NEW YORK'S FOOD AND LIFE SCIENCES BULLETIN NO. 14, FEBRUARY 1972

PLANT SCIENCES

NATURAL RESOURCES • NUMBER 1

CORNELL UNIVERSITY AGRICULTURAL EXPERIMENT STATION, NEW YORK STATE COLLEGE OF AGRICULTURE AND LIFE SCIENCES, A STATUTORY COLLEGE OF THE STATE UNIVERSITY, CORNELL UNIVERSITY, ITHACA, NEW YORK

Natural vacuum and the flow of maple sap

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In 1967, Blum (1) reported that 43 percent more sap was obtained from closed tubing installations on slopes than from open or vented tubing. He associated this increase with the natural vacuum created in the closed tubing. Gains in sap yield from natural vacuum[1] are especially important, since the collection of sap is the most costly and least profitable phase of making maple sirup. Moreover, sap costs for a tubing network are mostly fixed costs; increased sap flow from natural vacuum represents added profit with little or no added cost. Recently, Laing *et al.* (6) showed that sap produced with high vacuum differed little in chemical composition from sap produced without vacuum; both yielded sirup of comparable high quality.

While Blum's research results were exciting, they prompted numerous questions, answers to which were needed before successful field application of natural vacuum and tubing techniques could be assured.

The key questions were:

How does number of tapholes per tube line affect natural vacuum?

How does slope affect natural vacuum? How do results vary by season and locality? Where should vacuum be measured?

Is natural vacuum more effective at slow or fast flow rates?

What limits the production of natural vacuum?

What are optimum conditions for natural vacuum?

How does production with natural vacuum compare with pumped vacuum?

Our research commenced in 1968 with an attempt to answer the first two questions. In succeeding years it was extended to three localities and broadened in scope to gain information on the other questions. Altogether, about 4500 experimental tapholes were used, including 2000 in 1971. Moreover, in 1970 and 1971, tests were made of water flow through tubing to acquire theoretical knowledge concerning vacuum and flow rates, so that results of field tests could be properly interpreted.

Procedures

All experiments compared sap flow with natural vacuum in closed tubing with sap flow without vacuum in vented tubing or with sap flow with pumped vacuum in closed tubing. Naturalflow[2] tubing, with an inside diameter

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[1] Natural vacuum should be distinguished from pumped vacuum.

[2] Brand names do not constitute endorsement; they are used for identification purposes only.

approximating 0.3 inch, and fittings were used. All tubing was suspended in the air; it was supported by wooden props where distance between trees exceeded 25-30 feet. Tubing was run from tree to tree without tee lines, except in 1971 when 20 percent of the tapholes were on tee lines in the upper half of some installations. Tapping dates were consistent with commercial operations; all experiments lasted throughout the season.

Localities

Experiments were made at our Heaven Hill sugar bush near Lake Placid, New York, in all years. It features steep slopes and a high elevation; most sap flow is delayed until April and the season often is short. Other experiments were made near Chazy, New York, at the Miner Institute sugar bush during 1970 and 1971. It is higher and colder than most neighboring bushes and sap production has been low to moderate. Supplemental experiments were made at the Arnot Forest sugar bush, located southwest of Ithaca, New York. It is the warmest bush and commonly has early flows and good production. In all bushes the trees are mostly 1-bucket size (10-16 inches), nearly the same age (about 70-100 years), and usually slow in growth. The three bushes will be referred to as Heaven Hill, Chazy, and Arnot.

Experimental Design

The principal method used was that of *paired tapholes* (fig. la). It is similar to the one used and described by Blum (1). Each tree was tapped twice, about 6-8 inches apart, and two tubing lines connected trees in installations that were identical in number of taps, taphole exposure, slope, tube length and sag, and other factors. All tapholes were treated equally—sound wood, equal tapping depth (usually 2 inches), and one paraformaldehyde pellet. All equipment was the same and was cleaned before being installed. The only difference was in the treatment — such as closed vs. vented tubing or natural vs. pumped vacuum. Since paired tapholes make use of the same trees for each treatment, much variation in sap flow is eliminated. Therefore little replication is needed to show differences between treatments.

Research conducted by the U. S. Forest Service (3) showed that sap is not ordinarily drawn laterally from the vicinity of one taphole to another 6 inches away when vacuum is applied. Nevertheless our experiments with paired tapholes have produced enough more sap under vacuum to suggest that the experiments may be biased. Paired tapholes clearly show which of two treatments is better, but we suspect that they may not show how much better. Therefore, in 1971 both paired tapholes and *paired trees* were used. In the latter, two adjacent lines or groups of trees were selected on the basis of similarity in bole size, crown size, vigor, and exposure. The two treatments were then applied to the two tree lines, on a random basis, with precautions to achieve equality in tapholes, tube installation, and topography. To reduce bias from tree differences, the treatments were reversed from one to the other line of

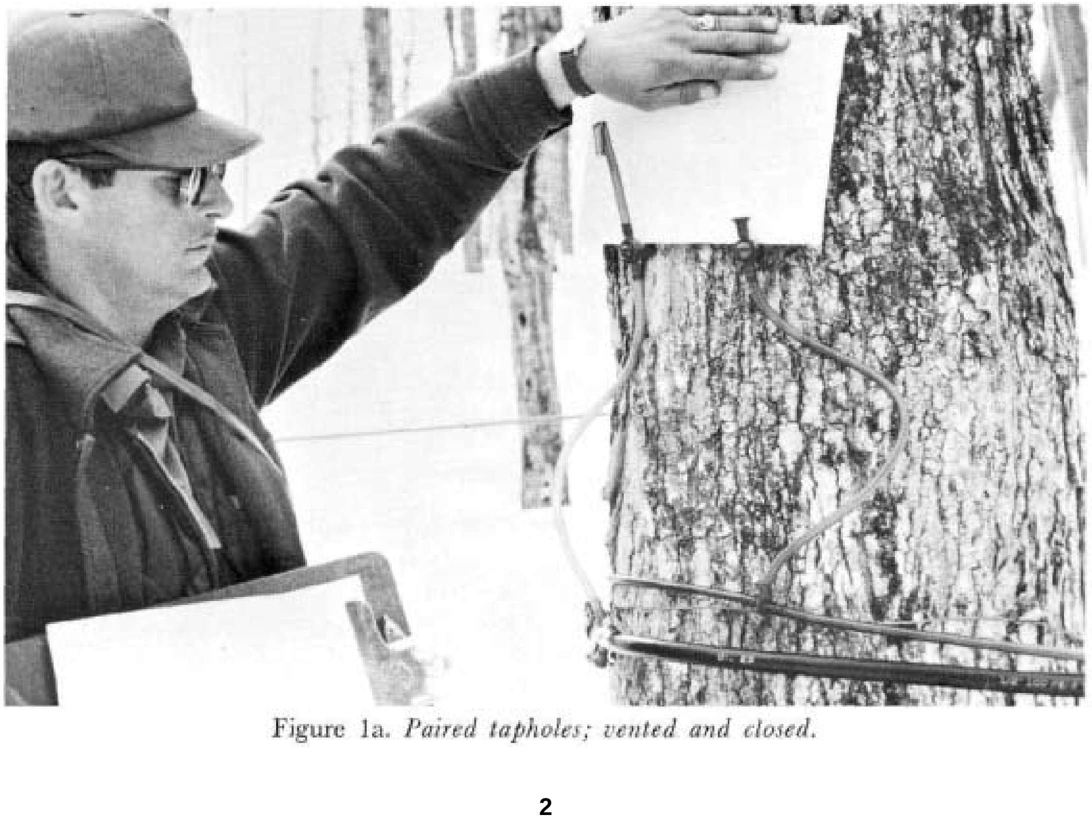

Figure la. *Paired tapholes; vented and closed.*

trees at midseason.[3] Our use of paired trees in lines may have been insufficient to show significant results in some cases. However, the results concur generally with those obtained from paired tapholes; they strengthen our overall conclusions.

The experiments, whether using paired tapholes or paired trees, were laid out in successive lines of trees so that the effect of numbers of tapholes and slope on vacuum and sap flow could be evaluated. The groups of trees were usually close together, and trees of similar quality were used. Insofar as possible, lines testing the same slope were adjacent, but with differing numbers of tapholes. At Chazy, however, there were fewer steep slopes and trees from which to choose; therefore a few treatments were located in an adjacent forest about a mile distant. Such separation of experimental trees sometimes produced different flow rates because of different local microclimates. Such flow differences might influence the interaction of slope or numbers of taps and vacuum on sap flow, although no such influence is readily apparent. On the other hand, there would be no influence on sap flow comparisons between primary treatments.

Precautionary Techniques

To further assure both proper and equal installations, the following field procedures were used:

Care was taken to drill straight with slow-speed tappers (700-1200 RPM).

Drop lines were equal; looping below tube line was avoided (fig. la and lb).

Tapholes and drop lines were checked for soundness and leaks, both at time of installation and removal, by trying to suck air from the installed drop line.

All vents contained a piece of bent tubing to reduce microorganism entry (fig. la).

Tapholes were inspected at season's end for gross differences in amount of microorganisms; no apparent differences were found between tapholes assigned to different treatments.

Most trees had a single pair of tapholes. A few of the larger trees (about 10 percent of total of all trees) had two pairs of tapholes.

Comparable tube installations used similar amounts of tubing; most averaged 18-20 feet per taphole.

Figure 1b. *Vacuum was measured in closed-tap installations after attaching gauge and opening petcock. (Arrow indicates petcock.)*

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[3] In 1971, the treatments were also reversed from one tap to the other in the paired taphole experiments at midseason.

Field Measurements

The following field measurements were made:

- Number of tapholes per tube line.
- Average, maximum, and minimum slope of tube lines. Slope is defined as the vertical distance (between the highest and lowest tapholes) divided by the tubing length or distance (corrected to show horizontal rather than slope distance), expressed as a percent. Maximum and minimum slopes are defined as the slopes of the tube lines for 5 successive tapholes at the steepest and smallest gradients; they show the variation in slope. The accuracy of average slope figures is within 1 percent; for example, a 20 percent slope may be between 19 and 21 percent.
- Amount of sap flow. Converted to quarts per taphole for each major sap run.
- Vacuum in inches of mercury. Measured at top of tube lines. Experience has shown that, for natural vacuum, readings are highest where tubes are empty at upper elevations. Vacuum may drop sharply at the lower tapholes if tubes are filled with sap. Thus natural vacuum readings tend to be maximum rather than average readings. On the other hand, there is less difference between upper and lower pumped vacuum readings. Vacuum loss from tube lines during measurement was avoided by use of a petcock at measurement points (fig. lb).
- Sugar percentage differences between treatments, measured by refractometer.
- Sap flow rate in quarts per minute, measured simultaneously with vacuum on natural vacuum lines.
- Midseason sag in tube lines. At Heaven Hill, average sag was nearly 1 foot. At Chazy in 1970, special efforts were made to pull tubing tight; as a result, the sag averaged less than 6 inches (fig. lc and Id).

Early Results

1968

An experiment was installed at Heaven Hill to test the effect of slope on sap flow in closed and vented tubing. On each of a dozen different slopes, installations with 20 paired tapholes were made. However, 1968 was the infamous peak year for rodent damage to tubing. Squirrels were especially abundant and harmful. They specialized

Figure 1c. *Very little sag was allowed in tube lines at Chazy in 1970.*

in biting the black caps used to close the vent spiles.[4] As a result, most tube lines were partially vented, little vacuum was formed, and there was no significant difference in flows from paired tapholes. The experiment was useful in pointing out the limitations of natural vacuum; it is affected by air leaks caused by rodent damage, poor fittings, or careless installation.

Among the vented lines, there was a general correlation between sap flow and slope. The sap flow on a 25 percent slope was twice that on a 1 percent slope; intermediate flows occurred on 5 to 15 percent slopes. This relationship seems appropriate since there is more tube friction on shallow slopes; also there is more sap loss from vent leaks. On the other hand, steep slopes appear to eliminate problems of sap flow through vented tubing. This is an important factor in interpreting sap flow experiments that seek relationships between slope and vacuum influences.

In addition to the above experiment, an installation with 50 paired taps was made on a 5 percent slope. After early season rodent damage was repaired, it was noted that the closed tubing had markedly more sap flow than the vented tubing. During early April the closed tubing often had 5 to 7 inches of vacuum; it yielded 50 percent more sap than the vented tubing. In fact it outyielded all but one of the other installations.

Finding a substantial increase in sap flow in a 50-tap line was of special significance. First it showed that the tubing used in maple sap networks had more capacity than previously thought. Even more important, it showed for the first time that the number of tapholes on a line might significantly influence the amount of vacuum and sap flow. Our experimental designs in succeeding years were fundamentally changed to test the influence of number of tap-holes per line.

1969

An experiment to test the effects of both slope and numbers of taps on sap flow in closed and vented tubing was made at Heaven Hill. Paired taphole installations included 15, 30, and 50 tapholes each at slopes of 5, 11, and 17 percent. Table 1 shows the sap flow in quarts per tap-hole by sap run for the 1969 season. Table 2 depicts some of the effects of slope and numbers of tapholes on seasonal sap flow in closed and vented tubing.

The steeper slopes yielded more additional sap in the closed tubing than the 5 percent slope. On land with shallow slopes of 5 percent or less, it is difficult to install tubing quickly without an occasional error in tap location that may force sap in the tubing to run uphill. This may cause leakage through vents or dissipation of vacuum. Although shallow slopes may cause difficulty in sap flow through either closed or vented tubing, we found that the closed

Figure 1d. *More typical installation at Heaven Hill.*

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[4] Use of the older nonvent spile or of newer and less vulnerable caps might have reduced the damage.

Table 1. *Sap flow in closed and vented tubing, by slope and numbers of taps. Heaven Hill — 1969*

Slope percent	5						11						17					
Slope variation	2–8		2–6		2–6		8–18		8–13		8–13		10–20		10–20		11–23	
No. of tapholes	15		30		50		15		30		50		15		30		50	
Date	*																	
March 23–24	4.0	3.7	3.8	3.2	3.6	3.3	5.9	4.3	4.7	4.0	3.6	2.6	5.4	5.9	4.8	4.5	4.2	3.9
March 28–29	.8	.8	2.0	1.4	.9	1.1	2.5	1.6	1.9	1.2	1.1	.8	1.3	1.6	1.7	1.3	1.9	1.1
April 4–5	2.4	1.9	3.2	2.5	3.0	3.2	4.1	3.6	3.8	2.6	3.8	2.0	5.2	5.1	3.6	3.3	4.1	3.1
April 6–9	6.4	5.5	5.3	2.5	5.9	5.4	7.6	5.9	7.3	4.5	7.9	4.0	8.8	6.7	7.2	5.9	8.1	4.8
April 11–13	5.9	4.0	5.7	3.6	5.8	4.9	6.7	3.7	5.3	4.4	7.6	4.4	8.3	6.4	6.1	4.7	6.9	3.9
April 20–22	8.3	6.7	7.7	5.0	6.3	5.4	6.9	6.1	6.4	4.7	7.0	4.2	11.7	9.3	6.4	5.5	9.1	4.9
Season total	27.8	22.6	27.7	18.2	25.5	23.3	33.7	25.2	29.4	21.4	31.0	18.0	40.7	35.0	29.8	25.2	34.3	21.7

**Data are quarts per taphole. Closed tube data on left, vented tube data on right, of each column.*

tubing was superior. Nevertheless we prefer pumps wherever possible to create vacuum and more sap flow on slopes of less than 5 percent.

It is of interest that for the closed tubing the 11 percent slopes produced larger gains than the 17 percent slopes. Perhaps this is partly because sap flow in vented tubing is at its best on the steepest slopes; consequently the gains for closed tubing on very steep slopes are relatively less than on medium slopes.

Except for the 50-tap line on the 5 percent slope (which showed a 50 percent superiority for sap flow in the closed tubing in April 1968), increases in the number of taps were associated with further superiority of sap flow in the closed tubing. Unfortunately we were able to obtain only a few vacuum readings during the year. They were generally low (average of 3 inches, maximum of 11 inches mercury) in comparison with those obtained in succeeding years and showed little relation to sap flow.

Altogether the closed tubing, even with low vacuum, was significantly better, by a third, than the vented tubing. Nevertheless it became more clear that the relationships between natural vacuum and sap flow were complicated. Of special concern was the inability to explain the superiority of large numbers of tapholes. Theoretical knowledge of sap flow and vacuum under controlled conditions was necessary to understand the field experiments.

Table 2. *Increase in sap flow in closed tubing, by slope and numbers of taps. Heaven Hill —1969*

Treatment		*Yield per taphole*			*Percent increase*
		Closed	*Vented*	*Difference*	
			— quarts —		
	15 taps	27.8	22.6	5.2	23
5%	30 taps	27.7	18.2	9.5	52
	50 taps	25.5	23.3	2.2	9
	15 taps	33.7	25.2	8.5	34
11%	30 taps	29.4	21.4	8.0	37
	50 taps	31.0	18.0	13.0	72
	15 taps	40.7	35.0	5.7	16
17%	30 taps	29.8	25.2	4.6	18
	50 taps	34.3	21.7	12.6	58
5%	combined	27.0	21.4	5.6	26
11%	combined	31.4	21.5	9.9	46
17%	combined	34.9	27.3	7.6	28
15 taps combined		34.1	27.6	6.5	24
30 taps combined		29.0	21.6	7.4	34
50 taps combined		30.3	21.0	9.3	44
Overall mean		31.1	23.4	7.7	33

Vacuum and Flow Rate — Theoretical Considerations[5]

Standing Sap Columns

Atmospheric pressure equals approximately 14.7 pounds per square inch. This will support a column of water of about 33 feet or a column of mercury of approximately 29 inches.[0] If water enters through the top of an open piece of tubing and the top is then sealed, up to 33 vertical feet of water will be supported (even if the bottom of the tubing is open). The weight of this water creates a vacuum in proportion to its height. For example, 11 feet of water will cause one-third of the maximum vacuum or a little

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[5] This portion of the research was principally accomplished with the guidance and cooperation of Prof. Terry, using the engineering facilities of Cornell's Riley Robb Hall.

[0] 14.7 pounds per square inch (PSI) of air, 33 feet of water, and 29 inches of mercury (vacuum) are approximately equivalent. Thus 1 PSI is nearly equivalent to 2 inches of vacuum, and 1 inch of vacuum is roughly equivalent to 1 foot of supported water.

less than 10 inches of mercury. Thus the first prerequisite for vacuum in a tube line is a lot of sap, preferably enough to fill the tube to at least a height of 30 feet.

Vertical columns of sap form rather easily in the lower portions of tube lines. The tube itself is small, with resultant high friction and some capillarity; thus tubes do not empty easily. Any dip or sag in the tube line can cause a column to start; there is usually some sag between trees. At the beginning of a sap flow, the amount of sap from the tapholes may exceed that flowing out of the tube line and the sap column is built up. Eventually a pressure equilibrium is reached wherein the sap inflow from the taps equals the outflow at the lower end of the tubing. It is probable that changes in equilibrium and sap columns occur throughout the sap run. As the sap flow dwindles near the end of a run, the sap column can be expected to lower. The effect of mixtures of sap and gas in a column is not clear; we suspect that slow runs with high proportions of gas may create little vacuum. However, excellent runs have been observed to create a nearly gas-free column of sap with a vertical height of 75 feet.[7] Much smaller columns are more typical; also sap columns may remain in tight tubing installations between runs.

Pressure and Flow Rate

While the vacuum associated with a standing column of sap is easily predicted, the vacuum (negative pressure) associated with moving sap or combinations of sap and gas is less well understood. Hydraulic engineers have long known that flowing water creates head loss and more pressure (less vacuum); as flow rates increase, pressure may change from negative to positive. In view of this, the *decreased* pressure (greater vacuum) associated with more tapholes and faster flow rates was especially puzzling. Therefore a series of tests was made, using Naturalflow maple tubing, to find relationships between pressure and flow rate. These tests were conducted in a 6-story laboratory that permitted a total vertical drop of 60 feet and injecting water into the tubing at 5 points that were 12 feet apart in elevation. By winding maple tubing around posts at each floor level, different tube lengths and slopes could be simulated. Water flow to the tubing at different elevations could be regulated to simulate different sap flow rates.

A deficiency of the experiments was an inability to control the room temperature (70°F. or higher) and the water temperature (40-60°F.). These warm temperatures led to a substantial amount of tube collapse (at 10 or more inches of vacuum) which increased friction and slowdown of the lower flow rates. Tubes collapse far less in the field because temperatures are much colder; also, most collapse is in the upper part of the installation, coinciding with maximum vacuums and minimum amounts of sap (sap from fewer tapholes enters the upper tubing). In general we followed a procedure of cooling the tubing by running cold water through it between tests. Nevertheless, duplication of absolute values of pressure-flow rate relations should not be expected in the field. Similar relative values and trends, however, may be expected in both the laboratory and the field.

Figure 2 shows typical curves, familiar to hydraulic engineers, that resulted from continuous flow when water was admitted only at the upper end of the tubing. As expected, low flow rates caused less head loss and more negative pressure (vacuum). Longer lines have more head and more vacuum for the same flow rate; they also have faster flow rates. Finally, steeper slopes[8] cause reduced friction and head loss; both flow rate and vacuum are increased. Thus, low flow rates, long lines, and steep slopes all tend to increase vacuum.

The curves of figure 2 do not simulate sap flow conditions, since the only source of water was at the upper end. Under field conditions, sap may enter the tubing at any level, depending on location of trees. This condition can be closely simulated by allowing near-equal amounts of water to enter the tubing from 5 sources of successively equal lower levels - at 60, 48, 36, 24, and 12 feet. Figure 3 shows a comparison of pressure-flow rate curves for this situation and the one depicted earlier in figure 2. High temperatures and variable amounts of air in the tube line caused variation in results at the lower flow rates; this is shown by the dashed portion of the curves.

It is clear that, where water enters tubing from several sources as in maple sap situations, an entirely different type of pressure-flow rate curve occurs. First of all, there is less water in the upper tubing. Consequently there is less friction loss and both more flow and relatively more vacuum at the faster flow rates than when water enters at the top only. Secondly, at low flow rates (about a quart per minute or less) vacuum *decreased* as flow rates decreased. This most important finding substantiates our field results — that is, more vacuum with faster flows occurs with large numbers of tapholes. Also, sap flow rates from sugar maple seldom exceed 1 quart per taphole per hour for very long (all 1971 flows at Heaven Hill and Chazy were at less than this rate). Therefore a tube line with 60 taps will have a flow rate that seldom exceeds 60 quarts per hour or 1 quart per minute. For most field installations then, more vacuum can normally be expected with the better flow rates.

Loss of Vacuum

At moderately fast flow rates, it appears that the flow is continuous and pressure-flow rate relations are normal.

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[7] This occurred in a 50-tap line on a 10 percent slope. The tube was filled for three-fourths of its length, vacuum was 23 inches, much of the upper tubing was collapsed, and sap flow through the tubing was continuous and rapid.

[8] The effect of tube size is predictable. The larger of two tube sizes would have reduced friction and head loss. It would have an effect much like that of a steeper slope.

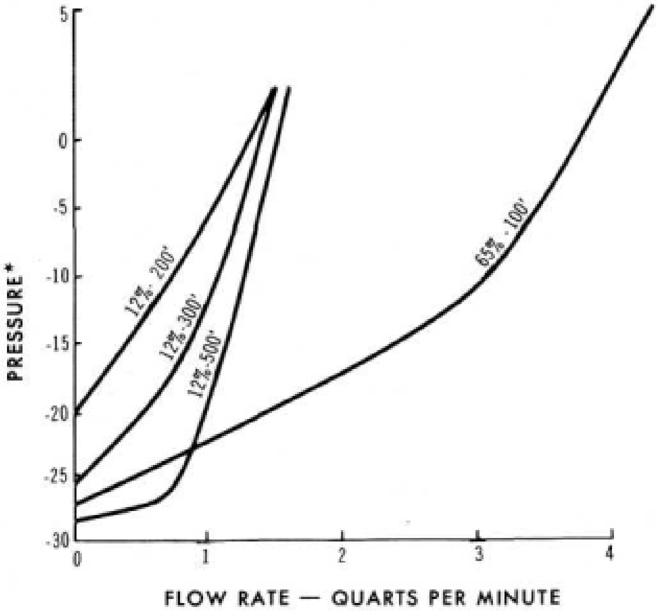


Fig. 2. *Typical pressure-flow rate curves for varying slopes and lengths of maple tubing for water source at top only.*

* *Negative pressure in inches of mercury; positive pressure in pounds per square inch.*

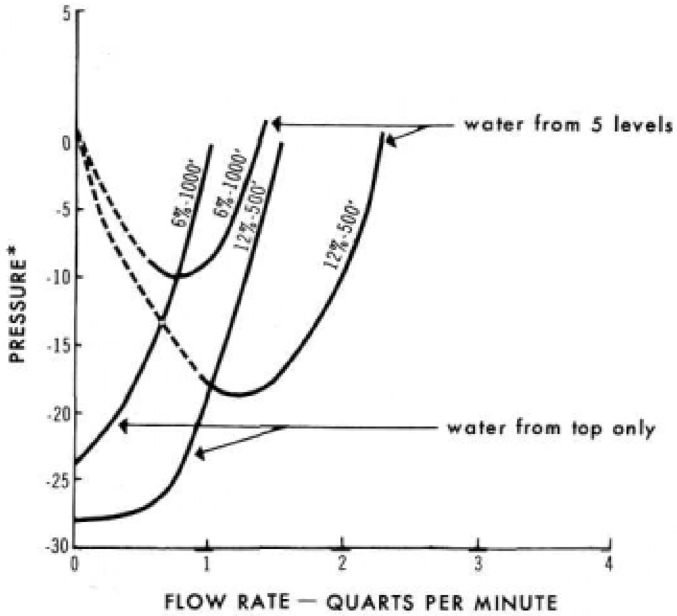


Figure 3. *Comparison of pressure-flow rate curves between 1 and 5 sources of water.*

* *Negative pressure in inches of mercury; positive pressure in pounds per square inch.*

At lower rates, the flow becomes discontinuous and this may be a principal cause of vacuum loss. Because there is less water in the upper than in the lower tubing, flow rates fluctuate unevenly. Water may accumulate in a portion of the upper tubing for a time; then it is released in a slug flow. Discontinuous or slug flow is more apparent at the slowest flow rates; this coincides with maximum vacuum loss.

A comparison was made between flows in tubing without sag and flows in tubing with vertical loops which forced uphill flow. At slow flow rates these loops caused a marked reduction in vacuum. Presumably vacuum was dissipated in the process of siphoning water uphill. The effect on vacuum of gas emitted from tapholes is unknown. Fast flow rates may remove gas from the tube line quickly, while slow rates permit it to remain and possibly reduce vacuum. We conclude that, in slow and discontinuous flows, vacuum loss is associated with the nature of the flow, sags or loops in tubing, and possibly gas from the tapholes.

Uneven Slopes

Starting with a 12 percent slope (500 feet of tubing with a 60-foot elevation drop), the even slope was interrupted by adding 100 feet of coiled tubing at different floor levels. This simulated a level stretch of 100 feet at various points in an otherwise downhill slope. It is well known that the friction loss of sap flow through tubing is increased with decreasing slopes. The amount of increased friction and its effect on sap flow, however, is often not appreciated. When the 100 feet of tubing was added at the first floor (12 feet), where all the water had to pass through it, increased friction markedly reduced both the flow rate and vacuum. The vacuum was generally less than half that previously experienced for the same flow rates.

Placing the added 100 feet of tubing at the 60-foot level, where only 20 percent of the water had to flow through it, had less severe effects. A strong vacuum was maintained on the lower side (greatly reduced vacuum on the upper side) of the added coil of tubing. When the 100-foot coil was added at the 30-foot level, intermediate effects were found but the level of vacuum was markedly reduced. Thus, level stretches of tubing cause much vacuum loss when located at the base or lower portions of a hill and little loss when located at the top of a hill.

Summary

Numerous tests of pressure-flow rates were made with maple tubing in the laboratory. Typical curves are presented in figures 2 and 3. Exact duplication of results under field conditions is not expected because of variations in such factors as height of sap column, temperature, and gas. For example, an 80-tap line on a steep slope at Heaven Hill had 20 inches of vacuum with a flow of only .37 quart per minute or double that indicated by laboratory results. However, in the field, both the elevation and the sap column were higher than the 60-foot limit in the laboratory. Nevertheless, the laboratory data indicate the conditions favorable to production of natural vacuum. These conditions are:

A high column of sap to permit a good head — obtained by steep slopes and/or long lines; also sufficient numbers of tapholes per line.

A fast flow rate — obtained by numerous tapholes per line; also vigorous trees, good sap flow weather, etc.

Reduction of sag in tube lines as far as practical.

Avoidance of shallow slopes, especially in the lower and middle portions of tubing installations.

Field Results —1970

The 1970 experiments were considerably enlarged over those of the previous year. Sap flows in closed and vented tubing were compared on 3 slopes, for a range of 5 to 50 tapholes per line, and in 2 climatic localities. Also in a few vented installations, the Naturalflow tubing connecting trees and drop lines was replaced by half-inch plastic water pipe (fig. la).

Ten or Fewer Taps

Table 3 shows that there was little difference in sap flow between closed and vented tube lines with few tapholes. The steeper slopes appeared to be slightly better. Vacuum was either nonexistent or low. Of 50 measurements during sap flows, only 18 indicated any vacuum, and the maximum reading was less than 3 inches.

Our laboratory tests suggest that these results are normal and predictable. Very little vacuum can be expected because there was too little elevation difference in the tube lines to permit a high sap column or head and, even more important, the few tapholes provided too little sap for either a high column or more than a minimum flow rate. Thus the physical conditions for creating a good vacuum in the closed tubing were lacking; therefore there was little difference in sap flow.

Table 3. *Sap flow in closed and vented tube lines with 10 or less tapholes — 1970*

Treatment			*Yield per taphole*		
Slope	*No. taps*	*Locality*	*Closed*	*Vented*	*Difference*
			— *quarts* —		
6%	5	Heaven Hill	29.4	29.2	.2
	10	Heaven Hill	27.3	24.0	3.3
	10	Chazy	19.4	22.5	−3.1
11%	5	Heaven Hill	23.2	22.6	.6
	10	Heaven Hill	29.5	28.4	1.1
	10	Chazy	23.5	20.7	2.8
16%	5	Heaven Hill	26.6	22.6	4.0
	10	Heaven Hill	37.4	34.2	3.2
	10	Chazy	26.7	22.6	4.1
6% combined			25.4	25.2	.1
11% combined			25.4	23.9	1.5
16% combined			30.2	26.5	3.8
5 taps combined			26.4	24.8	1.6
10 taps combined			27.3	25.4	1.9
Overall mean			27.0	25.2	1.8

Twenty-five to Fifty Taps

Tables 4 and 5 give the 1970 data for the many-tap installations by major flow periods. The closed tubing was superior in most installations and most sap runs, but there were exceptions. Apparently particular sap flow conditions, such as flow rate or temperature, can influence the relative value of closed tubing. For example, a small flow

Table 4. *Sap flow in closed and vented tubing, by slope and numbers of taps.* *Heaven Hill—1970*

Slope percent	5				10				15			
Slope variation	2–6		2–6		8–13		8–13		10–20		11–23	
No. of tapholes	30		50		30		50		30		50	
Date	*											
March 22–28	7.2	8.2	9.8	6.9	9.2	8.5	10.4	6.2	9.1	7.3	12.3	6.7
April 1–2	1.8	2.0	2.4	1.7	2.2	2.0	2.6	1.6	2.3	1.8	3.1	1.7
April 6–9	3.2	3.6	4.3	2.6	4.6	3.5	3.8	3.0	2.9	2.7	4.9	2.2
April 12–16	7.9	6.6	10.6	6.7	14.1	5.7	8.5	6.6	6.7	6.4	9.6	5.2
April 19–20	5.0	3.7	6.1	3.4	7.5	3.3	7.3	3.7	3.2	3.5	3.8	3.0
April 23	1.8	2.6	2.9	1.7	3.7	3.3	6.6	2.0	2.4	1.6	2.7	1.9
Season total	26.9	26.7	36.1	23.0	41.3	26.3	39.2	23.1	26.6	23.3	36.4	20.7
Mean vacuum†	3		6		3		16		0+		10	

**Data are quarts per taphole. Closed tube data on left, vented tube data on right, of each column. -fData are inches of mercury; mean of 5 measurements made during sap flows.*

Table 5. *Sap flow in closed and vented tubing, by slope and numbers of taps.* *Chazy — 1970*

Slope percent	5						10						15					
Slope variation	3–7						8–12						13–17					
No. of tapholes	25		25*		50		25		25*		50		25		25*		50	
Date	†																	
March 18–20	.7	1.0	.9	1.1	1.3	1.0	1.6	.3	1.4	1.0	1.0	1.7	1.3	1.3	1.6	1.2	3.0	1.1
March 25–28	4.2	4.8	9.2	5.3	9.7	3.5	12.2	3.1	14.3	5.3	11.2	6.4	7.3	4.2	9.2	3.5	9.6	3.4
April 1–6	4.9	3.2	4.7	4.4	6.5	2.5	7.6	2.0	9.6	5.5	8.4	2.6	8.8	5.5	10.8	6.9	11.2	4.9
April 11–12	1.7	1.7	4.3	1.8	2.9	1.1	2.6	.5	5.5	1.1	7.6	.8	2.6	1.2	2.0	1.3	4.5	.8
April 16–20	2.1	2.7	7.3	2.9	3.6	2.0	6.3	3.4	7.8	2.2	12.1	.9	1.7	1.6	2.0	1.3	2.1	.8
Season total	13.6	13.4	26.4	15.5	24.0	10.1	30.3	9.3	38.6	15.1	40.3	12.4	21.7	13.8	25.6	14.2	30.4	11.0
Mean vacuum‡	0+		6		10		4		10		19		3		5		10	

**Half-inch water pipe between trees and drop lines.*

†Data are quarts per taphole. Closed tube data on left, vented tube data on right, of each column.

‡Data are inches of mercury; mean of 7 measurements made during sap flows.

may create no vacuum, while the vented tubes would empty more easily. There was a tendency for closed tubing to be relatively better near the end of the season in some, but not all, installations; for example, the 10 percent, 50-tap line at Chazy.

Season-end checks revealed 3 tube lines with leaks, as follows:

Heaven Hill: 15%, 30-tap, closed line. Leak at uppermost tee; taphole in hollow wood in one of the upper trees; relatively more sap on April 23 after leaks were removed. Leak was predicted because of negligible vacuum throughout the season.

Chazy: 5%, 25-tap, closed line. Numerous leaks caused by oversize tubing which did not properly fit tees and spiles. Leaks were predicted because of negligible vacuum throughout the season.

Chazy: 10%, 25-tap, vented line. Leak near base of tube line. Vented line had relatively better flow after leak was corrected on April 15. The seasonal total of 9.3 quarts per taphole is low and not suitable for comparison with flow in the closed tubing.

Since a leaky installation is a normal hazard of either closed or vented tubing, the results of these three tube lines are retained in the data in table 6. However, data from the two leaky closed lines are omitted from the vacuum comparison in table 7. Also data from the leaky vent line and the companion closed line are omitted in figure 4. Table 6 shows the marked increase in seasonal sap flow from closed tubing, the general relationship between sap gain and vacuum, and interactions of slope, numbers of taps, and locality. Of particular interest is the difference between localities. Closed tube installations at Heaven Hill produced 45 percent more sap than vented tubing. This is comparable with the 43 percent reported by Blum (1) and the 33 percent increase found at Heaven Hill in 1969. But at Chazy there was a gain of 118 percent, more than ever previously measured. Perhaps this gain was due partly to the extremely careful installation at Chazy (an abney level was used between each tree to maintain tube slope within 2 percent of the mean; most sag was eliminated by pulling the tubing tight after installation) compared with the more normal and easily applied installation at Heaven Hill. Also the high percentage gain was due in part to abnormally low production in the vented lines at Chazy. This suggests that gains are more meaningful when expressed in seasonal totals; the total gain at Chazy was not unduly greater than at Heaven Hill (15.1 vs. 10.6 quarts per tap). Finally, the low production in the vented lines at Chazy is puzzling. We might suspect that vacuum drew some sap from one to the other of the paired tapholes. This possibility influenced us to use paired trees in addition to paired tap holes in the 1971 experiments.

As expected, sap gains in closed tubing were better for 50-tap installations than for the 25- or 30-tap lines. Without exception, 50-tap lines were superior in both vacuum and sap gain for each slope at both Chazy and Heaven Hill. For the season they produced an average of 8 more inches of vacuum and over 7 quarts of sap per taphole. Clearly, the large amount of sap from numerous taps is most important in making high sap columns, increased flow rates, and resultant high vacuums. The high vacuums in turn are correlated with large increases in sap flow.

The sap gains and vacuum in closed tubing were much better for the 10 percent than for either the 5 or 15 percent slopes. This substantiated the 1969 results. Ten percent slopes are clearly better than 5 percent slopes where tubing must be very carefully installed to prevent vacuum losses. For closed tubing, 10 percent slopes may be superior to

Table 6. *Increase in sap flow in closed tubing, by slope and numbers of taps —1970*

Treatment			*Yield per taphole*			*Percent increase*	*Mean vacuum*
Location	*Slope*	*No. taps*	*Closed*	*Vented*	*Difference*		
				— quarts —			*inches*
Heaven Hill	5%	30	26.9	26.7	.2	1	3
		50	36.1	23.0	13.1	57	6
	10%	30	41.3	26.3	15.0	57	3
		50	39.2	23.1	16.1	70	16
	15%	30	26.6	23.3	3.3	14	+
		50	36.4	20.7	15.7	76	10
Chazy	5%	25	13.6	13.4	.2	1	+
		25	26.4	15.5	10.9	70	6
		50	24.0	10.1	13.9	138	10
	10%	25	30.3	9.3	21.0	226	4
		25	38.6	15.1	23.5	156	10
		50	40.3	12.4	27.9	225	19
	15%	25	21.7	13.8	7.9	57	3
		25	25.6	14.2	11.4	80	5
		50	30.4	11.0	19.4	176	10
Heaven Hill	combined		34.4	23.8	10.6	45	6+
Chazy	combined		27.9	12.8	15.1	118	7+
5%	combined		25.4	17.7	7.7	44	5
10%	combined		37.9	17.2	20.7	120	10+
15%	combined		28.1	16.6	11.5	69	6−
25–30 taps	combined		27.9	17.5	10.4	59	4−
50 taps	combined		34.4	16.7	17.7	106	12−
Overall mean			30.5	17.2	13.3	77	7

steeper slopes for two reasons. First, there is less friction on steeper slopes which are optimal for vented tubing. Second, figure 3 shows that flow rate must increase with rise in slope for best results; if there are too few taps, both flow rate and sap column height may be limited. This should result in lower vacuums on very steep slopes and appears to do so, since the mean vacuum on the 10 percent slopes considerably exceeded that on the 15 percent slopes (10 + vs. 6 —). Conversely, more tapholes — perhaps a hundred — are needed for optimal vacuum on 15 percent slopes.

Relation of Sap Gain to Vacuum

From 5 to 7 vacuum measurements were made in each installation during flows throughout the season. This is insufficient to suggest accurately a true mean vacuum for the season. Nevertheless there was a close relationship between the mean of the vacuum measurements made and the increased seasonal sap yields in the closed tube installations. Figure 4 shows this relationship. The linear re-

Table 7. *Relationship of vacuum to numbers of taps and slope. Heaven Hill and Chazy —1970*

No. taps	*Slope*	*Mean vacuum*
		inches
50	10%	17.5
50	15%	10
50	5%	8
25–30	10%	5.7
25–30	15%	4
25–30	5%	4.5

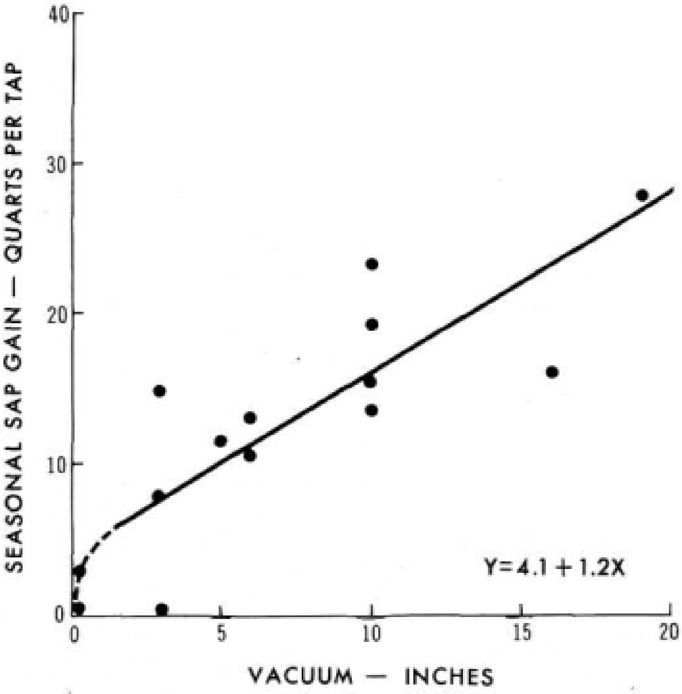


Figure 4. *Relation of seasonal yield increase and natural vacuum —1970.*

gression Y (sap gain in quarts per taphole) = 4.1 + 1.2X (mean vacuum) was computed. The correlation coefficient is .84 and is significant at the 0.01 level. The regression accounted for 70 percent of the variation in sap gain.

Since vacuum is so important to increased sap flow, it is necessary to understand the physical conditions that contribute to it. Large numbers of taps and 10 percent slopes were associated with high vacuums. Therefore in table 7, the factors of numbers of taps and slopes are ranked in decreasing order of their importance to producing vacuum. Again the significance of many tapholes is most important in producing high natural vacuums. Next in importance for our installations was a slope of about 10 percent.

Closed Tubing vs. Other Methods

Three of the vented installations at Chazy had half-inch plastic pipe to carry sap downhill. Thus sap flow was not restricted. Since the use of half-inch pipe did not cause results that differed significantly from comparable installations with small tubing, we conclude that gains from the use of closed tubing are real — that they cannot be attributed to deficiencies in the vented tubing. Also closed tubing would have similar gains over buckets.

Field Results —1971

Natural Vacuum

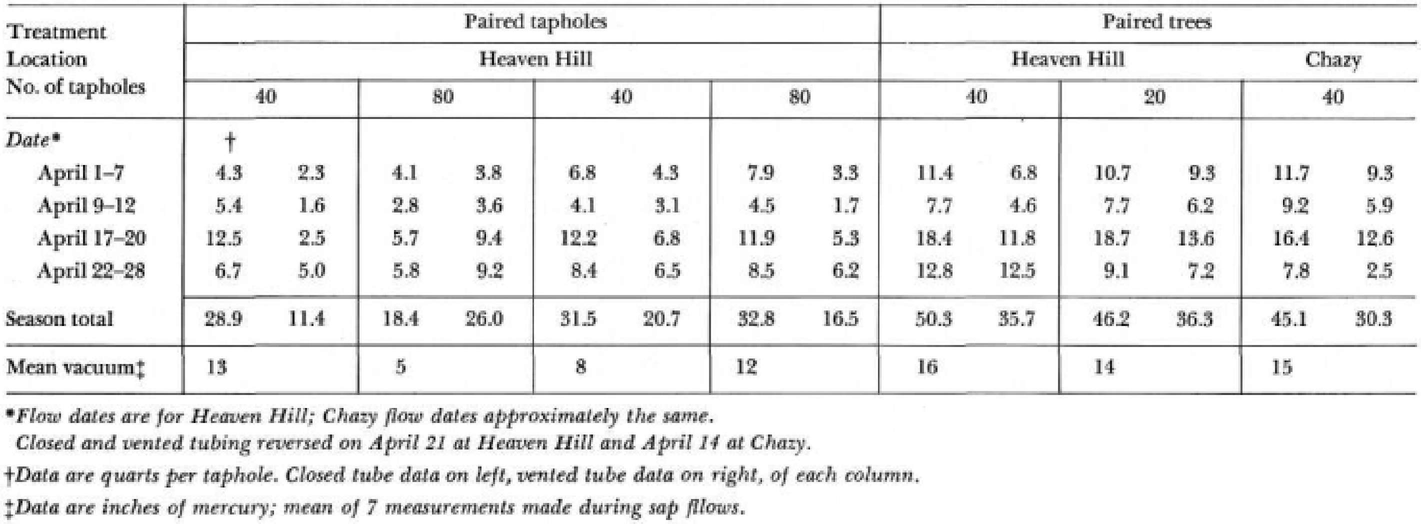
The 1971 experiments principally compared two treatment methods — paired tapholes and paired trees. In the latter adjacent lines of similar trees, each tapped once, were used to compare sap flow in closed and vented tubing. In midseason the treatments were reversed by closing or capping all vented lines and venting each taphole in the closed lines. Most test lines were installed at 12 percent slopes with 40 tapholes; two 80-tap comparisons and one of 20 taps were made. Results are shown in table 8.

For reasons unknown, one of the 80-tap vented lines outflowed the closed line, even though some vacuum was formed in the latter. The other 80-tap lines performed as expected; the sap flow from the closed line was twice that from the vented line. Also the closed 20-tap line was superior to the vented line, but the sap gain was less than in the 40-tap lines.

Results of all test lines, excepting the aberrant 80-tap line, were combined to compare the two methods (table 9). It is apparent that much less sap per taphole was obtained in the paired taphole experiments where the trees were double-tapped. I have shown (8) that multiple taps on otherwise similar trees reduce the sap flow from each tap-hole. In addition, the paired tree tests used somewhat younger and more vigorous trees; this would tend to enhance sap flow. It is also likely that the higher flow rates in the paired trees contributed to the higher vacuums recorded for this method.

When comparing the two methods on a percentage basis, there was more sap gain with less vacuum by the paired taphole method.[9] This suggests a bias that may cause the method to overestimate the value of closed tubing. Paired tapholes have an opposing bias, however, since added taps tend to reduce the amount of sap per tap and possibly the differences between treatments. This is suggested by the small difference in total sap gain (14.9 vs. 13.1 quarts per tap) between the paired taphole and paired tree methods. Such large gains by both methods confirm that consistent and substantial gains may be obtained from the use of closed tubing and natural vacuum.

Table 8. *Comparison of sap flow in closed and vented tubing, from paired taps and paired trees —1971*



Treatment	Paired tapholes								Paired trees					
Location	Heaven Hill								Heaven Hill				Chazy	
No. of tapholes	40		80		40		80		40		20		40	
*Date**	†													
April 1–7	4.3	2.3	4.1	3.8	6.8	4.3	7.9	3.3	11.4	6.8	10.7	9.3	11.7	9.3
April 9–12	5.4	1.6	2.8	3.6	4.1	3.1	4.5	1.7	7.7	4.6	7.7	6.2	9.2	5.9
April 17–20	12.5	2.5	5.7	9.4	12.2	6.8	11.9	5.3	18.4	11.8	18.7	13.6	16.4	12.6
April 22–28	6.7	5.0	5.8	9.2	8.4	6.5	8.5	6.2	12.8	12.5	9.1	7.2	7.8	2.5
Season total	28.9	11.4	18.4	26.0	31.5	20.7	32.8	16.5	50.3	35.7	46.2	36.3	45.1	30.3
Mean vacuum‡	13		5		8		12		16		14		15	

**Flow dates are for Heaven Hill; Chazy flow dates approximately the same.*
Closed and vented tubing reversed on April 21 at Heaven Hill and April 14 at Chazy.

†Data are quarts per taphole. Closed tube data on left, vented tube data on right, of each column.

‡Data are inches of mercury; mean of 7 measurements made during sap flows.

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[8] If data from the aberrant 80-tap test line were included, the 92 percent increase for closed tubing by the paired taphole technique would be reduced to 50 percent.

Table 9. *Increase in sap flow in closed tubing, by two treatment methods — 1971*

Method	Yield per taphole			Percent increase	Mean vacuum
	Closed	Vented	Difference		
	— quarts —				inches
Paired tapholes	31.1	16.2	14.9	92	11
Paired trees	47.2	34.1	13.1	38	15

Flow Rate and Vacuum

The laboratory studies showed that increased flow rates led to more vacuum for normal sap flow rates (figure 3). Numerous measurements were made on the closed-tube lines — flow rate at the base was measured simultaneously with vacuum. The 1971 season was generally poor; the fastest flow rate measured was only .62 quart per minute. Nevertheless, weak correlations between vacuum and flow rate were obtained at both Heaven Hill and Chazy for individual sap flows. Figure 5 shows a good correlation for the means of 5 sets of measurements obtained on 9 closed-tube lines at Heaven Hill between April 3 and 18. A comparison with figure 3 shows that natural vacuum obtained in the field generally exceeded that in the laboratory. This is attributed to the limitation of elevation and head available in the laboratory.

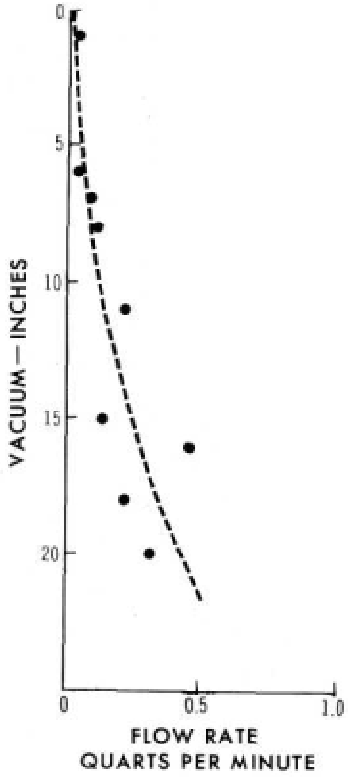

Figure 5.
Relation of vacuum to flow rate.
Heaven Hill — 1971.

Pumped versus Natural Vacuum

Vacuum in maple tubing can be created directly by pumping, and sap flow may be more than doubled in some instances (2, 5, 10, 11). However accurate comparison of pumped and natural vacuum for sap flow is difficult for the following reasons:

> Pumped vacuum tends to be consistent throughout the tube line; natural vacuum reaches a maximum at the upper trees. Thus natural vacuum readings tend to be maximal rather than average.
>
> Pumped vacuum exists while the pumps are turned on. Pumped vacuum may occasionally extract sap from trees which otherwise would not yield. Thus the operator's judgment concerning pumping time may affect the amount of sap gain from pumped vacuum. On the other hand, the duration and amount of natural vacuum and its effect on sap gain depends on sap flow rates and other physical characteristics.

Despite these limitations, we compared pumped and natural vacuum at two localities, using both the paired taphole and paired tree methods (table 10). Most slopes were 10 percent. Pumps were run some 100 hours during the season; this was about 70 percent of the pumping time on our commercial operation. Most of the pumping hours were during normal flow periods, but for approximately 15 hours the pumps produced sap while the non-pumped taps failed to produce. Nevertheless most of the gains in sap due to pumping came during normal flow periods.

Table 10 shows the superiority of pumped vacuum over natural vacuum (note that one natural vacuum line had very little sag and averaged 21 inches of vacuum). The natural vacuum on lines with 40-50 taps exceeded that on lines with 20-25 taps. Therefore pumped vacuum showed more gain on the lines with few tapholes. This result is consistent with prior results concerning the effect of numbers of taps on natural vacuum and sap flow. As with the natural vacuum study, there were greater yields per tap-hole, smaller percent gains, but equal total sap gains for the paired-tree method.

Sap yield and vacuum in tube lines were related for individual and total season flows at both Heaven Hill and Chazy. Figure 6 shows the relation between total season yield and mean vacuum, based on 10 measurements during sap flows, at Chazy. Half of the tube lines had natural vacuum; half had pumped vacuum. Note the higher level of yields from the paired-tree lines. Even though there are limitations in the comparison of pumped and natural vacuum, it is clear that added vacuum creates more sap flow. Even though excellent results can be obtained from natural vacuum under proper conditions, pumped vacuum can be even better.

Table 10. *Comparison of sap flow under pumped and natural vacuum — 1971*

Treatment			*Yield per taphole*			*Percent increase*	*Mean vacuum*	
Method	*Location*	*No. taps*	*Pumped vacuum*	*Natural vacuum*	*Difference*		*Pumped*	*Natural*
			— *quarts* —				— *inches* —	
Paired tapholes	Heaven Hill	25	28.2	13.5	14.7	109	12	4
			34.0	15.5	18.5	119	14	4
		50	35.1	22.2	12.9	58	10	6
			35.4	21.5	13.9	65	15	7
Paired tapholes	Chazy	20	31.5	15.3	16.2	106	15	5
			27.5	11.8	15.7	133	20	6
		40	30.2	13.8	16.4	119	16	9
			27.7	20.0	7.7	39	18	10
Paired trees	Chazy	20	44.1	25.0	19.1	76	22	9
		40	49.2	39.4	9.8	25	21	21
Paired taps combined		20–25	30.3	14.0	16.3	116	15+	5−
Paired taps combined		40–50	32.1	19.4	12.7	65	15−	8
Paired taps combined			31.2	16.7	14.5	87	15	6+
Paired trees combined			46.7	32.2	14.5	45	21+	15

Sap production in southern New York normally exceeds that from the Adirondack area. For nearly a decade vacuum pumping has been used on a majority of the trees at Arnot Forest; sap production has exceeded that from many similar sugar bushes (9). To test the effect of vacuum on a larger scale, a 300-tap commercial area was selected in 1971. Tube lines with 70 taps were on nearly level ground; little natural vacuum was expected. The remaining 230 taps were on tube lines with slopes mostly between 3 and 10 percent. The paired taphole method was used so that comparisons could be made between 300 pumped, 70 non-pumped, and 230 nonpumped taps. Treatment of the paired taps was reversed on March 24 and again on April 10 to reduce taphole bias. Time of vacuum pumping exceeded 200 hours and coincided with commercial practice. Vacuum was measured 17 times in a dozen locations. Table 11 shows a comparison of sap yield with vacuum, as well as mean flow for the entire commercial enterprise. Although some vacuum was found on the nonpumped 70-tap line on nearly level ground, back pressure also occurred at times and sap yield was less than half that obtained by pumping. Moderate natural vacuums occurred on the hillside, and sap flow was intermediate between that from the nonpumped flat land and the pumped taps. It is important to note that, while percent increases in sap yield from pumping on hillsides were similar at Arnot, Heaven Hill, and Chazy, the actual amount of increase was much greater at Arnot (21 vs. 14.5 quarts per tap). This suggests that the use of vacuum to increase sap flow can be even more effective for the normally longer seasons and higher yields of southern New York than for Adirondack conditions.

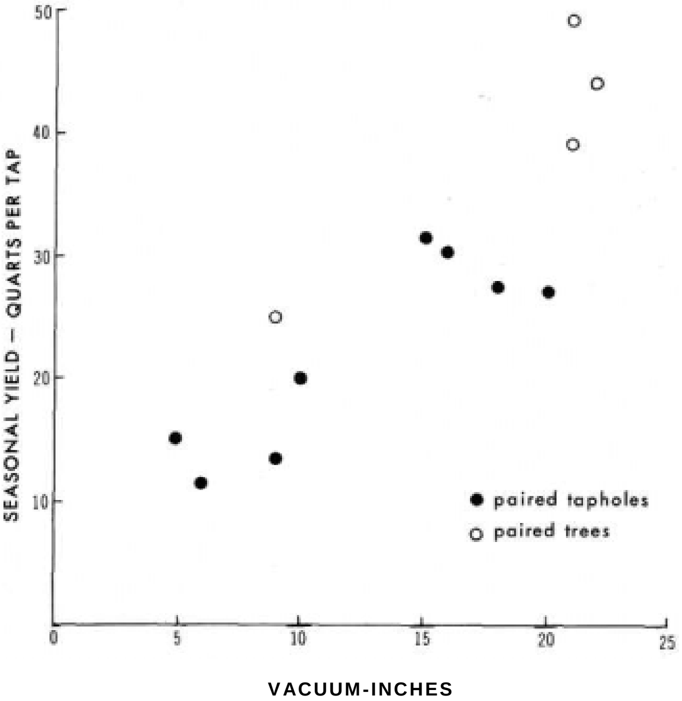

Figure 6. *Relation of seasonal yield to vacuum. Chazy —1971.*

Sugar Percentage

Sugar percentage was measured at numerous times at all three localities in both 1970 and 1971 in an attempt to discern differences between the various treatments. Although there was a tendency for sap that flowed under vacuum to have less sugar, seasonal mean differences in sugar content were .05 percent or less and not significant.

Table 11. *Comparison of sap flow and vacuum under commercial conditions Arnot — 1971*

Treatment	*300 taps pumped*		*230 taps nonpumped*		*70 taps nonpumped*		*Arnot mean*
	*yield**	*vacuum†*	*yield*	*vacuum*	*yield*	*vacuum*	*yield*
March 11–14	8.2		8.2		4.0		8
March 18–22	14.5		8.2		8.3		9
March 26–April 2	20.5	12 (60)	14.7	5 (40)	11.2	2 (20)	19
April 3–9	19.3	11 (30)	18.8	6 (20)	8.3	3 (10)	19
April 11–12	11.2	11 (12)	3.3	1 (8)	3.2	1 (4)	5
Season total	74	11+	53	5−	35	2	60

**Yield in quarts per taphole.*

†Vacuum in inches of mercury. No. of measurements given in parentheses.

Relation of Vacuum to Sap Production

Sap flow is the result of pressure gradients within the tree which cause sap to flow outward and drip from an open wound or taphole. Pressures may rise some 30 pounds per square inch above atmospheric pressure. At night, pressure may decrease to less than atmospheric and sap may be reabsorbed (7). Negative pressure or vacuum adds to the already existing pressure gradients (2" vacuum equivalent to 1 PSI). Laing and Arnold (5) found that vacuum was transmitted longitudinally within tree tissues for at least a foot. With high vacuums exceeding 25 inches, they increased low flow rates of single tapholes by as much as 0.8 quart per hour. Vacuum may also be present between flows because of either sap columns in tubing or pumping. In addition to enhancing normal sap flows, vacuum can also create earlier flows and delay flow stoppage.

The potential for increasing sap production with vacuum varies from zero in years of extreme tube damage by rodents, such as 1968, to the high increases found with vacuum application to single trees. The combined results of our experimental data may suggest practical sap gains that can be achieved in many commercial operations. In table 12, summary data from previous tables are presented with production figures rounded to the nearest quart per taphole. Where the comparison is between pumped and natural vacuum, the vacuum difference is used.

Great care must be exercised in interpreting table 12. Vacuum means for different years and localities are not necessarily comparable because they are affected by time of measurement in respect to flow conditions. Nevertheless some conclusions are suggested. As expected there was little relationship between sap gain expressed in total amount and in percent. Percent increases are unreliable because of lower base productions in the paired taphole method and in the Adirondack region. On the other hand, except for the low vacuum year of 1969, seasonal sap gain in quarts per taphole was remarkably constant (13-15 quarts) for the Adirondack area for both methods. The highest gain was for highly productive Arnot.

Although both our data and that of others suggest linearity between sap gain and vacuum, we are uncertain of the exact relationship. Our 1970 data (figure 4) were

Table 12. *Seasonal sap gain from vacuum, 3 years, 3 localities*

Treatment			*Sap gain per taphole*	*Percent increase*	*Mean vacuum*
Method	*Location*	*Year*			
			quarts		*inches*
Paired tapholes	Adirondacks	1969	8	33	3
		1970	13	77	7
		1971	15	92	11
		1971	15	87	9*
	Arnot	1971	21	40	6.5*
Paired trees	Adirondacks	1971	13	38	15
		1971	15	45	6.5*

**Mean difference in vacuum between pumped and natural vacuum installations. Other data are comparisons between closed and vented tubing.*

treated as if essentially linear. Blum (1) presents a similar graph which, although based on only one set of vacuum measurements, yields a linear regression nearly like ours when the scales are made equal. If linearity is assumed, our 1970 regression $Y = 4.1 + 1.2X$ shows a seasonal sap gain of 1.2 quarts per taphole for each inch of natural vacuum. Laing and Arnold (5) obtained gains sometimes exceeding 2 quarts per tap for each inch of vacuum with high-vacuum pumping on 200- to 400-tap areas. The higher level gains with vacuum pumping are expected since natural vacuums, as measured, tend to be maximal rather than average. Inspection of table 12 suggests seasonal gains of 1 to 2 quarts per tap per inch of vacuum for a combination of natural and pumped vacuum situations.

Measurements on our commercial production areas tend to confirm the experimental results. In 1970 and 1971 at Heaven Hill, pumped vacuum produced seasonal gains of 1 quart per tap per inch of vacuum (9-10 quarts for 8-11 inches vacuum) in two large areas. At Arnot in 1971 seasonal gains exceeded 2 quarts per tap per inch of pumped vacuum and reflect the excellent production year.

Most of our results were obtained in poor sap years, in cold localities, and with low-production trees. We conclude that sap gains from vacuum may commonly range from 1 to more than 2 quarts per taphole per inch of vacuum. The lower gains may be expected with natural vacuum, poor seasons, and low production localities and bushes. The better gains may be expected with pumped vacuum, good seasons, and high-production trees.

Conclusions

Field research, using 4500 tapholes, was conducted for 4 years at 3 geographical locations. This was supplemented by laboratory tests to determine the relationships of pressure to flow rate in maple tubing.

Good natural vacuum in closed maple tubing requires the following conditions:

A good, leak-free installation and freedom from rodent damage.

A high column of sap to make a good head. An elevation difference of 50 feet or more is best; this can be obtained by steep slopes and/or long lines, as well as sufficient numbers of tapholes per tube line.

A fast flow rate, obtained by numerous tapholes per line, vigorous trees, good climatic and weather conditions for sap flow, etc. Within the range tested, vacuum increased with larger numbers of taps; 10 taps per line were too few, while best vacuums were obtained with 50 or more taps.

Minimum sag in tube lines. We agree with Koelling *et al.* (4) that changes in elevation which restrict continuous downhill flow of sap will reduce vacuum in either aerial or ground tube lines.

Suitable slopes and matching numbers of tapholes. Five percent slopes had good vacuums with 50 taps per line; additional taps would likely overload the line. Ten percent slopes had the best vacuums; 50 to 80 taps were best. Fifteen percent slopes were not as good as 10 percent slopes probably because there were too few taps; we believe that 100 or more taps per tube line are necessary for best results with 15 percent or steeper slopes. On such steep land, tubing can be installed at less acute slopes simply by angling it away from the direction of steepest topography. On the other hand, good installations are difficult on slopes of less than 5 percent; we recommend the use of pumped vacuum where feasible. It is also important to avoid shallow slopes in the lower and middle portions of tubing installations. Gains in sap production tended to be proportional to increased vacuum, whether natural or pumped. Both experimental and commercial results suggest seasonal sap gains of 1 to 2 quarts per taphole for each inch of vacuum (33 to nearly 100 percent). The lower gains are associated with natural vacuum, poor seasons, and low-production localities and bushes. The better gains may be achieved with pumped vacuum, good seasons, and high-production trees.

Both the requirements for and potential sap gains from natural vacuum indicate the need for evaluation and proper use of slope for maple tube installations. Steep slopes, poorly regarded in the past, may now be considered assets.

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Acknowledgments

The author acknowledges the generous aid and cooperation received from several sources. His thanks go especially to the following:

Miner Institute, Chazy, New York for its commitment of land, facilities, equipment, labor, a supervisor, and other resources to this research.

Mr. and Mrs. Henry Uihlein for continuing gifts to the support of research.

Mr. Lewis Staats, Resident Manager, Heaven Hill, for technical services in field research.

Mr. Charles Hoag, Chief Forester, Miner Institute, for technical services in field research.

Mr. Fred Fontana, Resident Manager, Arnot Forest, for technical services in field research.

Prof. Cyrl Terry, retired, Cornell University, for guidance and technical services in theoretical vacuum experiments.