Extraction of Oil from Meadowfoam Flakes

Kenneth D. Carlson[a], Bliss S. Phillips[a,*], Terry A. Isbell[a], and Terry C. Nelsen[b]

[a]New Crops Research, NCAUR, MWA, ARS, USDA and
[b]Office of the Area Director, MWA, ARS, USDA, Peoria, Illinois 61604

ABSTRACT: As part of a program to improve meadowfoam seed processing, the authors examined the effects of seed moisture, seed temperature, and flaking roll opening on oil extraction efficiency in meadowfoam flakes. Flakes were prepared using a Wolf Mill with dual horizontal, unheated 12-in. diameter rolls. Roll openings of 0.005, 0.013, and 0.020 in. (0.127, 0.330, and 0.508 mm, respectively) gave average flake thicknesses of 0.013, 0.021, and 0.031 in., respectively (0.330, 0.533, and 0.787 mm). Seed moistures of 9, 12, and 15% and seed temperatures of 65, 190, and 210°F (18, 88, and 99°C) chosen for flaking were known to provide a range of conditions suitable for enzyme inactivation during seed cooking prior to flaking. Experimental flakes were examined for extractable oil content (petroleum ether extraction); this was compared to total oil content (31.5%) determined on finely ground flakes. Roll opening was the dominant variable determining flake thickness, the primary parameter affecting oil extraction efficiency. Thus, the thinnest flakes at 0.013 in. were only slightly less extractable (29.8%) than finely ground flakes (31.5%), but intermediate (0.021 in.) and thick (0.031 in.) flakes were significantly less extractable (28.0 and 26.0%, respectively). There was a slight but significant ($P < 0.01$) trend toward thicker flakes with increasing seed moisture (15 > 12 > 9%) during flaking. A similar trend to thicker flakes with increasing temperature was significant ($P < 0.01$) only for the thickest flakes produced at the largest roll opening (0.020 in.). Lower seed moisture and higher seed temperature significantly impacted extractable oil content of the thickest flakes, but negligibly affected extractability of the thinnest flakes. The authors conclude that meadowfoam flakes must be as thin as possible (e.g., <0.015 in.) for efficient oil extraction. Further, seed cooking temperatures >190°F at moistures >10% and <15% that are adequate for efficient enzyme inactivation in the whole seed are also suitable for seed flaking.
JAOCS 75, 1429–1436 (1998).

KEY WORDS: Flake thickness, *Limnanthes*, meadowfoam, oil extraction efficiency, seed flaking, seed moisture and temperature at flaking.

Development of a meadowfoam (*Limnanthes alba*) industry in the United States is progressing thanks to the efforts of private sector partnerships to sustain significant meadowfoam seed and oil production over the past 5 yr. This has required recruiting farmers for seed production, seed cleaning and shipping activities, the development of partnerships and techniques for oil extraction and refining, and aggressive development of markets for the oil. The authors observed these activities as advisors and active cooperators, particularly in the oilseed processing and product development arenas. The meadowfoam industry appears poised for significant further expansion using knowledge gained in the recent past and new technologies coming online.

Improving oil extraction efficiency from meadowfoam seed, whether in the form of flakes, collets, or press cake, is one goal the authors have that would positively impact future expansion of the meadowfoam industry. Inefficient oil removal by solvent from flakes, collets, or press cake usually relates to insufficient particle size reduction and poor solvent permeability of the substrate (1–3). Extraction efficiencies ascribed to collets formed with expanders can only be achieved if particle size within the collets has been adequately reduced. Usually this can be achieved by flaking the seed prior to expanding. Laboratory examination of colleted meadowfoam seed showed that if thick flakes are fed to the extruder and if significant particle size reduction does not occur there, then the expected result will be poor extractability of the collets (Carlson, K.D., unpublished results). Character and quantity of testa (seed coat, hull) associated with the prepared seed substrate can also affect oil extraction efficiency. In this regard, meadowfoam seed has an extensive, relatively tough, and irregularly surfaced testa that makes dehulling difficult and perhaps impractical (Carlson, K.D., unpublished results).

Thus, the authors undertook this study to examine the effect of meadowfoam flake thickness on oil extractability. Flake extractability was assumed to correlate directly with extractability of collets or press cake formed therefrom. The importance of inactivating thioglucosidase enzyme systems in rapeseed and crambe (4) and in lesquerella (5) has been discussed in consideration of their potential for releasing antinutritional compounds into the meals and sulfur or sulfur derivatives into the crude oils. Since meadowfoam seeds contain glucosinolates, optimal oil quality requires inactivation of a thioglucosidase enzyme system prior to flaking or crushing. Moisture and temperature levels suitable for inactivating the thioglucosidase enzyme system in whole meadowfoam seed (Carlson, K.D., unpublished results) were examined for their effects on flake thickness and oil extractability of the flakes.

*To whom correspondence should be addressed at New Crops Research, NCAUR, ARS, USDA, 1815 N. University St., Peoria, IL 61604. E-mail: ncbsp@mail.ncaur.usda.gov

MATERIALS AND METHODS

Seed source and moisture equilibration. Meadowfoam seed was obtained from the Oregon Meadowfoam Grower's Association (Salem, OR). The machine-cleaned seed contained approximately 1% plant debris in the form of small pieces of stems that were removed by hand from 4 kg seed in preparation for flaking (7.5% moisture, 31.6% oil dry weight basis). Cleaned seed (400 g) was then distributed into each of nine wide-mouth, screw-cap, glass jars (32 oz., Wilkens-Anderson Co., Cat. # 05800-05). To each of three jars was added 6.59 g distilled water (for 9% equilibrated moisture), to each of three others was added 20.45 g water (12% moisture), and to each of the last three was added 35.29 g water (15% moisture). The jars were then tightly capped, the lids secured with electrical tape, and the jars rolled and shaken to begin moisture distribution through the seed. Each jar was heated at 50% power in a domestic microwave oven (Litton, Model No. 1041, 115V, 13 amp, 60 Hz) for consecutive time intervals of 60, 35, and 30 s, between which the jars were vigorously rolled and shaken to mix the hot seeds (*ca.* 176°F; 80°C) and uniformly distribute the moisture throughout the seed mass. As the jars cooled to room temperature, each was periodically vigorously rolled and shaken to continue the mixing and moisture equilibration process (no liquid water was observable in any of the nine jars). The equilibrating samples remained at room temperature until flaking was initiated (4 d). Each three-jar set (9, 12, or 15% projected moisture) was sampled for moisture determination prior to the flaking experiments (actual moistures: 8.80, 12.25, and 15.45%). Seed (60 g) from each moisture equilibrated set was distributed into and sealed in each of 18 wide-mouth, screw-cap, glass jars (8 oz), serving as duplicate sets of nine samples at each moisture for flaking at three roll openings and three temperature levels (54 samples, Table 1).

Temperature equilibration of seed prior to flaking. The sealed 60 g seed replicates were heated in a microwave oven until the seed temperature (measured by insertion of a metal probe thermometer) was approximately that desired for flaking. The sealed samples were then equilibrated (15–30 min) in convection ovens set at 190 or 210°F (88 or 99°C) prior to flaking. Each temperature equilibrated sample jar was removed from the appropriate oven, opened and the seed sample quickly flaked (<5 s) as described below. Seed samples flaked at the ambient temperature of the milling laboratory (65°F, 18°C) were not otherwise heated prior to flaking.

Seed flaking. Seed samples were flaked using a Wolf Mill with two horizontal, unheated rolls (12 in. dia × 6 in. w; 30.5 cm × 15.2 cm). Any reference to flaking temperature in this paper is defined as the conditioned "seed temperature at flaking." Roll openings were set to the nearest thousandth in. in the range 0.003–0.025 in. (0.076–0.635 mm) using a feeler gauge. Moisture- and temperature-equilibrated seed samples (60 g) were rapidly hand-fed (5 s) into the nip of the rolls *via* an inclined Plexiglass chute riding on the rolls. Flakes were collected in a pan below the rolls and were then transferred to 8-oz wide-mouth, screw-cap, glass bottles for later flake thickness and oil content determinations. Preliminary experiments showed that seed at ambient moisture (6.5%) did not form flakes at any selected roll opening, whereas seed equilibrated to 12% moisture at ambient (65%F) or elevated temperature (176°F, 80°C) flaked readily at all but the smallest roll openings (<0.005 in.; 0.127 mm) where clumping and flake fracturing predominated.

In the formal experiments, the mill was set at 0.005-in. opening and all samples to be flaked at this opening were sequentially flaked. For example, replicate-1 seed samples equilibrated to 9% moisture were flaked at seed temperatures of 65, 190, and 210°F followed by replicate-2 samples in a like manner. Then, samples equilibrated at 12% moisture were flaked at these three seed temperatures, and then samples equilibrated at 15% moisture were flaked at these three temperatures. Next, the mill was set to the 0.013-in. opening, and the three moisture equilibrated series of samples were similarly flaked in sequence at the three selected seed temperatures. Finally, the mill was set to the 0.020-in. opening, and the above flaking sequence was repeated. Each series was replicated (Table 1).

Flake thickness measurements. Flaked samples were spread on Whatman filter paper (Maidstone, England) and visually examined for differences among samples in relative amounts of flake clumps, flake fragments, fines, and whole seeds. Differences were noted but not quantified. The few whole seeds that apparently bypassed the ends of the rolls and dropped into the receiving pan were removed by hand to ensure that oil extractability related only to flaked substrate. In using forceps, 10–20 flakes from each sample were randomly selected and measured for thickness using a Mitutoyo micrometer [0.0–1.0 in. (0.0–25.4 mm) in 1/1000-in. increments]. Mean flake thicknesses (and standard deviations) were determined for each replicated parameter series (Table 1). Although flake diameter was not a variable in this study, better specimens of the thinnest whole-seed flakes were noted to have diameters generally <0.354 in. (<9 mm).

Moisture and oil analyses. After flake thickness determinations, flaked samples were spread on paper towels to air dry uniformly (72 h) to approximately 6% moisture before oil extraction. Moisture content of the air-dried flakes was determined gravimetrically in duplicate by drying 2.5 g in an oven at 248°F (120°C) for 2 h. Extractable oil content of the air-dried flakes (3.5 g) was determined in duplicate using a 6-h petroleum ether butt flask (Fisher Scientific certified ACS, CAS 68476-50-6) extraction method similar to AOCS Method Ba 3-38. Mean oil extracted (and standard deviations) were determined for each replicated parameter set (Table 1). Controls for total extractable oil were established; six flake samples, prepared from seed equilibrated at 12% moisture and 190 or 210°F and rolled at 0.005-, 0.013-, or 0.020-in. opening (first replicates), were finely ground in a coffee mill and extracted in a similar manner with petroleum ether. Mean oil contents (and standard deviations) were determined to compare oil levels extracted from the corresponding unground flakes.

TABLE 1
Flaking of Meadowfoam Seed at Three Roll Openings, Three Moistures, and Three Temperatures

Protocol variables			Flake thickness (in./1000)			Oil extracted, % (db)[a]		
Roll opening (in./1000)	Seed moisture (%)	Seed temperature (°F)	Rep.1	Rep. 2	Rep. mean	Rep. 1	Rep. 2	Rep. mean
5	9	65	11	11.3	11.1	31.2	30.3	30.7
5	12	65	12.8	12.4	12.6	30.4	30.7	30.6
5	15	65	14.5	12.3	13.4	29.1	29.8	29.5
5	9	190	12	12.1	12	29.8	30.1	29.9
5[b]	12	190	12.7	12.1	12.4	29.7	30.4	30
5	15	190	12.9	14	13.2	28.7	28.6	28.7
5	9	210	12.3	11.3	11.8	30.4	30.5	30.4
5[b]	12	210	11.8	12.6	12.2	29.6	29.9	29.7
5	15	210	12.1	13.2	12.6	28.9	29.6	29.2
13	9	65	19.5	19.7	19.6	28.5	29.3	28.9
13	12	65	20.4	19.5	20	27.1	27.1	27.1
13	15	65	21	20.8	20.9	25.4	26.2	25.8
13	9	190	20.4	20.6	20.5	27.6	28.2	27.9
13[b]	12	190	20.9	20.8	20.9	28.6	29.6	29.1
13	15	190	21.4	21.6	21.5	27	28.3	27.6
13	9	210	20.2	20.5	20.4	29.6	29.1	29.3
13[b]	12	210	20.4	21.1	20.7	29.2	28.3	28.8
13	15	210	21.5	21.2	21.4	27.5	27.3	27.4
20	9	65	28.4	27.3	27.9	26.6	27	26.8
20	12	65	27.8	28.2	28	24.6	27.4	26
20	15	65	28.7	28	28.4	21.4	21.1	21.3
20	9	190	29.5	30.7	30.1	26.7	28.5	27.6
20[b]	12	190	31.5	31.3	31.4	26.1	27.2	26.6
20	15	190	29.9	31.3	30.6	23.4	23.7	23.5
20	9	210	31.3	31.2	31.3	27.4	27.2	27.3
20[b]	12	210	32.6	31.6	32.1	27.1	28.2	27.6
20	15	210	32.4	32.7	32.6	25.7	24.9	25.3

[a]Abbreviations: db, dry basis. Average of duplicate analyses for Replicate (Rep.) 1 and 2; Rep mean = average of four analyses.
[b]For controls, samples taken from these flakes were ground in a coffee mill and average extractable oil determined for each. Overall mean for all control samples = 31.5 ± 0.38% (RSD = 1.19%).

Statistical analyses of data. Analysis of variance (ANOVA) procedures (SAS software) were used to evaluate the effects of roll opening, temperature, and moisture individually and in all possible combinations on flake thickness and extractable oil.

RESULTS AND DISCUSSION

Preliminary experiments. Ambient moisture (6.5%) meadowfoam seeds failed to yield flakes regardless of flaking roll opening (0.005–0.015 in.; 0.127–0.381 mm); the narrower the roll opening, the greater the amount of fines produced. However, flakes were produced at all roll openings tested when the seed was first conditioned to 12% moisture. These experiments demonstrate that roll openings choices to flake moisture-tempered seed were a tradeoff between generating excessive amounts of fines (0.003-in. gap) and simply squashing the seeds (0.025-in. gap) without true flake formation. Visually, the amount of fines increased as the roll opening narrowed. An experiment in which heat- (104–176°F) and moisture- (12%) tempered seeds were rolled at different roll openings suggested that flake thickness might be impacted by temperature only at wider roll openings. Flakes produced in these preliminary experiments had oil extractabilities dependent on flake thickness; once the flakes were ground, maximal oil extraction was attained regardless of prior flake history. A single experiment in which 0.016-in. flakes were rerolled at a 0.004-in. opening suggested that double rolling of flakes may be beneficial to oil extractability, although the results may be due as much to particle size reduction (increased fines) as to thinner flakes.

Multivariable study. These preliminary results encouraged the authors to establish a three-variable experimental protocol (seed moisture, roll opening, and seed temperature) to evaluate extractability of oil from meadowfoam seed (Table 1). Seed moisture contents (9, 12, and 15%) and elevated seed temperatures (190 and 210°F) at flaking were chosen to span the ranges known to be critical for inactivation of seed enzyme systems, particularly thioglucosidase inactivation. Ambient temperature (65°F) seed tempered at the three moistures was also flaked for comparison with the "cooked" seed.

In order to obtain the thinnest flakes possible with acceptable fines content, the authors selected a 0.005-in. roll opening for the narrowest gap and 0.020 in. for the widest gap; these provided visually acceptable flakes. Within this range more fines were observed with narrower gap. The authors chose an intermediate gap of 0.013 in. for the third setting.

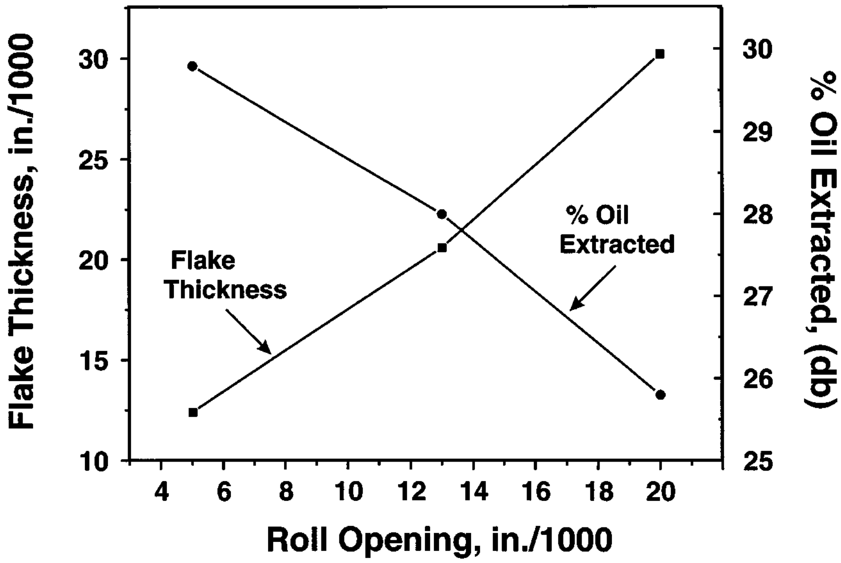

FIG. 1. Extractability of meadowfoam flakes: flake thickness and percentage oil extracted vs. flaking roll opening (averaged across all temperatures and moistures); db, dry basis.

Figure 1 shows the relationship between roll opening and flake thickness independent of moisture and temperature (each point represents the mean of 18 samples; 2 replications × 3 moistures × 3 temperatures). The authors observed more clumping of flakes as seed moisture increased, and more flake fragility with increasing seed temperature (drying effect).

Table 1 contains the results of key analyses for flake thickness and percentage oil extracted from the flakes. The experiments were run in ascending order of roll opening on replicated (duplicate) samples. Flake thicknesses were measured on 10–14 individual flakes for each sample replicate (20–26 measurements for the two replicates), and extractable oil was determined in duplicate on each sample replicate (four analyses). There was generally good agreement among replicate means for both flake thickness and oil extracted. Six flake entries in Table 1 (roll openings marked with a superscript "b") were chosen as controls to determine maximal oil extractability. They were finely ground in a coffee mill, and the mean and standard deviation for percentage oil extracted were determined in duplicate for each. There were no differences among the six ground flake samples (31.5 ± 0.38% oil, RSD = 1.19%), which yielded more oil than any of the flake samples. Thus, maximal oil is extracted when particle size reduction is maximized by grinding the flakes, and flake extractability will be seen to be uniquely related to preparation conditions under the experimental protocol.

General observations from raw data. Figure 2 is a scatter plot of oil extracted vs. flake thickness across all temperatures and segregated by moistures (54 samples). Several observations are worth mentioning. First and foremost, in comparing

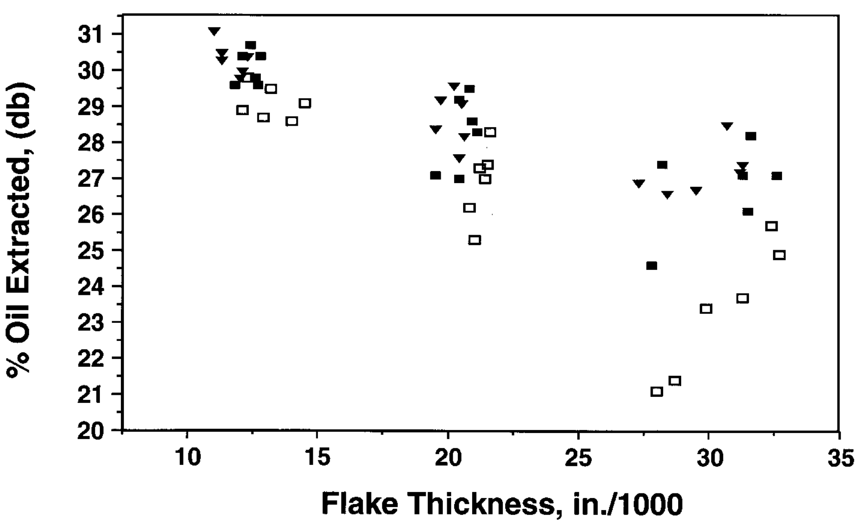

FIG. 2. Extraction of meadowfoam flakes: percentage oil extracted vs. flake thickness segregated by seed moisture at flaking. Moistures (%): ▼ = 9, ■ = 12, □ = 15. See Figure 1 for abbreviation.

the three clusters, oil extractability decreases with increasing flake thickness (or roll opening). Solvent diffusion into and out of the thinnest flakes is more efficient than for the thicker flakes. Hence, more efficient and uniform oil extraction results with thinner flakes. Second, the three clusters of data points result from the three roll openings chosen. Scatter within each cluster is related to moisture and temperature effects, and to inherent variability associated with rolling meadowfoam seeds of different sizes and shapes at a given roll opening. This inherent variability associated with the flaking process is probably largely responsible for the third observation, the increased scatter within clusters at larger roll openings (or flake thicknesses). For example, extensive scatter in the cluster associated with the 0.020-in. roll opening centered around 0.030-in. flake thickness undoubtedly results from the fact that smaller seeds were merely squeezed or squashed, whereas larger seeds were rolled into imperfect "flakes" of variable thicknesses. Either result would lead to variable flake extractability. On the other end, at 0.005-in. roll opening (left hand cluster), seeds were rolled more perfectly into true flakes of more uniform thicknesses centered around 0.012 in. Hence, more uniform flake extractability and less scatter within the cluster are observed. Fourth, the effect of seed moisture (within clusters) is apparent when each cluster is visually incorporated into a quadrantized circle. For example, for the small cluster centered at approximately 0.012-in. flake thickness and 30% extracted oil, flakes were produced from 9% moisture seed group in the quadrant of thinnest flakes and highest oil extractability. Flakes were produced from 15% moisture seeds group in the quadrant of thickest flakes and lowest oil extractability. Flakes produced at 12% moisture fall in between. Thus, for these generally thin flakes a direct relationship between flaking moisture and flake thickness and an inverse relationship between flaking moisture and oil extractability are suggested. For the middle cluster of flakes centered at approximately 0.020-in. thickness and 28% oil extractability, the flakes produced at 15% moisture again are grouped in the quadrant of thicker flakes and lower oil extractability. The distinction between flakes produced at 9 and 12% moisture is more obscure, though on average both appear to be thinner and more extractable than the 15% moisture flakes. For the thickest, the cluster of flakes centered at approximately 0.030-in. thickness and 25% oil extractability, the distinction between the 9 and 12% flakes is further obscured, although they appear generally to be more extractable than the 15% moisture flakes, which are again gathered in an incorporating circle's quadrants of lower extractability.

Figure 3 is a scatter plot of oil extracted vs. flake thickness across all moistures, but now identified by temperature. Any temperature effect is obscure in the small thinnest-flake cluster, but partial separation by temperature is apparent in the middle cluster where flakes produced at 65°F appear to segregate. The thickest-flake cluster at 0.030-in. thickness and 25% oil extractability, vertical separation by temperature is apparent. Thus, for intermediate and large roll openings, ambient temperature flaking tended to produce thinner flakes than elevated temperature flaking (flake thickness at 65 < 190 < 210°F), but flakes at each temperature exhibit wide scatter in oil extractability.

Statistical analyses of the data. The authors sought verification of these observations using ANOVA procedures. Table 2 collects the results of statistical analyses of the experimental data (Table 1). Differences in roll opening, seed flaking temperature, and seed flaking moisture are statistically significant for both flake thickness and for extracted flake oil ($P < 0.01$). The interaction, roll opening × seed temperature (R × T), is also significant for both measured parameters ($P < 0.01$). The interaction, roll opening × seed moisture (R × M), is significant for extracted oil ($P < 0.01$), but not for flake thickness ($P < 0.36$). Temperature × moisture (T × M) and roll opening × temperature × moisture (R × T × M) interactions are not significant for flake thickness, but are for extracted oil ($P < 0.02$).

Table 3 shows the statistical relationships among mean flake thicknesses and percentage extracted oil vs. roll open-

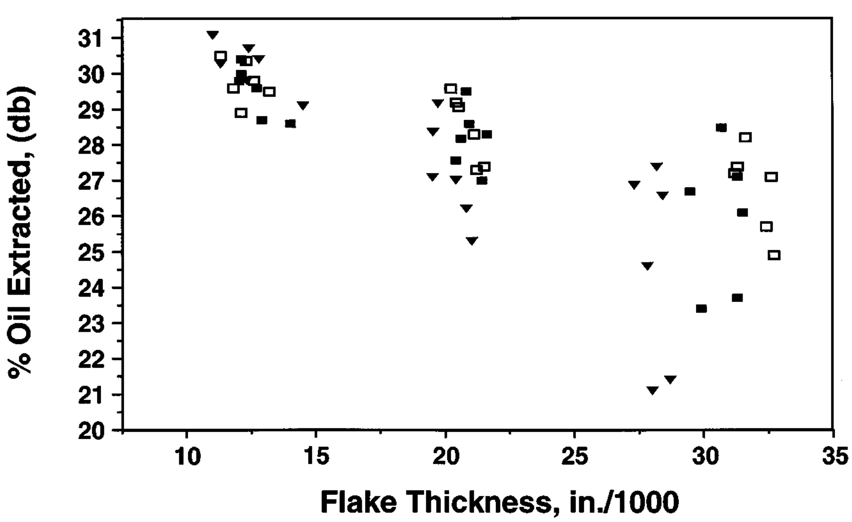

FIG. 3. Extraction of meadowfoam flakes: percentage oil extracted vs. flake thickness segregated by seed temperature at flaking. Temperatures (°F): ▼ = 65, ■ = 190, □ = 210. See Figure 1 for abbreviation.

TABLE 2
Analysis of Variance Results

Source	DF	Mean squares[a] Flake thickness	Mean squares[a] Oil extracted
Roll opening (R)	2	1434.0**	78.7**
Temperature (T)	2	11.1**	4.6**
Moisture (M)	2	5.7**	25.8**
R × T	4	7.0**	2.6**
R × M	4	0.4	3.6**
T × M	4	0.1	1.4*
R × T × M	8	0.3	1.2*

[a]**$P < 0.01$; *$P < 0.05$.

TABLE 3
Overall Average Flake Thickness and Oil Extracted for Each Roll Opening, Seed Temperature, and Seed Moisture[a]

Variable	Flake thickness (in./1000)	Oil extracted, % (db)
Roll opening (in./1000)		
5	12.4A	29.9C
13	20.6B	27.9B
20	30.2C	25.7A
Seed temperature (°F)		
65	20.2A	27.3A
190	21.4B	27.7A
210	21.7B	28.3B
Seed moisture (%)		
9	20.5	28.6B
12	21.1B	28.4B
15	21.6C	26.4A

[a]Values followed by different capital letters are significantly different. For abbreviations see Table 1.

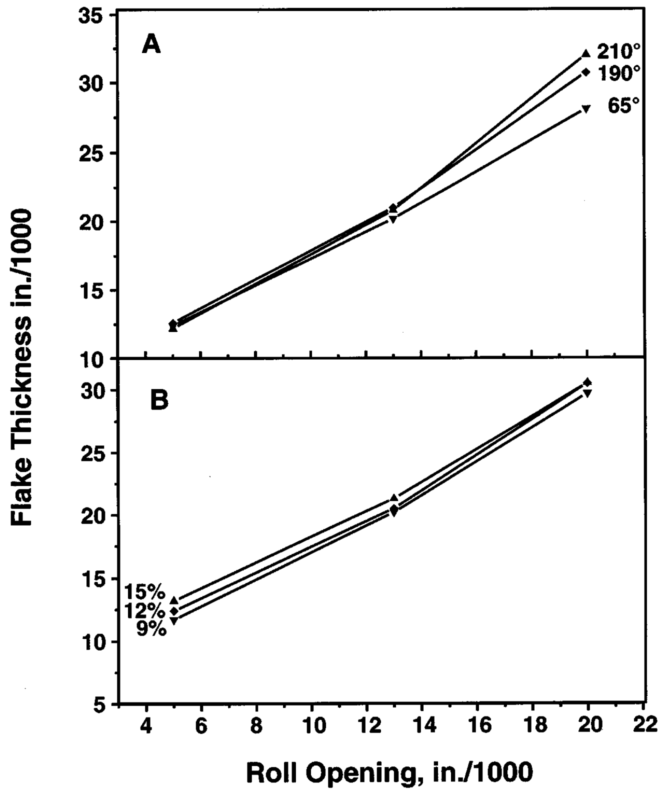

FIG. 4. Impact of seed temperature and moisture at flaking on flake thickness vs. roll opening. A. Temperature effect (°F), averaged across all moistures. B. Moisture effect, averaged across all temperatures.

ing (across all moistures and temperatures), temperature (across all roll openings and moistures), and moisture (across all roll openings and temperatures). As observed from the scatter plots (Figs. 2 and 3), the obvious direct relationship between roll opening and flake thickness and their inverse relationship to percentage oil extracted (oil extractability) are confirmed (see also Fig. 1). The smaller yet significant relationships of seed flaking temperature and moisture relative to flake thickness and oil extractability also are affirmed statistically. An experimental protocol that produced more data points would likely further delineate these small moisture and temperature effects on flake thickness and oil extractability.

Temperature and moisture effects on flake thickness. Temperature effects on flake thickness are separated out by averaging across all moistures at the three experimental roll openings (Fig. 4A). At the smallest opening (0.005 in.), differences in flake thickness are not significant for temperature. At a 0.013-in. roll opening, flakes produced at 65°F are thinner ($P < 0.01$) than those produced at either 190 or 210°F. At the largest roll opening (0.020 in.), differences in flake thickness are significant ($P < 0.01$) at all temperatures. Moisture effects on flake thickness are determined by averaging across all temperatures at the three roll openings (Fig. 4B). The impact of moisture on flake thickness is slight but significant ($P < 0.01$) in the order 15 > 12 > 9%, most noticeably at the smaller roll openings (0.005 and 0.013 in.). Thus, both temperature and moisture influence flake thickness predictably.

Temperature and moisture effects on oil extractability. Temperature effects on percentage oil extracted are evaluated by averaging across all moistures at experimentally determined flake thicknesses (Fig. 5A). In thin flakes, oil extractability was not impacted by seed temperature at flaking. The largest temperature impact was in thick flakes in which oil extraction rose with increasing flaking temperature even though flake thickness also rose with flaking temperature (Figs. 4A, 5A). Moisture effects on percentage oil extracted are determined by averaging across all temperatures at experimentally determined flake thicknesses (Fig. 5B). Flakes produced from seed with the highest moisture (15%) were significantly less extractable than flakes produced from the lower moisture seeds (9 and 12%).

Putting it all together. In Figure 6, replicated means for percentage oil extracted are plotted against the three study variables, seed flaking moisture, seed flaking temperature, and flaking roll opening (solid/dashed lines). Looking first at the 0.005-in. roll opening set, there were no significant differences in percentage oil extracted ($P < 0.05$) among temperatures at any given moisture level. Likewise, there were no differences in percentage oil extracted among moisture levels within any given temperature. Averaging across temperature at each moisture, percentage oil extracted for the 15% moisture samples was different ($P < 0.05$) from the 9 and 12% moisture samples. Averaging across moisture levels at each

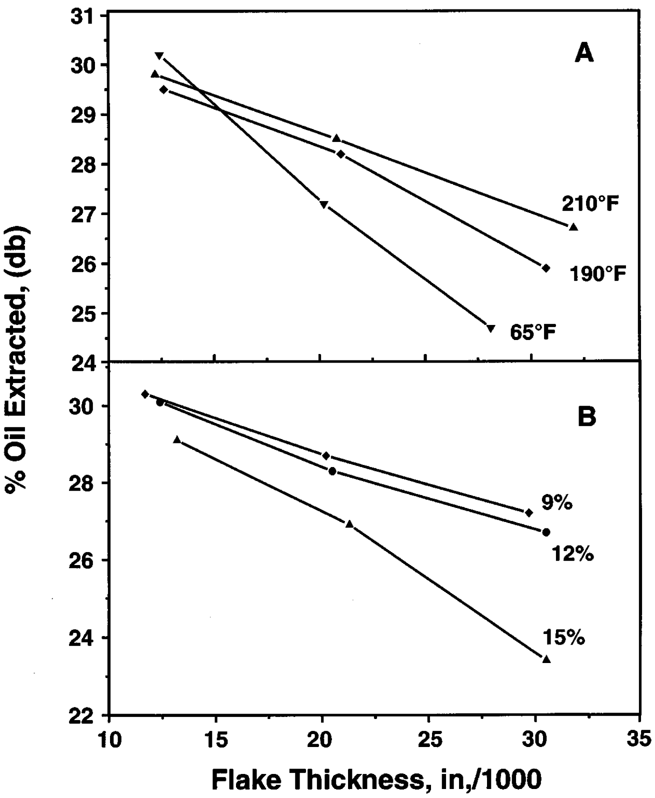

FIG. 5. Impact of seed temperature and moisture at flaking on oil extractability vs. flake thickness. A. Temperature effect, averaged across all moistures. B. Moisture effect, averaged across all temperatures. See Figure 1 for abbreviation.

temperature, there were no differences in percentage oil extracted ($P > 0.05$) among temperatures. Next, consider samples prepared at 0.013-in. roll opening. At 9% moisture, less ($P < 0.05$) oil was extracted from the 190°F samples than from the 210 and 65°F samples. At 12 and 15% moistures, more oil was extractable ($P < 0.05$) from the 190 and 210°F samples than from the 65°F samples. Averaged over all temperatures, oil extracted from the 9 and 12% moisture samples was greater ($P < 0.05$) than from the 15% moisture samples. Averaged over all moistures, more oil was extracted from the 190 and 210°F samples than from the 65°F samples. Consider the 0.020-in. roll opening samples. At the 9% moisture level, there were no differences in percentage oil extracted among the three temperatures. At 12% moisture, more oil was extractable ($P < 0.01$) from the 210°F samples than from either the 65 or 190°F samples. At 15% moisture, the oil extractability decreased ($P < 0.01$) with temperature in the order 210 > 190 > 65°F. Averaged over all moistures, percentage oil extracted similarly decreased with temperature ($P < 0.01$). Averaged over all temperatures, oil extractabilities were greater ($P < 0.01$) for samples with moisture levels of 9 and 12% than for samples at 15% moisture.

These data clearly show that flake thickness (roll opening) is the dominant factor for efficient extraction of oil from meadowfoam seed (Fig. 1). Seed temperature and moisture at flaking play small but not trivial roles. A more complete experimental protocol with more data points likely would further delineate these small moisture and temperature effects on flake thickness and oil extractability, and perhaps define the optimal moisture and temperature levels. These data suggest that approximately 10% moisture and 200°F are satisfactory. For straight solvent extraction on flakes, the data show that it is imperative to achieve flake thicknesses of roughly 0.013 in. for reasonable oil extraction efficiencies (94%). With thicker flakes, oil recovery dramatically decreased on average to 87% for 0.021 in. flakes and 82% for 0.031 in. flakes. It seems logical also that if screw pressing or extruding (expanding) follows flaking of meadowfoam seed, then the screw press or expander must reduce particle size significantly if thick flakes are fed to them or oil extraction will not be very efficient. Without flaking, it appears that screw presses

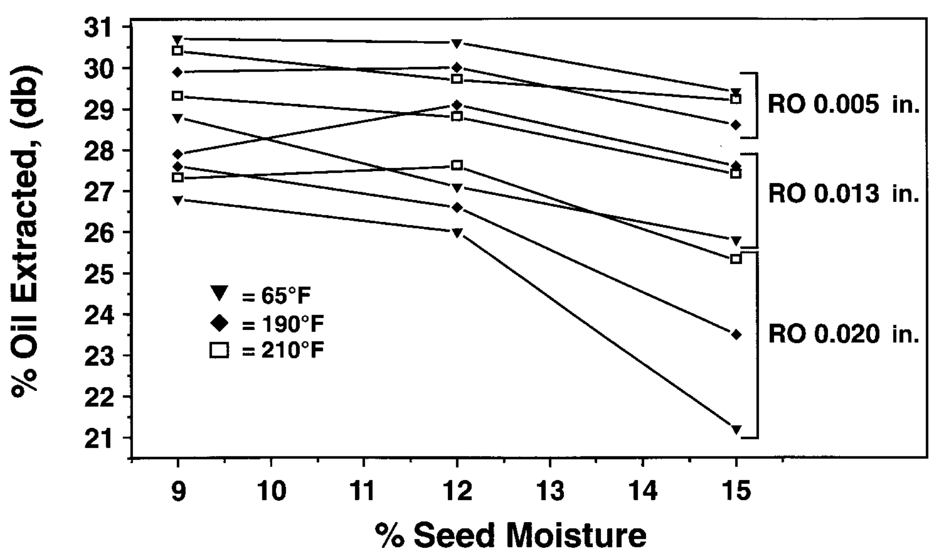

FIG. 6. Percentage oil extracted from meadowfoam flakes as a function of seed moisture, seed temperature, and roll opening. RO = roll opening for flaking.

or expanders would have to reduce particle size to that similar to the thinnest flakes, or to particle sizes associated with our coffee mill compositions, in order to efficiently prepare meadowfoam seed for solvent extraction. Generally, new crop oilseeds, such as meadowfoam, crambe and lesquerella, have been initially processed on a commercial basis in mills that are designed to extract commodity crops (soybeans, sunflowers, cottonseed, etc.). Furthermore, equipment changes (e.g., screw and barrel arrangements) for optimal extraction of the new crops are not made because of short runs and unknown processing requirements. However, flaker modifications can often be made to adapt to the needs of the new crops. The authors suggest that such may be possible for more efficient recovery of meadowfoam oil. If optimal cooking conditions (ca. 10% moisture, 200°F, 45 min) precede optimal flaking, then better quality oil will also be produced.

REFERENCES

1. Williams, M.A., Extrusion Preparation for Oil Extraction, *INFORM 6*:289–293 (1995).
2. Kemper, T.G., Guidelines for Pellet/Flake Ratios in Soy Crushing, *Ibid. 6*:1231–1236 (1995).
3. Heimann, M., Flaking Mill and Cracking Mill Maintenance, *Ibid. 7*:1191–1197 (1996).
4. Carlson, K.D., E.C. Baker, and G.C. Mustakas, Processing of *Crambe abyssinica* Seed in Commercial Extraction Facilities, *J. Am. Oil Chem. Soc. 62*:897–905 (1985).
5. Carlson, K.D., R. Kleiman, L.R. Watkins, and W.H. Johnson, Jr. (1990), in *New Industrial Crops and Products*, edited by H.H. Naqvi, L. Estilai, and I.P. Ting, Office of Arid Lands Studies, College of Agriculture, University of Arizona, Phoenix, pp. 169–175.

[Received October 31, 1997; accepted June 3, 1998]