Reprinted from FOOD TECHNOLOGY, 1965, Vol. 19, No. 6, pages 121–126

Rate of Heating and Location of the Slowest Heating Zone in Sweet Fresh Cucumber Pickles

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SUMMARY

Temperatures were measured with thermocouples and dial thermometers in several locations in fresh cucumber slices and spear pickle products to determine heating characteristics under processing conditions. At the slowest heating zone cucumber spears were found to receive significantly lower lethality values than slices; for the same product the lethality was greater when 30° Brix covering liquor was used compared to 50° Brix. Reduction in processing temperature (with or without decreased Brix) and increased liquor viscosities or holding times both retarded convection and appeared to affect f_1, g_{bh} and axial points nearer the top and bottom more than other characteristics or location. Bimetallic thermometers tended to sense smaller j and F, but larger f and lower temperature differences than did thermocouples. An increase in fill ratio and reduced volume-to-surface ratio caused nearly significant increases in j, but decreases in f. The slowest heating zone was near the geometric center in the case of the conduction heating spears in 50° Brix but moved toward the bottom of the jar for the spears and slices in 30° Brix syrup or brine. The greatest relative variability in line packs was observed in x_{bh}, j, f_1, f_2, T_0, and T_1, in that order.

INTRODUCTION

The objective of this study was to develop data for use in designing and monitoring heat processes for fresh cucumber pickle products. Location of slowest heating zone, effect of sucrose concentration in covering liquor, effect of heating-medium temperature, effect of fill ratio and comparison of dial thermometer vs. thermocouple are variables included in this study and are evaluated in terms of the heating parameters f and j (Ball, 1923) and process lethality F^{18}_{160}.

EXPERIMENTAL

Materials and methods. Four-inch-long spears were made by removing the ends from cucumbers and slicing the remaining portion lengthwise into four or five wedges, depending on the cucumber diameter. Slices were made by cutting the cucumber into ¼-in. disks; ends were discarded. Both the slices and spears at room temperature were packed by weight in 16-oz vegetable jars.

Two covering liquor compositions were tested, 30% and 50% sucrose by weight; these liquors also contained 2.8% acetic acid and 4.0% salt, by weight. The covering liquor was heated to 130–135°F and then added to the jars until the headspace was about 3/16 in. The jars were heated in an agitated water bath (described by Pflug and Nicholas, 1960). The jars were held for the time necessary to fill all in each run, introduce the thermocouples, and obtain an initial temperature reading for each jar.

Single-point copper-constantan thermocouple rods were inserted into jars through stuffing boxes in the covers as described in Pflug and Nicholas (1960). Nine-thermocouple probes were designed and constructed so a nine-point temperature profile could be obtained in the same jar. The units were constructed of a ¼-in. OD Bakelite rod and 30-gage copper-constantan thermocouple wire. The individual thermocouple junctions were ½ in. apart with the first junction located ⅛ in. from the end of the rod. Small holes were drilled in the rod where the thermocouple wire was brought out and a small groove made around the rod at this point; the thermocouple junction was made on the side of the rod opposite the hole. This allowed an isothermal length of wire between the junction and the point where the wire entered the center of the rod. Successive thermocouples were on opposite sides of the rod. The inside of the rod was filled and the surface coated with epoxy resin to finish the unit. A photograph of a 9-thermocouple rod is shown in Fig. 1. Temperatures were measured and

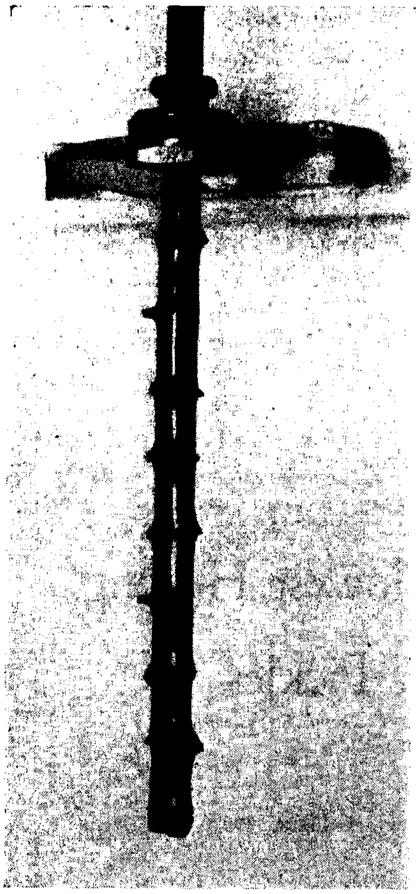

Fig. 1. Photograph of 9-thermocouple rod.

recorded with a 12-point 5-second-print 1°F-least-division recording potentiometer. Bath temperature was recorded during each run. The average temperature was used for calculations.

Dial thermometers, range 0 to 220°F, with 6-in. stems were used. The stem of the bimetallic thermometers passed through a packing gland (half a ⅛-in. copper compression coupling soldered to the can lid) and extended slightly above the bath surface so the dial could be read without disturbing the jar.

Procedure. Tests were made of the heating of spears and slices in 30° and 50° Brix liquors using single-point thermocouple rods. The thermocouple junctions were along the central axis of the jars at fractional distances of 0.0, 0.1, 0.2, 0.3, 0.5, and 0.9 from the bottom of the jar to the top of the liquid level; the total height of liquid in these jars, L, was about 4¼ in. Six replicate heat penetration measurements were made for each product-liquor-position combination (except the 0.9 location, which is near the top of the jar, for which only 3 replications were made). A fill ratio (ratio of product weight to the fluid ounce capacity of the jar) of 0.63 was used in these experiments.

Tests using the 9-thermocouple rods, were made on sweet spears at 180°F for 50° Brix with a 3- and 6-min hold before processing and at 195 for 30 and 50° Brix syrup with a 3-min hold. A fill ratio of 0.62 was used. Tests were replicated; the number of replications is shown in Table 2.

In the bimetallic dial-thermometer vs. thermocouple studies the experimental procedure for cucumber spears in 50° Brix (described above) was repeated but with the center of the sensing elements at about 0.1 and 0.5 L for fill ratios of 0.6 and 0.7 in each of four replications. Six temperature readings were made for each jar test.

Single-point thermocouple rods at ¾ in. above the bottom of the jar (a fractional height of 0.18) on sweet spears (50° Brix) with an 18-sec hold before processing were used to determine the effect of 210.5 vs. 180°F processing temperature.

Single-point thermocouple rods were used to measure the f and j values about 0.9 in. above the bottom of the 16-oz vegetable jars of line-packed sweet cucumber spears heated in water bath at 180 or 195°F. Temperatures were also measured about 1 in. above the bottom of 26-oz vegetable jars containing line-packed dill spears heated in water bath at 180°F.

Analysis. The heating parameters, f and j, were determined from plots of the temperature below processing temperature T_1. Final analysis of these single-point data was based on the calculated sterilizing value of the process for each jar at the end of 45 min of processing time. Calculation of the sterilizing value, F^z_T, during the heating period was made with the equation of Ball (1923) when the curve could be represented by one or more straight lines on semi-logarithmic coordinates, and with a modification of the general method of Bigelow *et al.* (1920) for other forms of the heating curve. In this study a z of 18°F and a reference temperature, T, of

Table 1. Effect of product shape, covering liquor, and position on f and j for 0.63 fill ratio of cucumbers in 16-oz vegetable jars heated at 180°F. Temperatures measured using single-point thermocouples.

Treatments			Heating characteristics						
Product	Liquor ° Brix	Position (X/L)	T_0 (°F)	j	f_1 (min)	% broken heating	f_2 (min)	g_{bh} (°F)	F^{18}_{180} (45 min) (min)
Spears	30°	0.0	102.3	1.12	24.3	67	34.6	28.3	10.84
		0.1	101.6	1.23	34.0	67	41.6	27.3	5.84
		0.2	106.4	1.55	29.2	67	46.5	37.6	5.23
		0.3	105.7	1.43	29.0	100	49.6	38.2	4.23
		0.5	104.6	1.27	35.0	67	46.6	27.8	5.15
		0.9	94.8	.59	26.8	100	43.6	7.8	15.58
	50°	0.0	105.5	1.04	41.6	0	......	......	5.51
		0.1	106.2	1.41	45.8	0	......	......	2.72
		0.2	105.0	1.52	47.7	0	......	......	1.95
		0.3	101.0	1.47	48.4	0	......	......	1.61
		0.5	104.2	1.34	52.9	0	......	......	1.43
		0.9	97.5	.63	30.6	100	51.0	13.6	11.44
Slices	30°	0.0	97.1	1.03	25.3	50	32.4	28.4	12.60
		0.1	96.0	1.40	33.0	0	......	......	5.90
		0.2	99.6	1.33	33.0	0	......	......	6.85
		0.3	99.7	1.25	38.5	0	......	......	4.65
		0.5	98.5	1.26	33.0	50	38.5	18.6	6.45
		0.9	94.8	.79	26.5	100	35.3	13.2	13.30
	50°	0.0	97.7	.97	29.2	33	32.8	29.6	10.33
		0.1	97.2	1.23	36.4	33	41.3	16.0	5.26
		0.2	98.7	1.41	38.8	0	......	......	3.83
		0.3	99.3	1.51	40.1	0	......	......	3.03
		0.5	100.3	1.45	41.3	0	......	......	3.14
		0.9	95.2	.98	30.9	33	43.1	17.4	9.20

Table 2. Effect of bath temperature, covering liquor, holding time, and axial position on sweet spears, 0.62 fill ratio, 9-thermocouple rods.

T_1 (°F)	° Brix	Hold (min)	Heating characteristics	Position above bottom of jar[a] (X/L) 0.03	0.15	0.26	0.38	0.50	0.62	0.74	0.85	0.97
180	50	3	T_0 (°F)	104.0	103.4	101.1	99.0	97.6	97.1	97.2	96.0	97.0
			j	.98	1.47	1.66	1.50	1.43	1.46	1.43	1.20	.64
			f_1 (min)	25.5	34.6	36.8	42.4	43.0	36.6	30.9	28.0	23.9
			f_2 (min)	37.0	45.5	47.0	48.2	51.6	52.4	56.8	59.5	58.7
			g_{bh} (°F)	14.1	23.9	29.5	26.0	28.0	33.5	29.6	21.8	10.3
			No. broken (of 4)	4	4	4	3	3	4	4	4	4
		6	T_0 (°F)	100.2	101.0	97.9	95.7	94.8	96.9	98.0	99.9	97.0
			j	.94	1.43	1.71	1.65	1.54	1.47	1.37	1.03	.71
			f_1 (min)	33.2	40.7	41.1	47.9	41.4	36.9	32.1	23.0	15.3
			f_2 (min)	42.5	46.8	47.9	52.2	48.4	57.0	60.4	59.8	51.7
			g_{bh} (°F)	25.4	40.5	40.5	32.0	31.8	30.4	23.3	13.2	15.0
			No. broken (of 4)	4	3	2	1	3	4	4	4	4
195	30	3	T_0 (°F)	102.8	100.5	96.2	85.3	87.5	94.7	102.9	10[illegible].5	102.8
			j	1.21	1.62	1.43	1.54	1.38	1.73	1.59	1.[illegible]2	.60
			f_1 (min)	21.4	21.8	21.7	23.2	23.6	19.6	13.9	14.2	14.5
			f_2 (min)	36.7	36.8	40.3	37.5	38.2	39.2	44.2	45.0	44.4
			g_{bh} (°F)	14.5	42.0	34.5	32.5	29.5	26.3	20.5	17.5	7.6
			No. broken (of 2)	2	2	2	2	2	2	2	2	2
	50	3	T_0 (°F)	101.7	99.0	98.1	93.8	95.6	98.7	106.3	107.5	104.3
			j	.95	1.98	1.80	1.65	1.44	1.55	1.52	1.32	.75
			f_1 (min)	27.0	26.2	33.2	37.7	35.5	25.6	22.4	17.3	12.4
			f_2 (min)	36.3	39.8	47.5	46.9	42.0	42.4	55.9	61.7	57.4
			g_{bh} (°F)	23.8	26.7	19.6	13.8	15.4	48.5	30.0	19.7	13.6
			No. broken (of 3)	3	3	3	2	2	3	3	3	3

[a] ⅛-inch and successive ½-inch intervals above jar bottom.

180°F was used. Forty-five minutes was chosen as the time for computing the sterilizing value so the processing results would correspond generally with the recommended heat for pasteurization of Esselen *et al.* (1951).

RESULTS AND DISCUSSION

Heat penetration and lethality data for two covering liquors and several locations in jars of cucumber spears and slices using single-point thermocouples are shown in Table 1; data for cucumbers spears gathered using 9-point rods are shown in Table 2.

The 9-thermocouple rods were developed after the data in Table 1 using single-point rods had been obtained. Since there is large jar-to-jar variation in cucumber products, the measurement of 9 points in one jar yields more usable data than 9 single-point rods in 9 jars.

Lethality data were analyzed by analysis of variance. The heat penetration data converted to composite heat penetration curves for tests in Table 1 are shown in Fig. 2. From these curves were constructed the vertical temperature profiles shown in Fig. 3. Temperature profiles for the Table 2 tests are shown in Fig. 4.

In Table 1 the F values at the slowest heating zone are significantly lower ($P = 0.02$) for spears than for slices. An increase in Brix of the covering liquor reduced the F much more for spears than for slices ($P < 0.1$); for both spears and slices, increasing the sugar concentration in

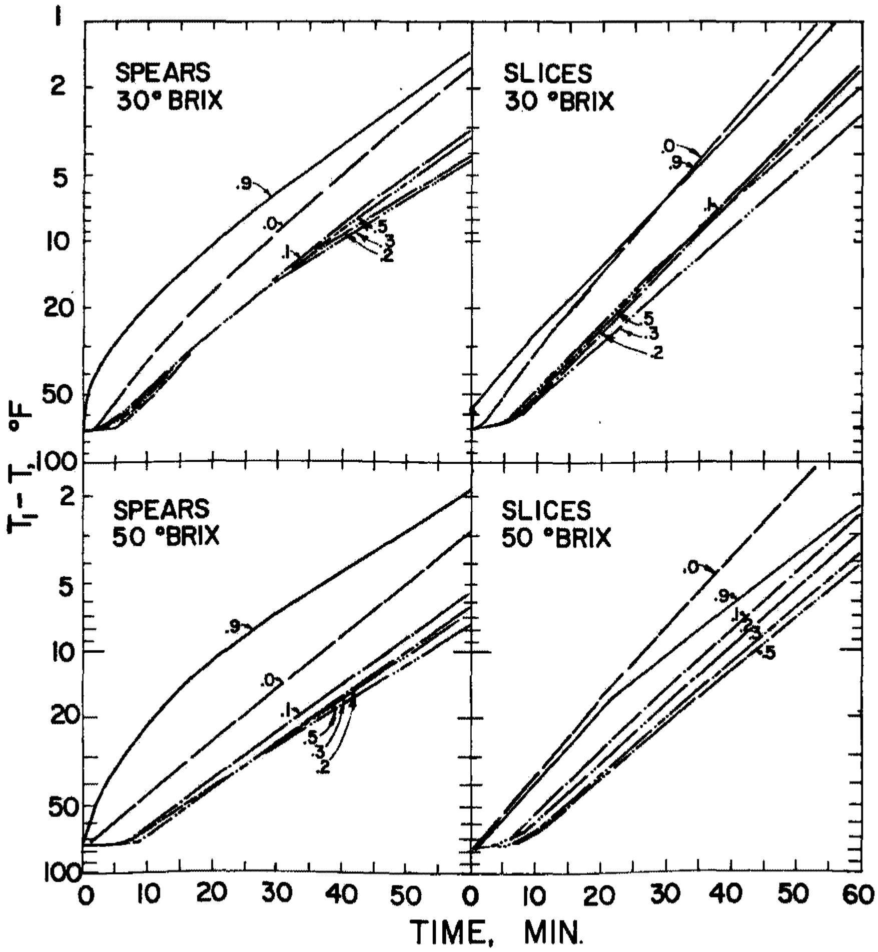

Fig. 2. Composite heat penetration curves for various axial positions in 16-oz jars containing slices or spears in 30 or 50° Brix syrup.

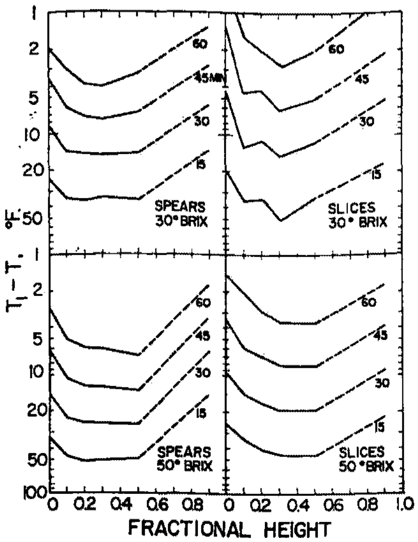

Fig. 3. Axial temperature profiles at selected times for data in Table 1 and Fig. 2.

the syrup increased the f value at the slowest heating zone; however, the j value increased in slices but decreased in spears.

Increases in liquor Brix of test data in Table 2 produced changes in heating characteristics analogous to those from data in Table 1. In Table 2, however, j values are larger, f_1 and f_2 values are smaller than before, and broken heating—with f_1 values indicative of convection—is now evident for 50° Brix.

The results in Table 1 as shown graphically in Fig. 3 indicate that the lethality at 0.3 L was generally least for slices. The coldest zone was in the vicinity of 0.2–0.5 L for spears and 0.3–0.5 L for slices. The results in Table 2 as shown graphically in Fig. 4 indicate that for sweet spears with 50° Brix syrup the slowest heating zone is at a height of 0.38–0.50 L; these results are in agreement with the results in Table 1 for single-point rods.

Axial temperature profiles shown in Fig. 3 and 4 permit direct examination of the relative temperature driving force vs. position at selected time intervals, the relative change of these driving forces with time, and of changes in the slow-point location. The precision of these profiles decreases rapidly as $(T_1 - T)$ decreases or when, as in cucumber slices, thermocouple rods are forced through the product and hence may retard floating and at the same time form a new fluid channel. Increasing the Brix increased f values throughout and not only increased j at the slow point but tended to shift the distribution of j and F in addition to the shift due to differences in product. A significant interaction between sucrose concentration and location appeared as decreased lethality at 0.2, 0.3, and 0.5 L but decreased less markedly at 0.0, 0.1, and 0.9 L. These locations are nearer the source of both conduction and convection transport. Interaction effects were more pronounced ($P \approx 0.16$) for spears than for slices, and the characteristic that the temperature above the product center is hotter (greater lethality) than symmetrically below appears more pronounced for spears than for slices. These data were analyzed assuming that the treatment levels themselves are subject to sampling error; assuming them fixed increases the product (P), sugar (S), location (L), PS, PL, and SL probability levels to 0.08, 0.05, 0.01, 0.10, 0.25, and 0.40, respectively, but PSL is unaffected.

The temperature throughout the jar is more nearly uniform for rapid convection—such as in slices or spears in 30° Brix syrup or brine than in the slow convection observed for

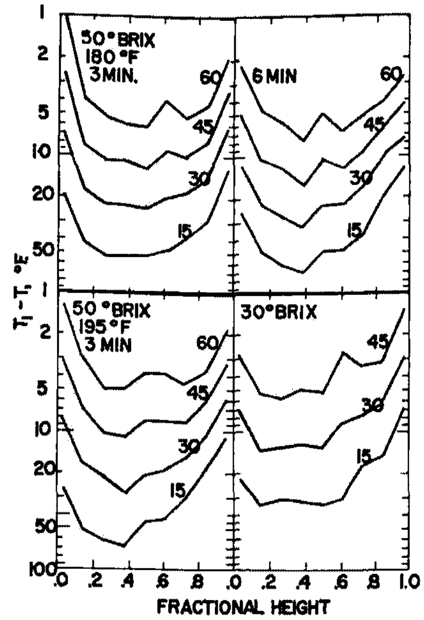

Fig. 4. Axial temperature profiles at selected times for data of Table 2 (spears).

spears in 50° Brix syrup. It is more difficult to make precise studies of cold-point location when axial temperatures are nearly uniform; however, the error in f and j values is reduced when a zone apart from the true cold zone is used. In general, the slow-point location is determined by the relative heat transferred by convective flow vs. conduction. When conduction heat transfer dominates, the slow point will be near the geometric center; however, as convective flow increases, the cold point, during heating, will move toward the bottom of the container, the displacement of the cold zone from the geometric center being proportional to the rate of convection heat transfer.

Table 3. The heat-penetration parameters and variability encountered in line-packed cucumber spears in syrup and in brine in 16-oz vegetable jars processed in a water bath with industrial controls.

Treatments			Heating characteristics							
			T_0 (°F)		T_1 (°F)		j		f_1 (min)	
Product	T_1 (°F)	Replications n	$\overline{T_0}$	s	$\overline{T_1}$	s	$\overline{j}$	s	$\overline{f_1}$	s
Sweet spears (50° Brix)	180°	10	97.7	4.1	179.1	1.2	1.49	.20	46.6	3.7
		10	98.0	4.7	180.2	.7	1.63	.25	46.6	5.7
		10	101.1	6.2	179.5	.8	1.63	.15	45.8	3.8
		19	93.0	7.1	179.1	....	1.48	.26	42.0	7.7
		Av.	96.6	5.8	179.6	.9	1.54	.22	44.7	5.7
	195°	10(8) [a]	88.3	6.7	195.7	1.4	1.56	.21	36.2	4.2 [a]
		9	87.7	4.0	195.7	1.1	1.64	.14	32.2	1.9
		10	91.9	6.6	196.2	1.5	1.56	.43	38.3	5.8
		Av.	89.4	5.8	195.9	1.3	1.58	.23	35.1	4.4
Dill spears (brine)	180°	10	93.7	3.8	180.7	.1	1.16	.13	23.0	1.9
		10	94.5	3.5	179.9	1.2	1.15	.08	22.4	2.2
		10	94.6	3.9	178.8	1.3	1.09	.08	23.4	3.0
		Av.	9[illegible].3	3.7	179.8	.9	1.13	.10	22.9	2.4

[a] $f_2 = 15.1$, $s_{f2} = 3.9$; $x_{bh} = 36.2$, $s_{x_{bh}} = 7.1$.

Table 4. Effect of location, sensing element, and fill ratio on sweet spears, 50° Brix, in 16-oz vegetable jars.

Treatment			Mean heating characteristics						
Sensing element	Fill ratio	Element location	T_0 (°F)	j	f_1 (min)	% broken heating	f_2 (min)	g_{bh} (°F)	F^{18}_{180} (45 min) (min)
Thermocouple	0.6	0.1	104.6	1.29	45.2	0	......	......	2.90
		0.5	107.8	1.25	40.8	50	52.7	17.3	4.35
	0.7	0.1	99.0	1.52	41.3	0	......	......	2.51
		0.5	101	1.59	36.0	75	55.5	22.7	3.43
	LP	0.1	98.7	1.67	42.2	0	......	......	
		0.5	99.1	1.61	35.8	13	63.4	24	
Bimetallic	0.6	0.1	107.0	1.25	47.2	0	......	......	2.86
		0.5	106.5	1.30	45.4	25	68.2	17.8	2.82
	0.7	0.1	96.5	1.51	45.2	0	......	......	1.74
		0.5	99.7	1.37	36.7	75	53.3	25.4	3.21
	LP	0.1	97.6	1.62	44.8	0	......	......	
		0.5	90.7	1.61	43.6	0	......	......	

The heating medium temperature has an effect on the heating characteristics—higher heating-medium temperatures produce smaller f values, as shown by the results in Tables 2 and 3 where an increase in T_1 markedly reduced f values but did not significantly affect j. In a heating-medium-temperature study of sweet spears where 180°F was compared with 210.5°F the f values were smaller (highly significant) for 210.5°F than for 180°F; 44.4 vs. 53.10; j values were somewhat larger ($P \approx .25$), 1.69 vs. 1.30, at an axial position of 0.25 L for the seven replication tests.

The results in Table 3 where cucumber spears in 50° Brix syrup processed at 180 and 195°F are compared with spears in a non-sugar brine processed at 180°F show that a higher processing temperature and a lower liquid viscosity have a significant effect on f. The processing temperature did not appear to affect j; however, the decreased liquid viscosity of the non-sugar vs. the sugar pack which produces a higher effective thermal diffusivity and conductivity affected the lag factor j.

The data in Table 3 indicate that the greatest relative variability in line packs of these products are in x_{bh}, j, f_1, f_2, T_0, and T_1 in that order. The values of x_{bh} variability are due to the combined effects of $(T_1 - T_0)$, j, and f. Although the variability of T_0 is relatively large, the relative variance of the initial convective driving force $(T_1 - T_0)^n$ is only about 1.7%, hence it is very likely not the major contribution to variance in f_1 or j. The variation reported here is in the range of 10–15% of Jackson and Olson's (1940) data but much less than that found in cucumber products by Esselen *et al.* (1951).

The results of tests comparing temperatures measured using a dial-type thermometer vs. a single-point thermocouple are shown in Table 4. In pickle plants, temperatures in the containers are usually measured with dial thermometers whose sensing element is more than an inch long whereas the temperature measurements made with thermocouples are essentially for a point. Differences between these temperatures measured by these two systems are important in relating the results of experimental studies with commercial pickle pasteurization. The bimetallic thermometers sense temperatures over a wider region; therefore they may sense the start of convection earlier than the thermocouple; they have more lag and are more sensitive to conduction loss or gain along the stem. In general the dial thermometer data have smaller j ($P \approx 0.27$), larger f ($P \approx 0.11$), lower F ($P \approx 0.10$), and lower temperatures at moderate times than the thermocouples. The reduction in j appears less than for a large-diameter metallic thermocouple in a conduction heating product with f and F values increasing rather than decreasing, as reported by Ecklund (1956) and Cowell *et al.* (1959).

An increase in fill of product increased the j value ($P = 0.01$), decreased f ($P = 0.11$), and decreased the lethality ($P \approx 0.18$). Fig. 5 combines the data from these experiments with data from Pflug and Nicholas (1960) and Nicholas and Pflug (1961 a,b) to show the effect of fill ratio on f for sweet spears. A variation of fill ratio of from 0.12 to 0.28 could produce a large fraction of the variance in f and j. The j-value could be expected to be sensitive to variations in the initial temperature distribution, which is not known to affect f at long times.

SYMBOLS

- F Equivalent minutes at a specified reference temperature and destruction rate z of a thermal process (z = °F for 90% change in lethal rate)
- f Time required (in min) for the asymptote of the heating or cool-

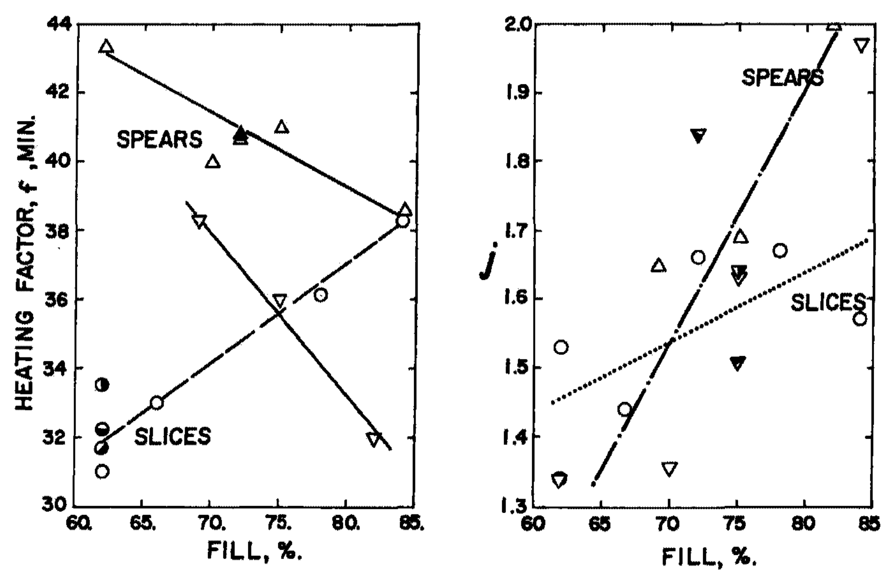

Fig. 5. Effect of fill ratio on f and j, after published and unpublished data of Nicholas and Pflug.

ing curve to cross one log cycle, i.e., the time required for a 90% change in temperature on the linear portion of the curve. Subscripts are used to denote successive values if more than one linear portion is used to describe a heating or cooling curve

g_{bh} Temperature (°F) below T_1 at time of change in slope of heat penetration curve

h Surface heat-transfer coefficient, Btu/hr-ft^2-°F

L Height of fluid in container

P Probability that chance variation has caused the difference observed

s Standard deviation

T Temperature; T_0 initial temperature of product; T_1 temperature of external heating or cooling media; T_a apparent initial temperature as defined by the linear portion of the heating or cooling curve, i.e., the ordinate value of the origin of the asymptote to the curve

t Time, minutes

X Axial height above bottom of jar

x_{bh} Time at which broken heating occurs, min

REFERENCES

Ball, C. O. 1923. Thermal process for canned foods. *Natl. Research Counc. Bull. No.* **37**, Part I. 76 pp.

Bigelow, W. D., G. S. Bohart, A. C. Richardson, and C. O. Ball. 1920. Heat penetration in processing canned foods. *Natl. Canners Assoc. Bull.* No. **162**. 128 pp.

Cowell, N. D., H. L. Evans, E. W. Hicks, and J. D. Mellor. 1959. Conduction errors in thermocouples used for heat penetration measurements in foods which heat by conduction. *Food Technol.* **13**, 425.

Ecklund, O. F. 1956. Correction factors for heat penetration thermocouples. *Food Technol.* **10**, 43.

Esselen, W. B., E. E. Anderson, L. F. Ruder, Jr., and I. J. Pflug. 1951. Pasteurized fresh whole pickles. I. Pasteurization studies. *Food Technol.* **5**, 279.

Jackson, J. M., and F. C. W. Olson. 1940. Thermal processing of canned food in tin containers. IV. Studies of the mechanism of heat transfer within the container. *Food Research* **5**, 409.

Nicholas, R. C., and I. J. Pflug. 1961a. Heat processing characteristics of fresh cucumber pickle products. II. Heating rates of whole pickles. *Quart. Bull. Mich. Agr. Expt. Sta., Mich. State Univ.* No. **43**, 522.

Nicholas, R. C., and I. J. Pflug. 1961b. Heat processing characteristics of fresh cucumber pickle products. III. Heating rates of slices. *Quart. Bull. Mich. Agr. Expt. Sta., Mich. State Univ.* No. **43**, 808.

Pflug, I. J., and R. C. Nicholas. 1960. Heat processing characteristics of fresh cucumber pickle products. I. Heating rates of spears. *Quart. Bull. Mich. Agr. Expt. Sta., Mich. State Univ.* No. **42**, 407.

Ms. rec'd 5/26/64.

Journal Paper No. 3494 of the Michigan Agricultural Experiment Station, East Lansing, Michigan.

Presented before the Twenty-fourth Annual Meeting of the Institute of Food Technologists, Washington, D. C., May 26, 1964.

The assistance of A. P. Blaisdell, P. J. Fellers, J. Kopelman, T. R. Mulvaney, and A. Stewart in collecting and plotting some of these data is appreciated. The cooperation of Aunt Jane Pickle Co., Division of Borden Co., Dearborn, Mich., is gratefully acknowledged.