Popping Behavior and Zein Coating of Popcorn

P. JOHNNY WU[1] and HENRY G. SCHWARTZBERG[2]

Cereal Chem. 69(5):567–573

ABSTRACT

Expansion ratios, extents of evaporation, popping temperatures, and heating-induced enthalpy changes were measured versus temperature and moisture content for popcorn. These were used to identify the conditions that induce popping and the levels of moisture loss needed to stabilize puffed structures. Popping probably initially occurs through expansion of vapor trapped in individual grains of starch. Pore walls rupture, vapor escapes, and pores merge when excessive vaporization occurs. The enthalpy balance during popping indicates that evaporative cooling during popping is counterbalanced almost quantitatively by release of heat as a result of melt solidification. Popping temperatures of popcorn in 200°C air inversely correlated with initial moisture content. The temperature dropped 5.4–6.2°C at popping. Coating popcorn with zein slightly reduced the rates of moisture loss during heating. Expansion bulk volumes increased 15% for coated popcorn, and the unpopped ratio decreased slightly, but only when the popcorn popper was not preheated. Expansion volume did not increase significantly when the popper was preheated. Zein coating did not significantly improve expansion bulk volume and unpopped ratios for samples with damaged pericarp.

Popping, upon heating, is caused by: 1) buildup of water vapor pressure in individual starch granules, 2) temporary counter-balancing of that pressure by tensile stresses that develop in the granules and the pericarp, 3) release of constraint due to failure of these elements, and 4) rapid generation and expansion of vapor after such failure. The endosperm of popcorn is covered by a tough skin, the pericarp, and contains two parts: the horny (translucent) endosperm, which lies near the crown and outer edges of the kernel, and the floury (opaque) endosperm, which surrounds the germ at the base and center of the kernel (Hoseney et al 1983). Popcorn contains more horny endosperm and a higher protein-carbohydrate ratio (1.8:1) than field corn (1.5:1), e.g., white or yellow dent corn. The horny endosperm contains tightly packed polygonal starch granules with diameters ranging from 8 to 17 μm, imbedded in a protein-rich matrix. The floury endosperm contains spherical starch granules of similar diameter. They are covered by protein films and separated by intergranular air spaces. Chemical analysis of the separated opaque and translucent endosperms showed that the two contained equal amounts of protein but that the types of protein are different (Hoseney, 1986). The germ does not pop, and popping does not alter it chemically or physically.

The pericarp acts as a pressure vessel, which allows vapor pressure to build up during the popping and limits moisture loss. The tissues of the pericarp and tip cap are continuous; hence these two structures form a complete covering for the kernel. Popcorn with damaged pericarp does not pop well, i.e., does not expand as much in popping. Hoseney et al (1983) found that initial breaks in the pericarp affected popped volume more radically than did subsequent breaks. Although it has been claimed that the mass percentage of pericarp is about the same in all types of corn, the thickness of pericarp ranges from 40 to 120 μm depending upon the variety (Richardson 1957). The thickness depends on both the location of the kernel on the ear and the position of the pericarp on the kernel. The pericarp is thinner on kernels near the tip of the ear; butt kernels have the thickest pericarp. The pericarp is much thicker on the crown of the kernel than over the germ (Wolf et al 1952, Richardson 1960). Therefore, variation of pericarp thickness, in terms of pericarp yield strength, might be an important factor that causes the optimum moisture content to vary for different popcorn varieties or even with location of kernels on the ear, causing different degrees of expansion for different kernels. Richardson (1957) has suggested that peri-

[1]Research associate, Department of Agricultural Engineering, University of Illinois, Champaign-Urbana 61801.
[2]Professor, Department of Food Science, University of Massachusetts, Amherst 01003.

carp thickness should be used as one indicator of popcorn quality.

The expansion volume of popcorn is important because popped popcorn is usually sold and bought by the consumer on the basis of volume rather than weight (Matz 1984). Popcorn with higher expansion potential generally has a more tender texture than does popcorn with lower expansion. Popped popcorn with a highly irregular pronged appearance is called "butterfly" shaped, whereas kernels that are predominantly spheroidal with few projections are "mushroom" or "ball" shaped. In general, popped kernels with "mushroom" shape have a lower expanded bulk volume and a smooth surface. Expansion bulk volume also depends on moisture content, popping temperature, kernel size, kernel shape, kernel location on the ear, hybrid type, test weight, initial specific gravity, dry matter per kernel, harvest maturity (moisture content), various drying parameters, stress cracks, and heating rate.

Moisture content strongly affects the expansion volume of popcorn. Several studies indicate that the moisture content that is optimum for maximizing expansion volume ranges from 12.5 to 14.0% wb (Bemis 1959, Eldredge and Thomas 1959, Huelson 1960). Haugh et al (1976) found that the optimum moisture content and the ranges of optimum moisture content were different for different hybrids. Hoseney et al (1983) explained that at low moisture contents there is insufficient superheated water for complete expansion, but high moisture contents weaken the pericarp, causing an early release of pressure. When water vaporizes at 180°C it expands 194-fold in volume. Low moisture contents also influence popping through their effect on the yield properties of the solid matrix.

Figure 1 qualitatively portrays changes in pore wall strength (S_y) and wall stress (S_w) due to internal vapor pressure for two feeds: one containing adequate moisture and the other too little moisture (Schwartzberg and Wu 1988). As temperature increases, stress due to internal pressure increases; and pore wall strength decreases. Puffing starts when S_w, the stress due to internal pressure, exceeds S_y, and it stops when internal pressure decreases due to venting or to diffusive vapor escape and increases in S_y due to evaporative cooling and to moisture loss cause S_y to exceed S_w. The puffed structure sets up when S_y exceeds S_w. In feeds with too little moisture, internal pressure never becomes high enough and/or S_y never becomes small enough for S_w to exceed S_y, and puffing does not occur. Puffing would fail to occur for the same reason if excessive moisture loss occurred during the heating process. Strong shells, such as the pericarp in popcorn, effectively increase S_y and allow more melting of starch to occur before puffing.

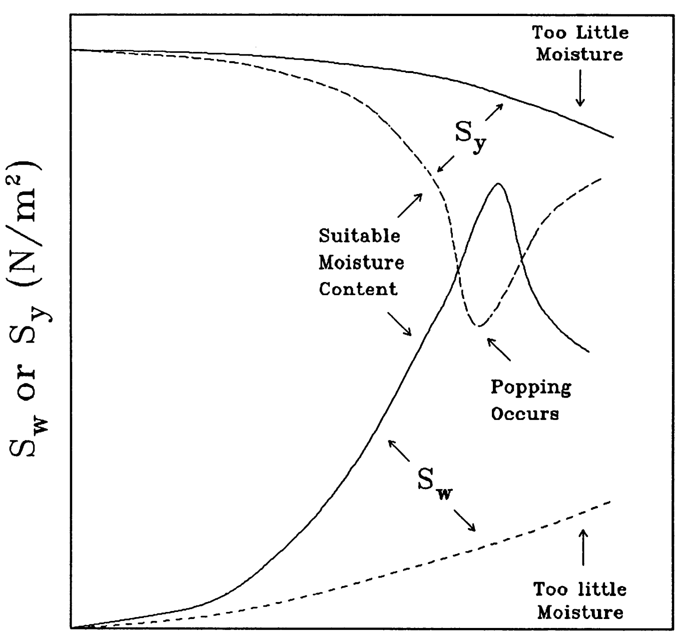

Fig. 1. Changes in wall stress (S_w) and wall strength (S_y) versus time during heating of popcorn kernels containing suitable and unsuitable moisture contents.

Expansion volume is influenced by the oil temperature during hot oil popping. Weatherwax (1921) recommended oil temperatures between 175 and 200°C and that popping be completed within 2–3 min. Hoseney et al (1983) reported that popping occurred at about 177°C, which for pure water is equivalent to a pressure of 931 KPa (135 psia) inside the kernel. He explained that most of the water in the kernel is superheated at the moment of popping, and vapor pressure exerted by the water provides the driving force for expanding the kernels when the pericarp ruptures. His approach is not completely correct, because he assumed that vapor that formed inside the popcorn kernel was saturated and neglected the volume occupied by dry solids in the popcorn. Moreover, effects due to oil temperature may be caused by a difference in heating rate rather than being a direct effect of the temperature used. For constant moisture content, the higher the oil temperature is, the higher the heating rate is. Roshdy et al (1984) measured an average temperature of 187°C at the center of kernels at the instant of popping in a continuous hot air popper. Interactions between moisture content and popping temperature may exist and affect the expansion volume. The optimum moisture content that maximizes expansion volume may be quite different at various heating temperatures or heating methods.

This study was to investigate the popping behavior of popcorn using hot air, to determine whether the yield strength of popcorn pericarp can be manipulated by a deposited coating, and to determine how rates and extent of vapor releases during heatup and puffing itself affect the puffing process.

MATERIALS AND METHODS

Popcorn

The popcorn used in this study was a commercial yellow popcorn, Bonnie Lee, distributed by Weaver Popcorn Co., Inc. (Van Buren, IN, and Ulysses, KS). After purchase, it was stored in an airtight glass bottle at room temperature before treatment. Samples with initial moisture content of 15.6%, db, were slowly dehydrated or rehydrated to provide the desired moisture contents and equilibrated in a sealed glass container at least 72 hr at room temperature. Samples with adjusted moisture contents were kept in a refrigerator at 4° C. Before each test, samples were equilibrated at room temperature 24 hr.

Rehydration of samples was done by spraying water on the inside wall and lid surface of the airtight glass jar. Any direct contact between water droplets and kernels was avoided to minimize steep moisture gradients that might induce stress cracks in the kernels and affect the expansion volume of popcorn. The containers were kept at room temperature (25° C), and the sample weights were measured every day until the sample had absorbed the appropriate amount of moisture. For dehydration, samples were dried slowly in a 40° C incubator without circulation to avoid crack formation in kernels. The moisture contents of popcorn samples were determined with at least three replications by AACC method 44-15A (AACC 1983) (drying a 15-g sample at 103 ± 1°C for 72 hr).

Measurement of Expansion Ratio

The expansion ratio (ER) used to characterize expansion in puffing, was determined using the formula:

$$ER = V_f / V_i \,, \qquad (1)$$

where V_f is the final specific volume of puffed samples and V_i is the initial specific volume of samples. Actual product volumes rather than bulk volumes were used. Specific volumes were determined by the displacement method (using 1-mm glass beads and a 86.5-ml container).

Measurement of Expansion Bulk Volume and Unpopped Ratio

Popcorn samples (15 g) were popped in a modified hot-air popper at the desired air temperatures. Before popping, the number and weight of popcorn kernels were measured. Bulk volumes were measured by pouring the popped popcorn into an 80-mm diameter, 1,000-ml graduated cylinder. The average of three measurements was recorded. Then, the popped and unpopped kernels were separated and the number of unpopped kernels was counted. From these data, the expansion bulk volume (in milliliters per gram) and unpopped ratio (in percent) were calculated:

$$\text{Expansion bulk volume} = \frac{\text{total bulk volume}}{\text{initial kernel weight}} \tag{2}$$

$$\text{Unpopped ratio} = \frac{\text{no. of unpopped kernels}}{\text{no. of total kernels}} \times 100. \tag{3}$$

Popping Temperatures

To determine temperatures at which rapid yielding occurs in moisture content ranges of interest in puffing, the popping temperatures of popcorn samples were determined. Samples with various moisture contents were popped in a modified hot-air popper equipped with a voltage regulator for temperature control. Twenty five popcorn kernels were randomly chosen and popped in 200°C air. Each kernel was popped separately, and the initial weight, popping temperature, popping time, and temperature drop during popping were recorded. Statistical analysis was performed to determine correlations among the initial weight, moisture content, popping temperature, popping time, temperature drop during popping, etc.

For temperature measurements, a 0.01-in. diameter Cu-constantan thermocouple was inserted into 1/32-in. diameter holes drilled in the base (germ end) of the popcorn kernels; holes were sealed with silicone sealant before popping. Then, each kernel was popped in the hot-air popcorn popper. The popping temperature and temperature drop during popping were recorded every 1 sec, using a Metra-Byte data acquisition system (DAS-8, MetraByte Corp., MA) with an IBM PC computer. Popcorn temperature readings were low, and kernels did not pop well when sealing was not used.

Zein Coating of Popcorn Kernels

To determine whether the yield strength of popcorn pericarp can be manipulated by deposited coatings, 100-g samples of popcorn with 15.5% (db) moisture content were used to evaluate effects produced by a deposited coating of zein. The samples were popped after coating and compared with uncoated samples. Figure 2 shows the infusion apparatus for depositing coatings on popcorn kernels. Zein-ethanol solutions were infused into a sample previously subjected to vacuum to reduce the internal pressure to 5.3 kPa. In some cases, 10 g of zein per 100 ml of 70% ethanol was used; in others, 3 g of zein per 100 ml of 70% ethanol was used.

Further, to determine whether deposition of zein can mend mechanical damage in the pericarp, kernels containing a single cut through the pericarp were infused with zein-ethanol solution at 5.3 kPa. The amount and thickness of zein deposited were estimated by measuring total weight, kernel size, and moisture content of samples before and after infusion. The zein-coated samples were dried without forced air circulation at room temperature. Then, both zein-coated and control samples were equilibrated at room temperature in a desiccator that held saturated NaCl solution in place of the desiccant. This equilibrated the samples to a water activity of 0.7547. After one week of storage, the equilibrium moisture contents were around 15.9% (db) with a standard deviation of 0.1%. Samples were popped in the modified hot air popper with 211°C air temperature. Expansion bulk volume and unpopped ratio were measured after popping to evaluate the effect of zein coating. Coatings of polyurethane spray enamel were also tested.

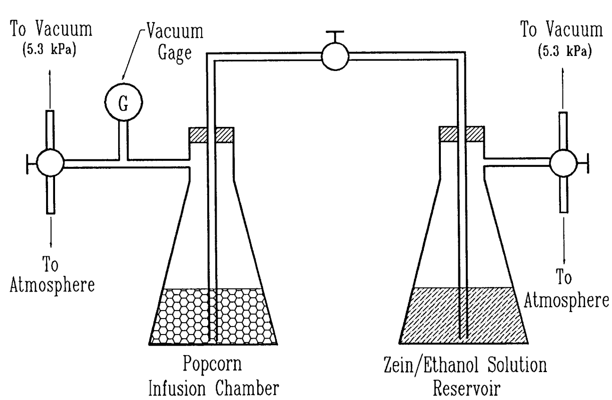

Fig. 2. Infusion apparatus for zein coating of popcorn kernels.

Determination of Vapor Release

To determine how rates and extent of vapor release during heatup and puffing itself affect the puffing process, popcorn samples with different moisture contents were popped at various air temperatures. The total moisture loss after popping (ΔW_t) is the sum of moisture loss before popping (ΔW_1) and moisture loss during popping (ΔW_2):

$$\Delta W_t = \Delta W_1 + \Delta W_2 \tag{4}$$

Since popcorn kernels don't pop at the same time, total moisture loss was measured by heating each kernel separately in a modified hot air popper fitted with a voltage regulator for temperature control. Controlled air temperatures in the 184–234°C range were used. The initial weight of each kernel was measured before the test. Then, the final weight of popped popcorn was measured immediately after popping. Samples with different moisture contents were popped at various air temperatures. For each condition, 10 kernels were randomly chosen and tested.

Since it is quite difficult to monitor the weight change of a popcorn kernel during popping, ΔW_1 was estimated based on the rate of moisture loss (R) and the heating time (Δt), and the ΔW_2 was calculated as:

$$W_2 = \Delta W_t - \Delta W_1 = \Delta W_t - (R \cdot \Delta t) \tag{5}$$

To determine R (percent, db, per second), preweighed 15-g popcorn samples with various moisture contents were heated at desired air temperatures for 10, 15, 20, 25, 30, 40, and 50 sec. After heating, samples were immediately sealed in an airtight, 25-ml glass bottle, which was weighed before the test and reweighed with the sample in it to estimate moisture losses of popcorn versus heating time. Expansion ratios of samples were measured. The measured expansion ratios were compared with estimated values calculated based on the volume of the vapor produced by moisture lost during popping.

Motion Pictures of Popcorn Popping

To measure the deformation rates of popcorn during popping, the popping motion of popcorn was recorded using a SONY F-40, 8-mm video camcorder at maximum frame speed (30 frames per second). Pictures were taken at various shutter speeds (exposure times) in the range of 1/60–1/4,000 sec.

RESULTS AND DISCUSSION

Popping Temperatures of Popcorn Using Hot Air

Popping temperatures depend on when the pericarp ruptures. This, in turn, depends on the pericarp thickness and strength and the internal vapor pressure, which depends on the initial moisture content of the popcorn. Therefore, popping temperatures vary because of variations in pericarp thickness and other physical characteristics. Figure 3 shows a typical curve of popcorn temperature versus time during popping in a hot-air popper using an inlet air temperature of 200°C. The temperature of the kernels sharply dropped roughly 6° C immediately after popping, then rose again and asymptotically approached the local air temperature, which was somewhat lower than the inlet air temperature.

Table I lists the average values for popping temperatures, popping times, and popping temperature drops obtained at different initial moisture contents. The mean temperature drop at popping ranged from 5.4 to 6.2° C, with standard deviations of 2.0–2.9° C. Similar data have been obtained for popcorn popped in hot oil (180° C), but in that case most popping occurred between 171 and 177° C (Hoseney et al 1983). The difference in the temperature range where popping occurred in these cases might be due to any one of many factors: variety of popcorn, heating rate regime, and initial moisture content.

Table II lists the correlation matrix of five variables for popcorn popping based on 125 observations. Based on the statistical analysis, popping time and popping temperature are inversely correlated with moisture content at the 95% level. Thus, in the 11.4–16.0% moisture content range, samples with lower moisture content pop at higher temperature. For moisture contents above 16.0%, there is no significant difference among popping temperatures. The test results also indicated that the popping temperature did not vary significantly with initial kernel weight. Temperature drop at popping did not vary significantly with moisture content. However, measured popping temperature drops may not be reliable because the thermocouple could have been loosened by popping. Since moisture loss during popping increased with initial moisture content and greater moisture loss should have produced more evaporative cooling, the lack of temperature drop correlation with moisture content is worth noting.

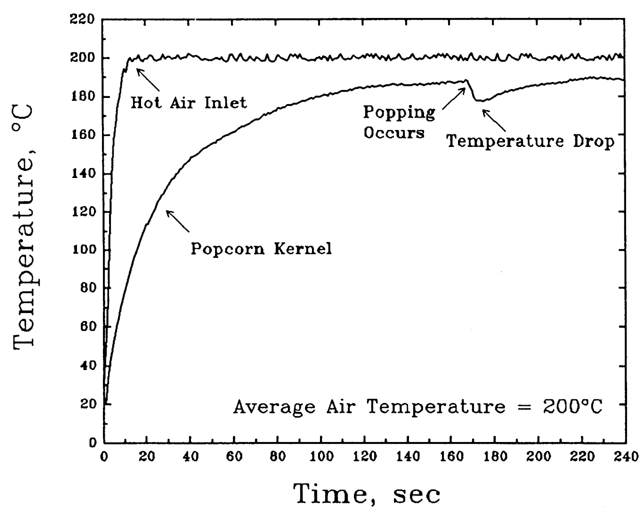

Fig. 3. Typical curve of popcorn kernel temperature versus heating time during popping with 200° C air temperature.

TABLE I
Average Popping Temperatures, Popping Times, and Temperature Drops During Popping of Popcorn at Various Moisture Contents in 200° C Air

Moisture Content (%, db)	Kernel Weight (mg)	Popping Temperature (° C)	Popping Time (sec)	Temperature Drop (° C)
11.4	143.6 ± 20.4	188.8 ± 4.5	123 ± 64	6.0 ± 2.0
14.8	140.2 ± 21.0	184.3 ± 7.9	95 ± 27	5.7 ± 1.2
16.0	138.4 ± 27.3	181.2 ± 5.9	110 ± 64	6.0 ± 2.9
18.7	139.4 ± 25.7	181.5 ± 7.0	94 ± 46	6.2 ± 2.3
20.0	141.2 ± 18.5	181.6 ± 9.2	98 ± 57	5.4 ± 2.8
Overall	140.6 ± 23.0	183.5 ± 7.7	104 ± 55	5.8 ± 2.4

TABLE II
Correlation Matrix of Five Variables for Popcorn Popping

	Moisture Content	Kernel Weight	Popping Temperature	Popping Time	Temperature Drop
Moisture content	1.0000	−0.3805	−3.6293	−2.0039	−0.2655
Kernel weight		1.0000	0.3678	0.8312	0.9846
Popping temperature			1.0000	3.8740	1.5965
Popping time				1.0000	1.6581
Temperature drop					1.0000

Zein Coating of Popcorn Kernels

Moisture plays an important role in popcorn popping. Zein coatings were used to slow down moisture loss before popping and to improve the yield strength of the popcorn pericarp. It was hoped that higher vapor pressures could be generated before popping and that this would consequently increase the expansion during puffing.

The thickness of the zein coating was about 9 μm for heavily coated samples and 6 μm for lightly coated samples. More zein (0.0152 g of zein per gram of dry solid) was absorbed by damaged samples than by heavily coated undamaged samples (0.0099 g/g of dry solid). Based on the moisture loss of popcorn samples with and without zein coating before popping at 211° C air temperature, the zein coating slightly reduced the rate of moisture loss from 0.057 to 0.049% (db) per second. Therefore, at the same heating condition, zein-coated samples contain more moisture than uncoated samples. This could assist popping and produce greater expansion. The water vapor transmission rate of zein film is about 300 g/m^2 per day at 25° C, which is much higher than those of polyethylene and polypropylene films (Mendoza 1975).

Table III shows the expansion bulk volume and unpopped ratio of popcorn with or without zein coating. The expansion bulk volume of heavily coated samples increased 15% (from 35.5 to 40.7 ml/g), and the unpopped ratio decreased from 8.4 to 5.0%, but only when the popper was not preheated. The expansion bulk volume of heavily coated samples did not increase significantly when the popper was preheated.

Zein coating did not improve expansion bulk volume and unpopped ratios much for damaged samples. The bursting strength of the zein coating is not strong enough to mend damage to the pericarp. The bursting strength of zein film 30 μm thick is 5.8 psi (Mendoza 1975). However, for 6- to 9-μm thick zein film, it would provide only 1.0–1.7 psi strength, which is not enough to sustain significant added internal vapor pressures in popcorn during heating. Besides, the strength of zein or other proteins decreases as temperature rises. It is noteworthy that use of a preheated popper increased popped bulk volume, more so for uncoated and lightly coated samples. This may be due to an increase in the rate of temperature rise relative to the rate of moisture loss and to the consequent increases on internal pressure and matrix flowability before popping.

TABLE III
Expansion Bulk Volumes and Unpopped Ratios of Popcorn Popped With or Without Zein Coating in an Unpreheated or Preheated Hot-Air Popper

Popcorn Samples and Condition of Popper	Expansion Bulk Volume (mg/g)	Unpopped Ratio (%)
Control		
Not preheated	35.5	8.4
Preheated	43.9	1.5
Lightly zein coated		
Not preheated	34.7	5.8
Preheated	45.6	0.8
Heavily zein coated		
Not preheated	40.7	5.0
Preheated	45.7	3.0
Damaged	8.1	38.3
Damage and coated		
Not preheated	7.4	49.1
Preheated	9.5	36.8

Coatings of polyurethane spray enamel did not improve popping (Table IV). During hot-air popping, polyurethane coatings became very sticky, and popcorn kernels stuck to each other. Although polyurethane coating provides some resistance to moisture loss, it may retard expansion during popping. Mechanical properties for coatings for popcorn should be high bursting strength, stability to temperature change (i.e., absence of melting or softening), and high resistance to moisture diffusion and physical stresses.

Effect of Air Temperature and Moisture Content

Air temperature may be a critical factor in popcorn popping. Expansion bulk volumes of popcorn samples were measured and compared with the results for individual kernels. Figure 4 shows the effect of air temperature on expansion bulk volume of popcorn samples with three different moisture contents (13.5, 15.3, and 20.0%, db). Expansion bulk volume increased as air temperature increased from 190 to 210°C and then leveled off or in one case slightly decreased. When the air temperature was above 210°C, the expansion bulk volumes were around 40 ml/g no matter what the moisture content was. However, for a moisture content of 20.0% (db), expansion reached a maximum around 210°C, then slightly decreased around 230°C. This may be caused by the shrinkage of popped popcorn at high air temperature.

Melting or a transition from a glassy state to a rubbery state (particularly attainment of temperatures greater than 1.05 times the glass transition temperature) would permit pressure-driven flows that provide large degrees of pore expansion during puffing. However, the extents of melting or glass transition increase as moisture content increases; and melting temperature and glass transition temperature of starch decrease as moisture content increases. Thus, moisture facilitates and increases extents of melting and glass transition in starch. Once temperatures reach the temperature at which maximum melting or glass transition occurs, a higher temperature does not favor any increase on expansion.

Several broken pieces of popped popcorn were found after the popping of samples with a 20.0% (db) initial moisture content. High moisture content may soften the popcorn endosperm and make it more fragile during popping. The inability of the large amount of water vapor produced to diffuse through pore walls during the period of vapor generation may also burst the popped popcorn apart. These could explain why the expansion bulk volume was smaller than those those of popcorn samples popped at lower moisture contents. The sound of popping for popcorn with moisture contents higher than 20% was much louder than the popping at low moisture contents.

TABLE IV
Expansion Bulk Volumes and Unpopped Ratios of Popcorn Popped With or Without Polyurethane Coating in a Preheated Hot-Air Popper

	Expansion Bulk Volume (mg/g)	Unpopped Ratio (%)
Control[a]	41.19	2.6
Polyurethane coated[a]	37.97	1.5
Control[b]	23.48	3.5
Polyurethane coated[b]	21.78	14.9
Damaged[b]	8.55	21.2
Damaged and coated[a]	8.82	29.7

[a]Samples with 15.9% db moisture content.
[b]Samples with 8.9% db moisture content.

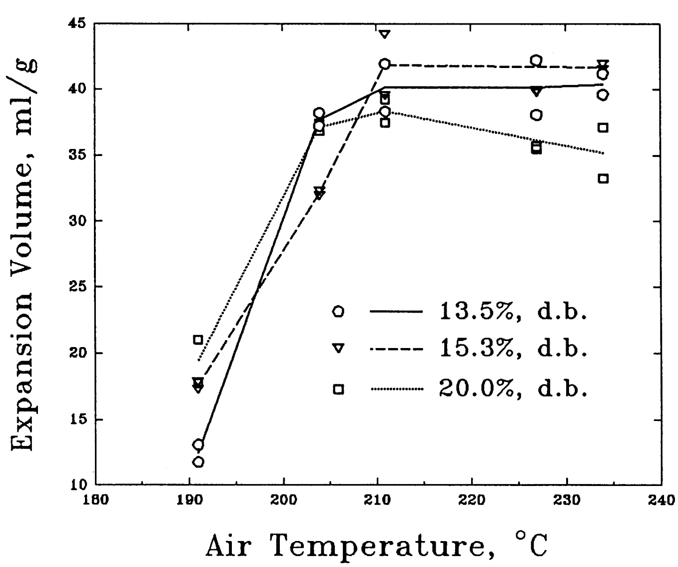

Fig. 4. Expansion bulk volume of popcorn samples with different moisture contents at various air temperatures. Labels indicate duplicate runs.

Moisture Loss During Popcorn Popping and Estimation of Expansion Ratio

Figure 5 shows the effects of initial moisture content and air temperature on total moisture loss, ΔW_t, and residual moisture contents for popping carried out in hot air. The results indicated that total moisture loss increased as the initial moisture content increased and that it was slightly higher at 191°C air temperature than at 211 and 234°C. However, other tests, which were carried out at a single fixed moisture content, 15.2% (db), indicated that total moisture losses did not vary significantly at the 5% level as air temperature varied in the range of 178–220°C. Since it took longer to pop at lower air temperatures, more moisture loss would have occurred before popping and less during popping. This could be why popped volume decreased as air temperature dropped to 190°C.

Rates of moisture loss before popping were estimated based on linear regression of experimental data, and they increased markedly as the initial moisture content of the popcorn increased (Fig. 6). Table V lists estimated rates of moisture loss and rates of drying normalized by dividing rates of moisture loss by corresponding initial moisture contents. The normalized drying rates ranged from 0.24 to 0.28 min^{-1}, except at 28.2% (db), where the normalized drying rate was 0.36 min^{-1}. This indicates that, at a moisture content below 22% (db), rates of moisture loss for popcorn before popping are roughly linearly proportional to the initial moisture content.

Moisture loss and residual moisture contents at various stages of popping when using 211°C air are listed in Table VI. The moisture loss during popping (ΔW_2) increased markedly as initial

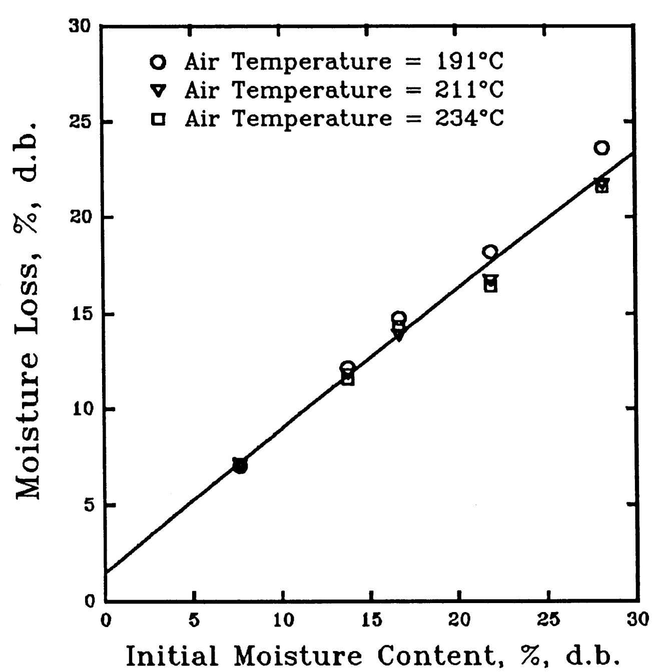

Fig. 5. Total moisture loss of popcorn samples at various initial moisture contents and air temperatures.

moisture content increased. Assuming that moisture was uniformly distributed inside the popcorn kernel at the instant of popping, and based on the moisture content right after popping (MC_2), the water activity at the instant of popping (A_{w2}) ranged from 0.06 to 0.67 at 180°C.

Assumptions were made that 1) the kernel temperature remains constant at 180°C and the corresponding saturated vapor pressure is 1.0021 MPa (145.3 psia); 2) water vapor partial pressure inside the popcorn kernel reaches equilibrium, so the water activity of popcorn during popping can be estimated using high-temperature isotherms for popcorn grits (Wu 1991); 3) no vapor escapes from pores during popping, so all the moisture loss, $\Delta W_2 = (MC_1 - MC_2)$, contributes to pore expansion. Using these assumptions, the expansion ratio was estimated by calculating the volume of vapor formed:

$$V_{vap} = \nu_{vap}\,(MC_1 - MC_2), \tag{6}$$

and addition of that volume to the volume of the solids and residual water gives:

$$ER = \frac{V_{vap} + V_s + MC_2 \cdot \nu_w}{V_s + MC_0 \cdot \nu_w} \tag{7}$$

where V_{vap} is the volume of water vapor (ml/g of dry solid); MC_0 is initial moisture content, dry basis; MC_1 is the moisture content right before popping; ν_{vap}, the estimated specific volume of water volume based on a kernel temperature of 180°C and equilibrium water activity at MC_2, is obtained from specific volume tables for superheated steam (ml/g); V_s is the specific volume of dry solid (ml/g); and ν_w is the specific volume of liquid water (ml/g).

Table VI also shows estimated and experimental expansion ratios for popcorn with various initial moisture contents. The estimated expansion ratios are much greater than the measured values. A possible explanation for this difference could be that vapor escaped during popping and that the kernel temperature was not constant during popping and was lower than 180°C due to evaporative cooling. However, the estimated expansion ratio would be much closer to the measured values if the water activity were estimated at MC_1.

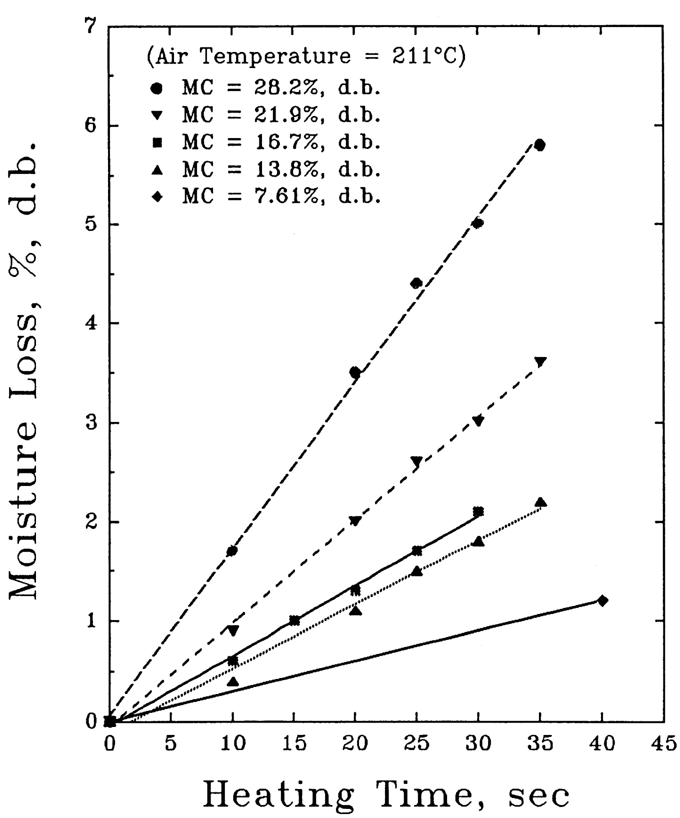

Fig. 6. Moisture loss of popcorn samples with various initial moisture contents in 211°C air.

Enthalpy Balance During Popcorn Popping

Enthalpy balances indicate that moisture loss during puffing should increase linearly with popping temperature and initial moisture content. Equation 8, an enthalpy balance for puffing, provides insight about what happens during popping. The reference temperature for the enthalpy balance is the temperature just before popping, at which temperature the matrix may be partially molten.

$$\Delta W_2 \cdot \Delta H_s = [(1 + MC_1)C_p \cdot \Delta T] + [(1 + MC_2)\Delta H_m] + Q, \tag{8}$$

where ΔT is the temperature drop at popping (°C); C_p is the heat capacity of the kernel just before popping (kJ/kg·°C); ΔH_s is heat of water sorption (kJ/kg); ΔH_m are exothermic latent heats such as the effective heat of solidification (kJ/kg); Q is the heat input during popping (kJ/kg of dry solid); and the units for ΔW_2, MC_1, and MC_2 are kilograms of water per kilogram of dry solid. The heat absorbed by evaporation during popping is provided by the sensible heat given up by the kernel, exothermic heat effects, and heat input.

Based on partial heat capacity contributions and heat capacity of water and dry solid ($C_w = 4.187$, $C_s = 1.42$, respectively), C_p is approximately 1.69 kJ/kg·°K just before popping. Using heat of vaporization from the steam table and heat of water sorption for corn starch, ΔH_s is approximately 1,000 kJ/kg based on previous studies (Wu 1991). Compared to the heat of vaporization, the magnitude of Q is quite small and can be neglected. Using the observed temperature drop of 6°C and the moisture loss data in Table VI, the calculated ΔH_m ranges from 48 to 130 kJ/kg and increases with increasing moisture content in the range of 7.6–28.2% (db). The magnitude of the calculated ΔH_m values are fairly close to the values obtained from endotherm areas for corn starch based on the differential scanning calorimetry test (Wu 1991). At low moisture contents there is less tendency to cool because there is less evaporation, but the heat of sorption is also small. Therefore, it appears that evaporative cooling is largely counterbalanced by release of heat due to melt solidification.

Motion Pictures of Popcorn Popping

Motion pictures of popcorn popping in heated air showed that the active popping lasted for either one or two frames at a frame speed of 30 frames per second and a shutter speed of 1/1,000 sec. Longer exposure times did not arrest popcorn motion during popping. Thus, it usually took at least 1/30 sec and no longer than 1/15 sec for popping to occur. Based on rates of kernel boundary movement, the deformation rates during popping ranged from 1.8 to 34.5 cm/sec (average 16.4 cm/sec). It appeared that as popping progressed, deformation rates gradually increased, then decreased. A slight amount of swelling occurred just before popping started. Expansion of vapor in the central pore, rather than expansion of pores in individual starch granules probably caused the observed swelling. High-speed photography is required for further investigation of popcorn popping and the deformation rates during popping.

TABLE V
Estimated Rates of Moisture Loss and Normalized Drying Rates at Various Initial Moisture Contents for Drying Using 211°C Air

Initial Moisture Content (%, db)	Rate of Moisture Loss (% [db]/sec)	Normalized Drying Rate (min^{-1})
7.6	0.030	0.24
13.8	0.064	0.28
16.7	0.070	0.25
21.9	0.104	0.28
28.2	0.167	0.36

TABLE VI
Moisture Losses During Popcorn Popping and Estimated and Measured Expansion Ratios of Popcorn at Various Moisture Contents in 211°C Air

	Initial Moisture Content (MC_0), %, db				
	7.61	13.77	16.69	21.89	28.17
Total moisture loss (ΔW_t), %, db	7.12	11.84	13.86	16.67	21.70
Moisture loss before popping (ΔW_1), %, db	1.20	2.56	2.80	4.16	6.68
Moisture loss during popping (ΔW_2), %, db	5.92	9.28	11.06	12.51	15.02
Moisture content right before popping (MC_1), %, db	6.41	11.21	13.89	17.73	21.49
Moisture content right after popping (MC_2), %, db	0.49	1.93	2.83	5.22	6.47
Water activity[a] (A_{w2})	0.06	0.25	0.36	0.60	0.67
Vapor pressure[a] (P_{v2}), MPa	0.0601	0.2505	0.3608	0.6013	0.6714
Specific volume of water vapor[a] (ν_2), ml/g	3,473	825	567	335	299
Volume of water vapor[a] (V_{vap}), mg/g of dry solid	205.6	76.6	62.7	41.9	44.9
Estimated expansion ratio[a]	274	102	83.6	55.9	59.9
Estimated expansion ratio[b]	22.62	36.89	42.37	47.84	58.84
Specific volume of popcorn[c] (V), mg/g of dry solids	11.67	18.03	16.93	16.97	8.21
Expansion ratio[c]	15.90	24.69	22.40	22.43	10.51

[a]Estimated, based on a kernel temperature of 180°C and equilibrium water activity at MC_2.
[b]Estimated, based on a kernel tempeature of 180°C and equilibrium water activity at MC_1.
[c]Based on direct measurements (10 replications).

CONCLUSIONS

Processes occurring during the popping of popcorn may be summarized in mechanistic terms as follows. Heating causes internal temperature and vapor pressure to rise before popping occurs, and starch concurrently softens. Roughly 16–19% of the popcorn's water content evaporates before popping. Internal pressure forces apart starch granules in the loosely packed floury endosperm, forming a central vapor-filled pore and stretching the pericarp. Starch granules in the endosperm soften and lose much of their structured strength before the pericarp ruptures. The pericarp, the strongest element in undamaged popcorn, ruptures when the internal pressure becomes excessive, i.e., when internal pressure is roughly 110–120 psia and differential pressure across the pericarp is 95–105 psi.

Popcorn with an intact pericarp and suitable moisture content pops soon after reaching a temperature of roughly 185°C when heated and fluidized in 200–230°C air. Just before popping, the pericarp bulges slightly, and small bubbles appear in the floury endosperm and then merge into a bubblelike central pore, roughly 1 mm in diameter. Apparently, pressure that builds up in the space between starch granules in the floury endosperm forces them apart. Rupture of the pericarp eliminates overall confinement of the horny endosperm, but vapor pressures act on starch granules in the endosperm's inner layers. Pressure on the outside of the outermost layer is not counterbalanced, and pores in that layer of starch granules expand rapidly. As the pores expand, water evaporates from the granule walls and transfers as vapor into the pores and to surrounding air, decreasing wall water content. Vapor pressure consequently drops inside the expanding pores; and pressure in the next layer of starch is no longer counterbalanced. Consequently pores in that layer expand and pressure drops in those pores. The process rapidly repeats itself in successive layers, and within a very short time expansion occurs in all pores. In popping, it expands 14–20 times in volume in 1/30th to 1/15th of a second.

Evaporative cooling somewhat tends to reduce temperatures and hence reduce internal pressure, but when popcorn pops, reductions in temperature that would normally be produced by evaporative cooling in other cases are almost completely counterbalanced by heat production caused by the solidification of melted starch. Based on evidence from differential scanning calorimetry, heat produced by starch solidification increases as the starch's water content increases (Wu 1991). Since evaporative cooling is small, increases in heat release due to solidification as water content increases are the main reason why higher water contents tend to cause more vaporization.

Coating popcorn with zein slightly reduced rates of moisture loss during heating. Expansion bulk volume increased 15% for coated popcorn and the unpopped ratio decreased slightly, but only when the popcorn popper was not preheated. Expansion volume didn't increase significantly when the popper was preheated. Zein coating was not strong enough to mend pericarp damages. Consequently it did not significantly improve expansion bulk volume and unpopped ratio for samples with damaged pericarp.

LITERATURE CITED

AMERICAN ASSOCIATION OF CEREAL CHEMISTS. 1983. Approved Methods of the AACC. Method 44-15A, approved October 1975, revised October 1981. The Association: St. Paul, MN.

BEMIS, W. P. 1959. Popcorn-harvesting and conditioning for maximum popping. Ill. Res. 1(1):10-11. (Univ. of Illinois, Urbana)

ELDREDGE, J. C., and THOMAS, W. I. 1959. Popcorn—Its Production, Processing, and Utilization. Bull. P127. Agricultural Experiment Station, Iowa State University: Ames.

HAUGH, C. G., LIEN, R. M., HANES, R. E., and ASHMAN, R. B. 1976. Physical properties of popcorn. Trans. ASAE 19:168-171, 176.

HOSENEY, R. C. 1986. Principles of Cereal Science and Technology. Am. Assoc. Cereal Chem.: St. Paul, MN.

HOSENEY, R. C., ZELEZNAK, K., and ABDELRAHMAN, A. 1983. Mechanism of popcorn popping. J. Cereal Sci. 1:43-52.

HUELSON, W. A. 1960. Search for reasons why some popcorn doesn't pop well. Ill. Res. 2(4):12-13. (Univ. of Illinois, Urbana)

MATZ, S. A. 1984. Snack Food Technology, 2nd ed. AVI Publishing Co.: Westport, CT.

MENDOZA, M. A. 1975. Preparation and physical properties of zein based films. Master thesis, University of Massachusetts: Amherst.

RICHARDSON, D. L. 1957. Purdue hybrid performance trials encouraging. Popcorn Concessions Merchandiser 12(4):10-17.

RICHARDSON, D. L. 1960. Pericarp thickness in popcorn. Agron. J. 52:77-80.

ROSHDY, T. H., HAYAKAWA, K., and DAUN, H. 1984. Time and temperature parameters of corn popping. J. Food Sci. 49:1412-1414, 1418.

SCHWARTZBERG, H. G., and WU, P. J. 1988. Heat and mass transfer during vapor induced puffing. American Institute of Chemical Engineers 1988 Annual Meeting, Paper No. 47d.

WEATHERWAX, P. 1921. The popping of popcorn. Proc. Indiana Acad. Sci. 31:149-153.

WOLF, M. J., BUZAN, C. L., MacMASTERS, M. M., and RIST, C. E. 1952. Structure of the mature corn kernel. Cereal Chem. 29:321-382.

WU, P. J. 1991. Study of mechanisms for vapor-induced puffing of starch-rich materials. Ph.D. dissertation, University of Massachusetts: Amherst.

[Received July 26, 1991. Revision received January 9, 1992. Accepted January 22, 1992.]