Kinetics of Popping of Popcorn

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ABSTRACT

Cereal Chem. 82(1):53–59

The rate of popping of popcorn was measured in oil and in air. Kinetic data for lifetimes of individual kernels from a large population were obtained in oil at six constant temperatures (180–250°C) and also in an air-popper at 202°C. The data are characterized by an induction period, which is, significantly, followed by a first-order decrease in the number of unpopped kernels versus time. The activation energy for the first order process is 166.7 kJ/mol between 180 and 210°C, and 53.8 kJ/mol between 210 and 250°C. These data are consistent with a model that assumes 1) that the rate of heat transfer into a kernel follows Newton's law of cooling; 2) that in a sample of kernels there exists a distribution of critical pressures; 3) that for an individual kernel, the probability of popping is directly proportional to the difference between the internal aqueous vapor pressure and the kernel's critical pressure; and 4) that the measured rate constant at any temperature is an average overall of the kernels in the sample with critical pressures equal to or less than the internal aqueous vapor pressure. Minimum popping temperatures predicted by the model are 181 ± 2°C (oil) and 187 ± 2°C (air), in good agreement with previously reported direct measurements.

The model that explains why popcorn pops is well established (Hoseney et al 1983; Wu and Schwartzberg 1992; Schwartzberg et al 1995). Essentially, a heated popcorn kernel acts as a pressure vessel. A tough, continuous outer layer called the pericarp encloses the contents of a popcorn kernel, which includes starch and water. At high temperature, the water is in the form of both steam and superheated water. Popping occurs when the internal aqueous vapor pressure exceeds the sum of the burst pressure of the pericarp and the atmospheric pressure. This occurs at an internal kernel temperature in the range 180–190°C. At this temperature, the starch is molten. When the pericarp ruptures, the superheated water rapidly expands (in less than 1/15 sec), causing the molten starch to expand and resulting in the light, fluffy, edible product. Assuming a popping temperature of 185°C, Wu and Schwartzberg (1994) estimated that the vapor pressure of water in the kernel at the instant of popping is ≈800 kPa. This is less than the vapor pressure of pure water at the same temperature (1,123 kPa) and is presumably due to the sorption of water by the starch and at high temperature to the formation of soluble sugars.

Anyone who has made popcorn knows that in a given sample of kernels, the kernels fortunately do not all pop at the same time. The kernels seemingly pop at random and exhibit a range of popping times (Roshdy et al 1984; Schwartzberg 1992; Shimoni et al 2001). The model described above does not explain this observation. It explains why popcorn pops, but has nothing to say about *when* a kernel will pop. The goal of this work was to use the methods of chemical kinetics to explain this observation. More specifically, we performed experiments in which the number of unpopped kernels in a sample was measured as a function of time at a constant bath temperature. This type of experiment has not been reported in the literature, and the data are amendable to the methods of chemical kinetics. In addition, we formulated a quantitative kinetic model for the popping of popcorn and have used it to interpret our results. The literature contains no kinetic model for the popping of popcorn.

MATERIALS AND METHODS

All temperature measurements were made with a mercury-in-glass thermometer with a precision of ±1°C. All time measurements were made with an electronic timer with a precision of ±1

sec. All heating of oil was done on a Corning laboratory hot plate that was in contact with the entire bottom surface of the container being heated.

Materials

Popcorn. The popcorn used was Orville Redenbacher's Original brand (Hunt-Wesson, Fullerton, CA). During the course of this study, the popcorn was stored at 20–22°C in the original container that was sealed to prevent loss of moisture. In all of the experiments, <10% of the kernels did not pop.

Popping oil. For all experiments that used oil, All Natural vegetable oil, Bonnie Hubbard brand (100% soybean oil) was used.

Popping Experiments

Single-kernel oil experiments. A 100-mL volume of vegetable oil was placed in a 4,000-mL beaker and brought to the desired constant temperature by heating on a hot plate. Single popcorn kernels were then dropped into the oil and the time elapsed, from when the kernel was dropped into the oil until it popped, was measured. The popped kernel was removed from the oil and the process was repeated with another kernel. In this manner, popping times were measured at six different oil temperatures (180, 190, 200, 210, 220, and 250°C). The oil temperature was monitored to ensure that it remained within ±1°C of the target temperature during all experiments. The popping of individual kernels caused no detectable change in the oil temperature.

Hot-air experiments. The popping times of individual kernels were measured in a commercial hot-air popper, PopCornNow brand (Presto, Eau Claire, WI) that was modified in two different ways to reduce the loss of unpopped kernels due to the airflow. In Modification I, the hopper was extended with an aluminum foil cone to increase the hopper height from 14 to 28 cm. In Modification II, the hopper was modified with a screen to reduce the volume available to a kernel to ≈20% of the full hopper and thus constrain the kernels within a smaller hopper volume. During these experiments, the air temperature at the bottom of the hopper was constant at 202°C. Using the popper with Modification I, a small sample (5–10 kernels) was placed in the hopper and the popping time for each kernel was recorded. No dependence on the number of kernels added was observed. The total number of kernels popped in this popper was 41. The initial temperature of each kernel was 25°C. Using the popper with Modification II, single kernels were added to the hopper and the initial and final mass of each kernel as well as its popping time were measured. In these experiments, a total of 53 individual kernels were popped. The initial temperature of these kernels was 23°C.

Table I summarizes the conditions used in the single-kernel oil experiments and in the hot-air experiments.

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Moisture Measurements

Moisture content. The moisture content of 290 unpopped kernels was determined by obtaining the initial mass of each kernel and then drying each to constant mass for at least 24 hr in a laboratory oven at 100°C.

Moisture loss. The moisture loss associated with popping of 50 individual kernels was determined by measuring each kernel mass before and after popping in the hot air popper (Modification II) during popping rate measurements.

Data Analysis

The data were analyzed for each popping experiment, assuming that the proposed model, described below, can account quantitatively for the experimental observations. The method used to find the best-fit sets of constants was a modified simplex optimization (Nelder and Mead 1965). A Bullrisch-Stoer numerical integration algorithm was used to integrate the systems of coupled, stiff, differential equations and provide predicted values of time-dependent variables (number of remaining kernels or temperature). The optimization goal was to minimize the root mean squared deviation about regression (RMSD) (Schunn and Wallach 2001)

$$RMSD = \sqrt{\frac{\sum_{i=1}^{k}(m_i - d_i)^2}{k}} \qquad (1)$$

Where, m_i is the value predicted by the model for each point, d_i is the experimental value of the point, and k is the number of points being compared. All optimizations were made until they converged where the successive changes in all fitted values was

TABLE I
Summary of Conditions for Single Kernel Experiments[a]

	Temp (°C)							
	170	**180**	**190**	**200**	**210**	**220**	**250**	**202****
Number of popped kernels	0*	95	89	71	38	49	49	41, 53

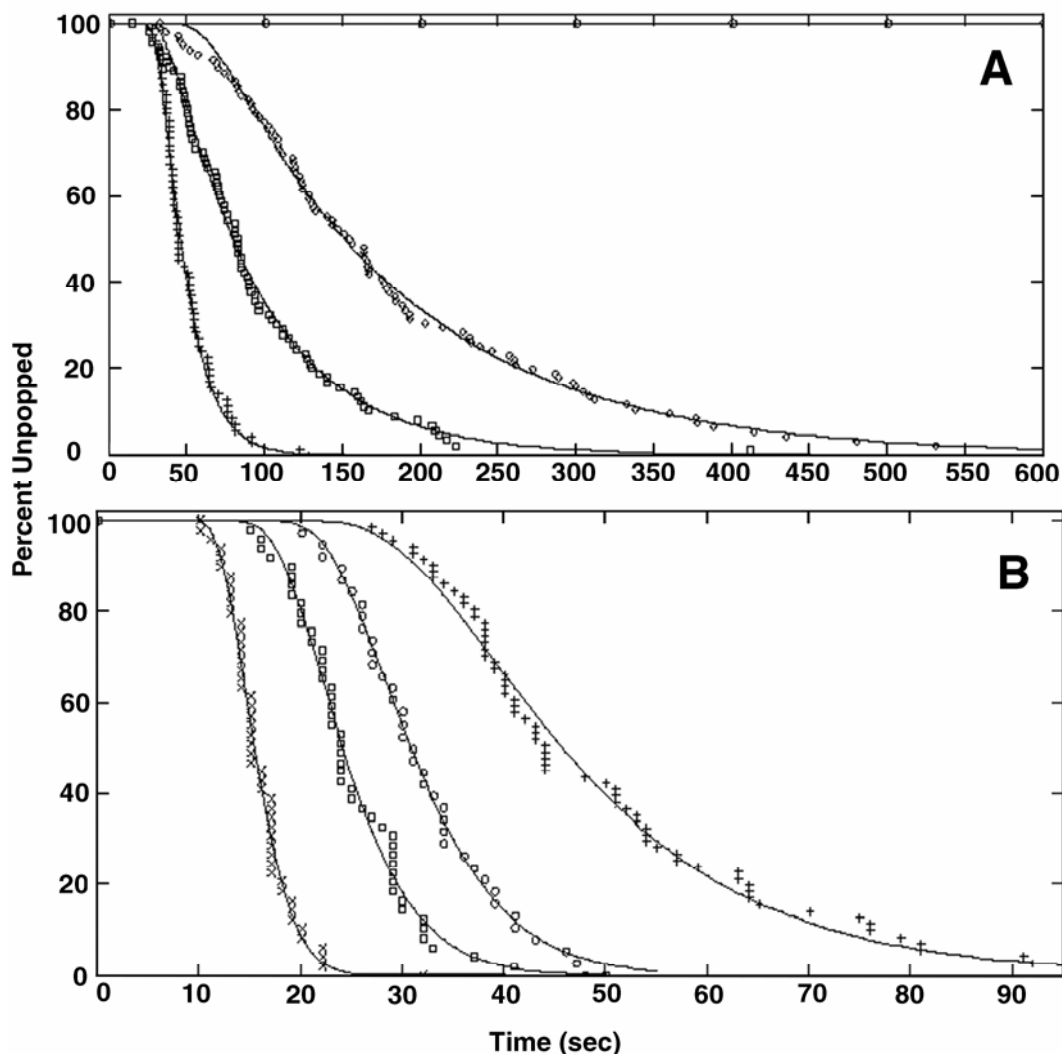[a] *No kernels popped; ** kernels popped in hot-air popper.

Fig. 1. Kinetic behavior for popping kernels in a constant temperature oil bath. Data have been split between two plots because of the wide range of time spans for different temperatures. **A,** 170°C (○); 180°C (◇); 190°C (□); 200°C (+). **B,** 200°C (+); 210°C (○); 220°C (□); 250°C (×). Symbols represent values (%) of the number of remaining kernels in each population as a function of time. Solid lines are calculated using the best-fit parameters for the model (see text and Table III) with fixed values of $B = 176.1$ kPa and $P_r = 952$ kPa.

<0.1%/iteration. All optimizations were done with several different initial guessed values of the constants that were being determined. For each optimization, similar values for the constants were obtained. The reported values for the constants are those that gave the best fits. In all cases, residual plots showed no significant trend. It should be pointed out that there are several constants that are being determined and the best fit may not be very sensitive to some of them.

RESULTS AND DISCUSSION

Moisture Content

The distribution of moisture contents for 290 individual, un-popped kernels was approximately Gaussian with a mean moisture content of 15.2% and an absolute standard deviation of 0.45%. The moisture loss on popping for 50 air-popped kernels had a mean value of 14.5% with an absolute standard deviation of 1.1%. These values are reported on a dry basis. Statistical analysis indicates that these mean values are different with a level of confidence >95%.

Single-Kernel Oil Experiments

As described above, the procedure used was to measure the lifetimes for a large number of individual kernels. These were then assumed to belong to a population of kernels popping at the oil bath temperature. By collecting these lifetimes into an ensemble and sorting them, the popping times for single kernels popping in identical temperature environments can be described. The results of such an analysis is depicted in Fig. 1A and B, where the percent of the number of kernels remaining in a population as a function of time is plotted for eight oil bath temperatures. The data are plotted as percent popped to allow all experiments to be presented on one graph and directly compared. It is interesting and significant that in this treatment of the kernel lifetimes, individual measurements collectively describe the kinetic behavior of a population. It is worth noting that this lifetime approach to kinetic behavior has been applied to unimolecular chemical reactions (Forst 1973) and nuclear decay (Kaplan 1955). It can also be viewed as an alternate approach to describing kinetic behavior as it reduces to the equations typically applied to the description of rates of chemical reactions. A detailed analysis of the kinetic behavior follows.

Kinetic Data

All of the kinetic data (see Fig. 1) are characterized by an induction period, during which no popping occurs. This is followed by a period of rapid popping which then slows down as the small number of remaining kernels pops. The single-kernel data show that the effect of increasing the temperature is to increase the overall rate of popping (the time required for N, the number of unpop-

ped kernels, to drop to zero decreases with increasing temperature), and also to decrease the length of the induction period. This is clearly seen in the alternate display of the results shown in Fig. 2, which shows a plot of the fraction of kernels popped during 10-sec intervals versus time. At high temperature, most of the pops occur at short times over a short time interval. At low temperatures, the pops are spread out over a greater time span.

First-order kinetics. The popping of the kernels, after the induction period, is a first-order process. This is evident from Fig. 3A and B, in which ln(N) versus time data are plotted for the single kernel experiments at all of the temperatures. The plots are linear, as expected for a first-order process, after the induction periods, and thus are described by the equation

$$\ln(N) = -kt + \ln(N_o) \qquad (2)$$

where t is the time, k is the first-order rate constant, N_o is the initial number of kernels, and N is the number of unpopped kernels remaining at time t. From the slopes of these plots, the values of k can be obtained at each temperature. These values, which vary by a factor of 40-fold, are shown in Table II. A plot of the rate constants versus temperature is shown in Fig. 4. The temperature dependence of the rate constants cannot be described by single activation energy as shown by the Arrhenius plot in Fig. 5. The activation energy is 166.7 kJ/mol for 180–210°C, and 53.8 kJ/mol for 210–250°C.

Kinetic model. Our model contains two time-dependent variables: N, the number of unpopped kernels and T, the temperature inside the kernel. Their variation with time is described by the two differential equations

$$\frac{dT}{dt} = c(T_b - T) \qquad (3)$$

$$\frac{dN}{dt} = -kN \qquad (4)$$

Equation 3 is a form of Newton's law of cooling (White 1998), and describes the rate of temperature change of the kernel. Equation 4 describes the actual rate of popping. The popping process is a first-order process, with the temperature-dependent rate constant k. N is the number of unpopped kernels at a particular time; t is the time (sec); k is a temperature-dependent first-order rate constant for popping (s^{-1}); c is a temperature-independent constant, the "Newton's Law constant" (s^{-1}); T is the temperature at the center of the kernel (°C); T_b is the temperature of the oil bath or heated air (°C).

Rate constant. By analogy with first-order chemical reactions and nuclear decay, the rate constant k gives the probability per unit of time that a kernel will pop (Kaplan 1955; Forst 1973). A kernel can pop when its internal pressure, due to the vapor pressure of water in the kernel, exceeds the sum of the burst pressure (P_P) of the pericarp and the atmospheric pressure (P_a). The burst pressure (P_P) is the pressure needed to rupture the pericarp. The minimum internal pressure required to cause a kernel to pop will be referred to as critical pressure (P) and is the sum of the burst pressure of the pericarp and the atmospheric
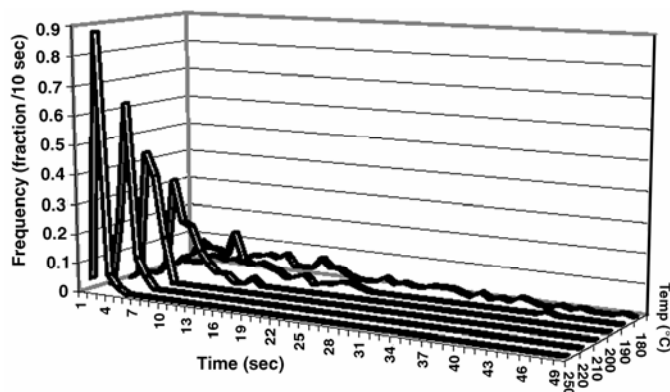

Fig. 2. Popping frequency vs. time. Fraction of pops in 10-sec intervals plotted vs. time from data shown in Fig. 1A and B.

TABLE II
First-Order Rate Constants[a]

Temp (°C)	k (s^{-1})
170	0*
180	0.00886
190	0.0166
200	0.0500
210	0.131
220	0.168
250	0.363
202**	0.0202**

[a] * No popping observed.** kernels popped in hot air.

pressure ($P = P_P + P_a$). For a kernel with a given value of P_P at atmospheric pressure P_a, popping will occur at the temperature at which the internal aqueous vapor pressure is equal to $P_P + P_a$. Thus, the rate constant for popping will depend on the kernel temperature. In a collection of popcorn kernels, there will be a distribution of critical pressures due to variations in pericarp thickness and possibly other factors that influence P_P. Thus, at a given temperature, not all kernels in the sample will have the same probability of popping because although they all have the same interior aqueous vapor pressure, they can have different critical pressures. The rate constant for the popping of an individual kernel with a critical pressure P will depend on P as well as on the temperature and will be written as $k(P,T)$. For a collection of kernels containing N_P kernels, all of which have the same critical pressure, the rate of popping is $dN_P/dt = -k(P,T) N_P$. In an actual trial in which a total of N kernels pop, not all of the kernels have the same value of P and the rate of popping is $dN/dt = -kN$, where k is an average rate constant (see Appendix)

$$k = \sum_{P=0}^{P_w(T)} k(P,T) f_P^* \qquad (5)$$

where f_P^* is the fraction of kernels with a critical pressure P, and $P_w(T)$ is the vapor pressure of water in the kernel at temperature T. The summation is over all possible values of critical pressure from zero to $P_w(T)$. This upper limit arises from the fact that kernels with a critical pressure greater than the vapor pressure of

water will not pop, and therefore do not contribute to the summation. The summation in Equation 5 can be replaced by an integral in which P is a continuous variable

$$k = \int_0^{P_w(T)} k(P,T) f_P \, dP \qquad (6)$$

where $f_P \, dP$ is the fraction of kernels with critical pressures in the range of P to $P + dP$, and $k(P,T)$ is the rate constant for kernels in that range. The function f_P is a distribution function that describes the distribution of critical pressures in the sample. Evaluation of the integral in Equation 6 requires functional forms for $k(P,T)$ and f_P. The value of $k(P,T)$ depends on the internal aqueous vapor pressure at a particular temperature relative to the critical pressure. Popping will only occur if $P < P_w(T)$. The greater the difference $P_w(T) - P$, the greater the value of $k(P,T)$. We have assumed the simplest possible expression for $k(P,T)$ consistent with this expectation: $k(P,T) = Z[P_w(T) - P]$ where Z is a constant of proportionality. The distribution of critical pressures is assumed to be Gaussian, where

$$f_P = \frac{1}{B^* \sqrt{\pi}} e^{-(P-\bar{P})^2/B^{*2}} \qquad (7)$$

where $\bar{P}$ is the mean critical pressure, and $B^* = \sigma\sqrt{2}$, where σ is the standard deviation of critical pressures. There is some justification, other than mathematical convenience, in assuming a Gaus-
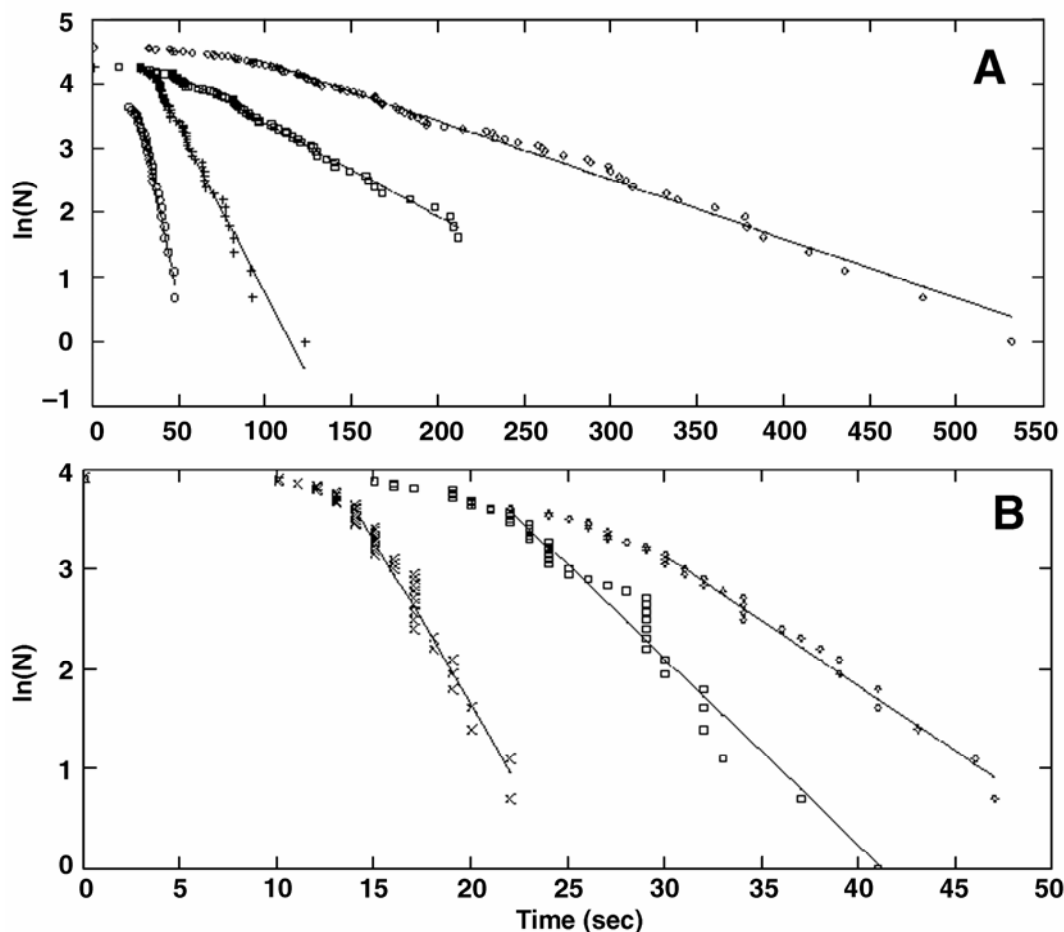

Fig. 3. First-order kinetics of isothermal bath popping at several temperatures. Data have been split between two plots because of the wide range of time spans for the different temperatures. **A,** 180°C (◇); 190°C (□); 200°C (+); 210°C (○). **B,** 210°C (◇); 220°C (□); 250°C (×). Symbols represent values of the natural log of the number of remaining kernels in the populations as a function of time. Lines show results of regression analysis of the linear portions of the curves. Slopes were used to obtain the values of the first-order rate constants listed in Table II.

sian distribution of critical pressures. An important factor that influences the critical pressure of a kernel is the thickness of its pericarp (Mohamed et al 1993). There is evidence that pericarp thickness and moisture content of the kernel are correlated. The pericarp thickness and the moisture content of kernels vary with location of the kernel on the ear. The pericarp is thinnest and the moisture content is lowest in kernels at the tip of the ear. The thickest pericarp and the highest moisture content occurs in kernels at the butt of the ear (Hoseney et al 1983; Song and Eckhoff 1994). The distribution of moisture content is approximately Gaussian, in agreement with earlier work (Song and Eckhoff 1994). Therefore, it is not unreasonable to assume a similar distribution of pericarp thicknesses and hence of critical pressures.

The complete form of the rate constant is

$$k = A^* \int_0^{P_w(T)} [P_w(T) - P] e^{-(P-\bar{P})^2/B^{*2}} dP \qquad (8)$$

where $A^* = Z/(\sqrt{\pi} B^*)$. In Equation 8, $P_w(T)$ is the aqueous vapor pressure in the kernel at temperature T and is related to the vapor pressure of pure water at temperature T, $P_w^*(T)$ by

$$P_w(T) = a_w P_w^*(T) \qquad (9)$$

where a_w is the water activity. Substitution of Equation 9 into Equation 8 yields

$$k = A \int_0^{P_w^*(T)} [P_w^*(T) - P_r] e^{-(P_r - \bar{P}_r)^2/B^2} dP_r \qquad (10)$$

In Equation 10, the parameter A is given by $A = A^* a_w$ and the variable of integration is now the reduced critical pressure $P_r = P/a_w$ and $\bar{P}_r$ is the mean value of the reduced pressure given by $\bar{P}_r = \bar{P}/a_w$. The upper limit of integration is unchanged because at the upper limit $P_r = P_w(T)/a_w = P_w^*(T)$. As a result of making the change of variable from P to P_P the assumption is now that the reduced critical pressures, rather than the critical pressures themselves, are described by a Gaussian distribution with a standard deviation given by $B/\sqrt{2}$. Thus, the rate constant k is a

function of temperature, the water activity a_w, and the parameters A, $\bar{P}_r$ and B.

The complete kinetic model is summarized by Equations 3 and 4 and contains four adjustable parameters (A, B, c, and $\bar{P}_r$). Values of $P_w^*(T)$ were obtained by fitting the vapor pressure of water to a third-order polynomial in temperature (CRC 1971).

There are four assumptions in our model. 1) For a given kernel, the probability of popping is directly proportional to the difference between the internal aqueous vapor pressure and the kernel's critical pressure. 2) In a sample of kernels there exists a distribution of critical pressures. 3) The measured rate constant, at a particular temperature, is an average over all of the kernels in the sample with critical pressures equal to or less than the internal aqueous vapor pressure at that temperature. 4) The heating of the kernel, and thus the temperature dependence of the first-order rate constant and the length of the induction period, can be modeled by Newton's law of cooling.

The results obtained from analyses of the single-kernel experiments are listed in Table III. Several conditions for finding the best-fit constants were used. In some of these optimizations, all of the constants (c, A, B, and $\bar{P}_r$) were allowed to vary until convergence. In others, the values of some of the constants (notably B and $\bar{P}_r$) were fixed at reasonable values to further test the generality of the kinetic model. Clearly, the best-fit values and the quality of the fit are not very sensitive to choice of fixed values.

In one approach to identifying reasonable values of these constants to fix, the estimates of only the first-order rate constants for each temperature were fit to the kinetic model using the simplex optimization method. For this data, the induction period is ignored and the constant c is eliminated from the set of differential equations. In Fig. 4, which shows the values of these first-order rate constants plotted against the temperature, the smooth line is calculated from Equation 10 and the best-fit values of A (0.00388/sec), B (176.1 kPa), and $\bar{P}_r$ (952 kPa). These values of B and $\bar{P}_r$ were then used to fit the kinetic data from the entire set of experiments to provide a uniform set of constants to allow further comparison of values of c and A across the entire data set, including the air-popped experiments. In Fig. 1A and B, where the entire collection of oil-popped data are presented, the solid lines were calculated using the best-fit values of A and c (see Table III) with B fixed at 176.1 kPa and $\bar{P}_r$ fixed at 952 kPa. Fixing $\bar{P}_r$ at a higher value (1,070 kPa), for example, gave comparable results.

Discussion of the Model

Consideration of the results for individual temperatures shows that several possible sets of constants give equivalent quality fitting of experiment to the kinetic model. There are undoubtedly
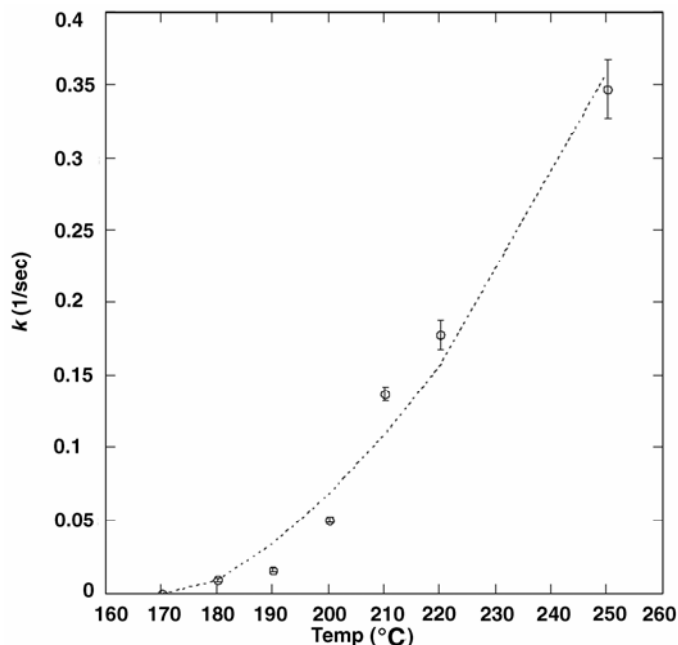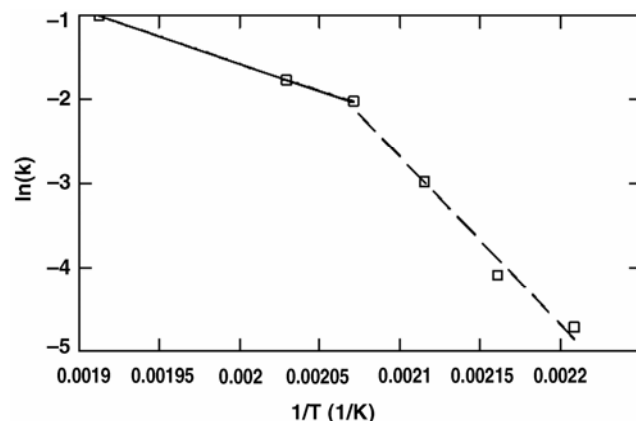
Fig. 4. Best-fit of values of first-order rate constants vs. temperature. Circles represent values of first-order rate constants from the linear portion of the plots in Fig. 3A and B. Smooth curves are calculated using the best-fit values of $B = 176.1$ kPa, $\bar{P}_r = 952$ kPa, and $A = 0.00388$/sec. Error bars are from the uncertainty in the slopes of the log plots of Fig. 3A and B .

Fig. 5. Arrhenius plot of rate constants in Fig. 4. Dashed line corresponds to an activation energy of 166.7 kJ/mol. Solid line corresponds to an activation energy of 53.84 kJ/mol.

many local minima and it is not possible to determine conclusively whether values shown in Table III have the smallest error possible. The actual values obtained from the data analyses for the different constraints are very similar. Furthermore, the values of c and $\overline{P}_r$ are reasonable, in light of previous work. This suggests that the values support a reasonable, semiquantitative, kinetic model, and that the range of values reported for the constants is indicative of uncertainties in the values of the constants.

The two extreme values of $\overline{P}_r$ (952 and 1,070 kPa) can be used to estimate $\overline{P}$, the mean critical pressure. At the instant of popping, $\overline{P}$ is equal to the aqueous vapor pressure at the temperature of popping [$\overline{P} = a_w \overline{P}_r = P_w(T)$]. Wu and Schwartzberg (1994) found that at 180°C, the water activity over popcorn grits is 0.769. Our model predicts a minimum popping temperature of 181 ± 2°C in oil and 187 ± 2°C in air. These values are not far removed from 180°C and we can reasonably assume that at the minimum popping temperature $a_w = 0.77$. This leads to values of the mean critical pressure $\overline{P}$ of 0.77 × 952 kPa = 733 kPa and 0.77 × 1,070 kPa = 824 kPa. Thus, our values are in reasonable agreement with the finding of Wu and Schwartzberg (1994) that the aqueous

vapor pressure inside a kernel at the instant of popping is in the range of 760–830 kPa.

Our values of c, the Newton's Law constant, are consistent with published data for air-popped popcorn. Analysis of Wu and Schwartzberg data yields a value for c of 0.034/sec, whereas analysis of the data of Roshdy et al (1984) yields a value for c of 0.039/sec. These values of c are within a factor of two of the value obtained in this work for air-popped kernels.

Induction periods and minimum popping temperatures. Previous studies of the popping of corn reported in the literature have included determinations of the minimum temperature required for popping. This is connected closely with the work reported here. The induction period is the time required for the kernel temperature to reach the minimum value required for popping. Inspection of Fig. 1A and B shows clearly that the length of the induction time decreases as the bath temperature increases, as predicted by Newton's Law of Cooling (Equation 3). Our model and data allow an indirect measurement of the minimum popping temperature. Quantitative prediction of the popping times in oil for the 396 kernels at six temperatures, and 94 kernels in an air

TABLE III
Values of Kinetic Model Parameters for Single Kernel Experiments[a,b]

Temp (°C)	N (kernels)	$10^3 A$ (s⁻¹)	$10^2 c$ (s⁻¹)	B (kPa)	P_r (kPa)	RMSD (kernels)
170	No popping	–	–	–	–	–
180	96	3.5	6.2	176.1*	952*	1.7
		5.8	6.3	229	1,070*	1.7
		5.3	6.4	192	1,013	1.7
190	90	1.9	9.2	176.1*	952*	2.0
		2.0	9.5	264	1,070*	2.0
		1.5	9.0	247	979	1.9
200	72	3.7	8.3	176.1*	952*	2.3
		6.1	9.3	130	1,070*	2.2
		5.7	7.3	92.2	770	2.3
210	39	7.2	8.8	176.1*	952*	0.7
		5.5	9.2	276	1,070*	0.7
		6.2	10.2	294	1,231	0.7
220	49	6.8	10	176.1*	952*	1.7
		4.9	10.7	266	1,070*	1.7
		6.4	12.4	219	1,301	1.7
		12.1	14.0	121	1,459	1.8
250	50	10.5	11	176.1*	952*	1.9
		14.0	12.0	117	1,070*	1.9
		9.57	11.4	187	1,018	1.9
202**	53	0.66	6.5	176.1*	952*	2.1
		0.34	6.9	187	1,070*	2.0
		0.76	6.4	163	969	2.0
202**	41	0.89	4.6	176.1*	952*	1.9
		0.85	4.6	234	1,070*	1.9
		1.1	5.0	186	1,052	1.9

[a] * Fixed; ** air popped.
[b] N is number of unpopped kernels remaining at time t; A and B are two empirical constants; c is a temperature-independent constant; P_r is reduced critical pressure; RMSD is root mean squared deviation about regression.

TABLE IV
Minimum Temperature for Popping (°C)[a]

This work*	This work**	Hoseney et al (1983)*	Wu and Schwartzberg (1992)**	Roshdy et al (1984)**
181 (±2)	187 (±2)	166–177	187 (±7.7)	187.0 (±2.2)

[a] * Oil popped; ** air popped.

TABLE V
Distribution of Moisture Content and Critical Pressures[a]

	Mean	SD*	RSD**
Critical pressure	952 kPa	124 kPa	0.13
Moisture content of unpopped kernels	15.2%	0.45%	0.030
Moisture loss of popped kernels	14.5%	1.1%	0.076

[a] * Standard deviation; ** relative standard deviation.

popper includes the prediction of the kernel internal temperatures as a function of time. Thus, the numerical integration of the set of coupled, differential equations permits the estimation of the predicted time for the first kernel to pop (induction time) and the corresponding temperature (minimum popping temperature). It is important to note that, even when all of the kernels reach this minimum temperature, they do not all pop simultaneously but have random lifetimes characteristic of a first-order process. Thus, the time and internal temperature at the first pop in a population of kernels does not necessarily coincide with the theoretical induction time/minimum temperature.

Results from analysis of the data described here are in agreement with the literature values reported previously from direct measurements with thermocouples (Table IV).

Moisture content, critical pressure, and kernel lifetimes. The average moisture loss from the popped kernels is slightly lower than that the moisture content found for the unpopped kernels (Table V). This difference, which is statistically significant, is likely due to a small amount of water remaining in the popped kernels.

Our kinetic model assumes a Gaussian distribution of reduced critical pressures with a standard deviation given by

$$\sigma = \frac{B}{\sqrt{2}} = \frac{176.1}{\sqrt{2}} = 124.5 kPa \qquad (11)$$

and a mean of 952 kPa. It is interesting to compare the distribution of critical pressures with the distributions of moisture content and moisture loss. For this purpose, a unitless relative standard deviation was obtained by dividing the standard deviation by the mean (Table V). The width of the reduced critical pressure distribution is greater than that of the moisture distributions of both the popped and the unpopped kernels.

In summary, perhaps the most significant result of this work is that the average popping times reported in the literature are actually the sum of an induction time, during which the kernel is heated to the minimum popping temperature, followed by a random first-order lifetime. According to our model, this first-order lifetime is a function of the kernel critical pressure, temperature, internal water activity, and two empirical constants (*A* and *B*).

CONCLUSIONS

The seemingly random popping times (or lifetimes) of popcorn kernels are actually the lifetimes expected for a process consisting of an initial induction period during which no popping occurs and the kernels are heated to the minimum popping temperature followed by a period of popping. During the popping period, the data obey the first-order integrated rate law *ln(N) = –kt + ln(N_o)*, where N_o is the initial number of kernels, and *N* is the number of kernels remaining unpopped at time *t*. Alternatively, *N* is the number of kernels with a lifetime greater than *t*. This conclusion is based on experiments in which the lifetimes of single popcorn kernels were measured by heating them in a constant temperature oil bath. Repetition of this experiment at several temperatures yielded the temperature dependence of *k*. A quantitative model is described that accurately reproduces the experimental *N* versus *t* data. The model is consistent with the existing explanation of "why popcorn pops".

The model also successfully reproduces the data obtained in similar experiments utilizing hot air instead of oil as the heating medium. Minimum popping temperatures predicted by the model are in good agreement with direct measurements by other workers.

APPENDIX

$$N = \sum_{P=0}^{P_w(T)} N_P$$

$$\frac{dN}{dt} = \sum_{P=0}^{P_w(T)} \frac{dN_P}{dt} = -\sum_{P=0}^{P_w(T)} k(P,T)N_P$$

$$= -N \sum_{P=0}^{P_w(T)} k(P,T)f_P^* = -kN$$

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