	8.4	45.1	23.4	18.7	-0.9	0.96
	30-20	16.1	71.0	9.0	46.6	24.9	18.6	-0.4	0.98
	35-20	16.0	70.8	6.2	47.7	21.4	15.1	-1.7	0.98
LSD	...	ns	ns	ns	ns	ns	3.0	0.5	ns

<sup>a</sup> Gliadin-to-glutenin ratio.

<sup>b</sup> Least significant difference ( $P < 0.10$ ).

<sup>c</sup> Not significant.

was applied 10 DAA until ripeness (Table IV). When excised spikes were dried at 40°C, the response of the DS to high temperature was similar at both cutting dates (Table V). Growing plants at high temperature from 20 DAA until ripeness (Table IV) and drying spikes at differing temperatures and rates (Table VI) decreased the DS similarly but less than high temperature applied from 10 DAA until ripeness (Table IV) or drying excised spikes at high temperature (Table V). The DS of the mixograph curve was associated quadratically with drying rate ( $Y = -0.0001X^2 + 0.0461X - 5.028$ ,  $r^2 = 0.89$ ,  $P \leq 0.05$ ).

The ratio of monomeric gliadin to polymeric glutenin proteins in the flour was measured as an indicator of temperature effects on protein quality. Changes in the gliadin-to-glutenin ratio as a result of the temperature treatments were few and contradictory. The ratio increased with temperature for treatments applied from 10 DAA until ripeness (Table IV), but decreased with high temperature when spikes were dried at the early-dough stage (Table V). The gliadin-to-glutenin ratio was stable across temperatures imposed 15 and 20 DAA (Table IV) and on spikes excised at the late-dough stage (Table V). When spikes were dried at different rates, the main effects of temperature and humidity did not affect the gliadin-to-glutenin ratio (data not shown).

## DISCUSSION

### Milling Quality

The three fractions from milling (flour, shorts, and bran) varied with the physical characteristics of the kernels, particularly kernel size. Diminished milling quality of wheat maturing under high-temperature stress resulted from the same kernel characteristics that decreased grain yield. The low KW that contributed to loss of grain yield was associated with decreased grain TW and kernel size, characteristics that also contributed to low flour yield.

Flour yield was linearly and positively related to the decrease in grain TW as temperature increased, an association that is typical of the relationship that occurs under many other conditions (Satumbaga et al 1995, Gwartz et al 1996). Although TW was reduced by high temperature, it always remained >77.0 kg/hL, well over the reported threshold for reduced flour yield. Satumbaga et al (1995) found flour yield did not differ in grain with TW > 74.7 kg/hL but decreased significantly in wheat with TW = 65.7 kg/hL. Our results suggest that grain from high-temperature environments with high TW might still have lower flour yields.

The SKCS for determining weight, diameter, moisture, and HI of individual kernels is a recent development (Martin et al 1993). Single kernel measurements for weight and diameter were adequate indicators of flour yield in the current study, but the fit was not as precise as the correlation of flour yield to TW or kernel size distribution. Single kernel diameter was a better indicator of flour yield than was single kernel weight.

Low flour yield from wheat produced at high temperature was associated with increased HI. However, the individual contributions

of increased hardness and decreased kernel size to reductions in flour yield were difficult to separate. An increase in hardness by high temperature would alter milling quality by requiring more power and break and reduction operations to fully mill the grain (Finney et al 1987). It would also slow water movement into the kernel during tempering, increase starch damage during milling, and produce flour with higher baking absorption (Pomeranz and Williams 1990).

Kernel hardness and size are under genetic and environmental control and might not be associated under some conditions. Flour yield of field-grown wheat blends correlated poorly with single kernel hardness but was associated positively with single kernel weight and diameter (Satumbaga et al 1995). The current study suggests that a combination of hard and small kernels may be an indication of high-temperature stress during wheat maturation. High temperature may also be a significant contributor to the hardness of hard red winter wheat.

### Flour Quality

Our experiments demonstrate that high-temperature during grain filling, as well as high-temperature and fast-drying conditions during grain desiccation alter flour quality of hard red winter wheat. Growth temperature of 35°C during early reproductive growth and rapid grain desiccation during ripening decreased dough strength as measured by peak mixing time. High temperature during early, middle, and late reproductive growth, and rapid desiccation during ripening, also reduced two indices of mixing tolerance: the slope and width of the descending portion of the mixograph curve (Finney et al 1987). The reduction in dough quality occurred independently of flour protein content.

The association of mixing time and tolerance with drying rates suggested that atmospheric humidity, and probably soil moisture, during grain desiccation influence the dough properties of wheat. This may explain the observation of Finney and Fryer (1958) that the physical and chemical condition of the soil was involved in regulating the extent of heat injury to wheat quality. They also noted that high humidity probably prevented high-temperature damage to wheat quality. High temperature coupled with rapid desiccation of the grain in dry air and limited soil moisture would cause the most damage to quality. The influence of drying rate of the grain would also explain the loss in quality after maximum grain dry weight was achieved (Randall and Moss 1990).

The reduced peak height on the mixograph curve of the dough contrasted with the increased protein content of the flour of grain grown at high temperature from early filling until ripeness. However, high temperature during middle and late grain filling had little influence on peak height, which was generally associated with protein content. Blumenthal et al (1995) also found that, in the absence of changes in protein content, peak height was unaffected by high temperature during late grain filling.

In previous studies, differences in the response of quality to high growth temperature among cultivars ranged from none (Randall

TABLE VI  
Flour Quality and Mixograph Characteristics of Wheat Cultivar Karl 92 at Hard-Dough Stage Exposed to Different Temperatures and Drying Rates During Grain Desiccation

Temperature (°C)	% rh	Drying Rate (mg/g • day)	Peak Time (min)	Peak Height (%)	Peak Width (%)	Peak Width + 2 min (%)	Descending Slope (%/min)
25	37	110	6.3	41.6	22.9	17.3	-1.6
25	0	164	5.3	38.6	22.1	17.9	-1.0
25	Air-dried	233	4.3	45.0	24.3	17.3	-1.4
35	37	170	5.8	39.5	21.1	15.2	-1.5
35	0	244	4.9	41.4	21.4	14.9	-2.3
35	Air-dried	290	3.7	45.3	23.8	15.2	-3.3
LSD <sup>a</sup>	...	15	0.8	6.2	3.0	2.7	1.3
Ripeness <sup>b</sup>	...	...	5.1	45.2	24.5	18.0	-1.5

<sup>a</sup> Least significant difference ( $P < 0.10$ ).

<sup>b</sup> Spikes excised from the field or greenhouse at harvest ripeness.

and Moss 1990) to considerable (Finney and Fryer 1958, Blumenthal et al 1995). Cultivars with long mixing times were more tolerant or resistant to high temperature than those with brief mixing times (Finney and Fryer 1958). Wheat genotypes with allele *Glu-D1d* coding for high molecular weight gluten subunit combinations 5+10 were more tolerant to the detrimental effects of high temperature than genotypes with allele *Glu-D1a*, which codes for subunits 2+12 (Blumenthal et al 1995). In the current study, the influence of high temperature during grain desiccation was similar on the two cultivars; Karl 92, which had a longer mixing time and subunits 5+10, and TAM 107, which had a shorter mix requirement and subunits 2+12. However, since the initial quality of TAM 107 was lower than that of Karl 92, it was also lower after high-temperature treatment. The results suggested that weakening of dough properties by high temperature during grain ripening would be most detrimental to cultivars with inherently weak dough properties.

A molecular basis for changes in dough properties from high temperatures during grain development of wheat was suggested by Blumenthal et al (1991a, 1993). They proposed that gliadin genes contain heat-shock elements that promoted the synthesis of gliadin at the expense of glutenin when plants were exposed to heat stress. The substantial reductions in mixing time and tolerance and the shift in gliadin relative to glutenin from high-temperature treatment during early grain filling until ripening agreed closely with that hypothesis. However, high temperature during late grain filling and ripening weakened dough properties without significantly changing the gliadin-to-glutenin ratio. The lack of change in molecular size distribution during grain ripening suggested that other chemical and physical relationships among endosperm constituents might also be involved in the weakening of dough properties by high temperature.

## CONCLUSIONS

Environmental conditions during maturation and ripening of wheat had a major influence on kernel characteristics that contribute to grain yield (Paulsen 1994) and milling quality (Johnson et al 1966, Bequette 1989). These results demonstrated that flour yield of wheat was reduced significantly by high temperatures that decreased grain yield, and that kernel weight was a key factor in both responses. High growth temperatures also increased grain hardness, another contributor to milling quality of wheat.

High temperature during grain filling and rapid desiccation during kernel ripening of hard red winter wheat diminished mixing tolerance of the flours. Elevated temperature during early grain filling and rapid drying during ripening also decreased mixing time. Flour quality was damaged most when high temperature was maintained continuously from early grain filling until ripeness, but injury also resulted from high temperatures during late grain filling. Weakening of dough properties by rapid drying of grain during ripening suggested that temperature, humidity, and probably soil moisture contribute to the final quality of bread wheat. No changes in the gliadin-to-glutenin ratio occurred in response to high temperatures during late grain filling or drying, suggesting that other chemical or physical relationships among the chemical constituents of the endosperm were involved in the diminished quality of wheat.

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