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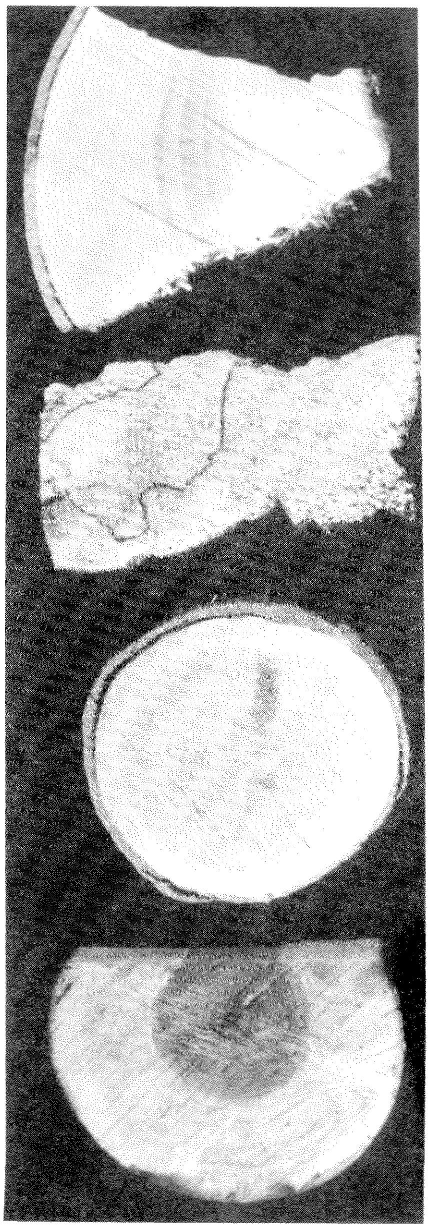
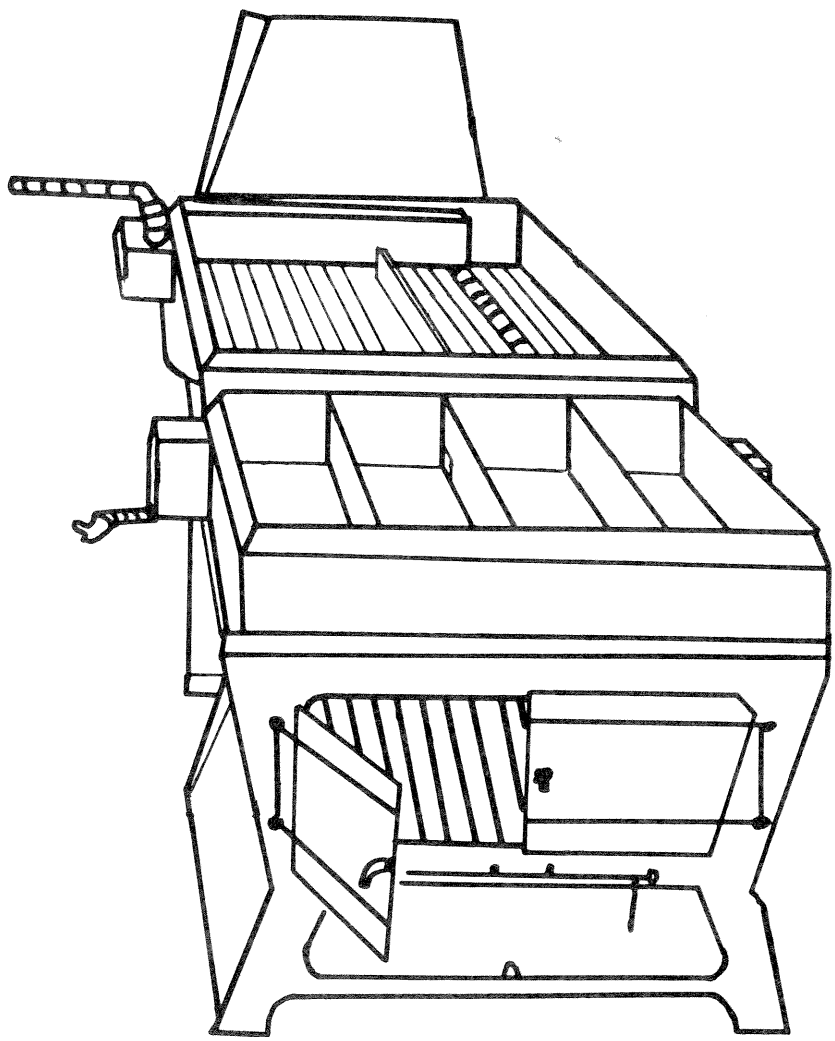
Efficiency of Using Solid Wood Fuels

in Maple Syrup Evaporators

by Lawrence D. Garrett





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Abstract

A study of commercial, wood-fired evaporators revealed that normal expected thermal efficiencies are between 35 and 50 percent. The moisture content and quality of wood fuels used and the design and method of firing the evaporator are critical in determining evaporator efficiency and the economic implications of using wood.

Introduction

In the United States and Canada, it is estimated that approximately 15,000 maple syrup producers process 3 million gallons of pure maple syrup annually. There are insufficient data on the percentage of total production that is processed by solid wood-fired evaporators. However, regional studies indicate that a significant number of producers are using wood (Kearl 1970, Acker et al. 1970). Oil also is used extensively and generally in larger and more modern maple processing plants.

Number 2 fuel oil is the most common fuel purchased by maple producers operating with oil. It also is the evaporator fuel that has experienced the most rapid rise in price. From a price of $0.12 to $0.14/gal in 1970, No. 2 fuel oil rose in one decade to the price of $0.95/gal in 1980. At $0.95/gal, $3.32 in oil alone is required to process 1 gallon of pure maple syrup. Possibly more critical than its price is the possible restricted availability of No. 2 fuel oil over the next 5 years.

This combination of restricted availability and rising price of fuel oil prompted research to determine the thermal efficiency of commercial, open-pan evaporators that use solid wood fuels, and to characterize the economic implications of these fuels as an alternative to oil and gas. There has never been a study of this type, though manufacturers have estimated the efficiency of open-pan evaporators using wood fuels, and have recommended appropriate species and evaluated the probable effects of using wet and deteriorated wood (Morrow 1959).

Procedure

To meet the study objective in a manner most beneficial to the industry, actual case studies were analyzed. Three commercial maple syrup operations (A, B, and C) in which solid wood fuels are used were selected as best representing actual production conditions. The evaporators had to be of commercial size (5 x 16 feet or 6 x 16 feet), in a good state of repair, installed to manufacturer's specifications, and have no modifications.

Four types of wood fuel were tested in each evaporator. Each fuel type had at least 80 percent of its total weight in beech, birch, and maple.

1. *Split or round hardwood*—Selected fuels were used by the operator at his plant during the study. The average moisture content (MC) was less than 25 percent.
2. *Split or round hardwood*—The average MC was less than 30 percent.
3. *Split or round hardwood*—Rot accounted for at least 50 percent of total volume. The average MC was less than 35 percent.

4. *Split or round hardwood*—The average MC was greater than 35 percent.

A total of 12 tests were conducted with the three evaporators; and each test consumed approximately 7,000 pounds of wood fuel and lasted approximately 5 hours.

Syrup quality was determined by taking samples coming off the evaporator at 1/2-hour intervals during each test. Analysis of the samples was made to ensure that the test procedures produced a quality product for marketing.

All factors affecting each evaporator's thermal efficiency and operating effectiveness were studied. These included: sap and syrup temperature; sap and syrup Brix; sap and syrup flow rates; stack, firebox, and air temperature; weight of fuel consumed; wood moisture; barometric pressure; stack-gas composition; and time intervals for opening and closing firebox doors.

For each of the four wood fuels, wafers were sawed at random from the center of solid fuel sticks during each test to provide an accurate assessment of MC (Fig. 1). Wood moisture was determined on the wet basis by the formula:

$$\text{MC (percent)} = \left(\frac{\text{wt. wet wood - wt. dry wood}}{\text{wt. wet wood}}\right) (100).$$

Factors Affecting Efficiency

The efficiency of the wood-fired evaporator is affected by the design and operability of the evaporator itself and by the type and condition of fuel used. In combination, these effects, defined as "equipment effect" and "fuel effect," produced evaporator efficiencies ranging from 20 to 60 percent.

Equipment effect

The open-pan evaporator was originally designed to use solid wood fuels (Willits 1965). The design requires a long firebox to accommodate 4-foot lengths of split or round-wood fuel set on a grate (Fig. 2). The sap and syrup pans are heated by convection and radiant energy. The design of the firebox is such that the cold-air draft creates a long fireball extending under the back pan. The rise in the arch from the firebox region actually forces the hot gases into the dropped flues of the back pan (sap pan). The cold draft also reduces the overall temperature of the hot gas mixture, thereby reducing the effective heat transfer to the underpan surface.

The oil-fired evaporator's firebox is shorter and deeper and has less grade in the arch (Fig. 3). The placement of the gun, the angle of the jet spray, and the angle of the rise in the

Figure 1.—Wood samples taken during each evaporator test to determine wood moisture and Btu value.

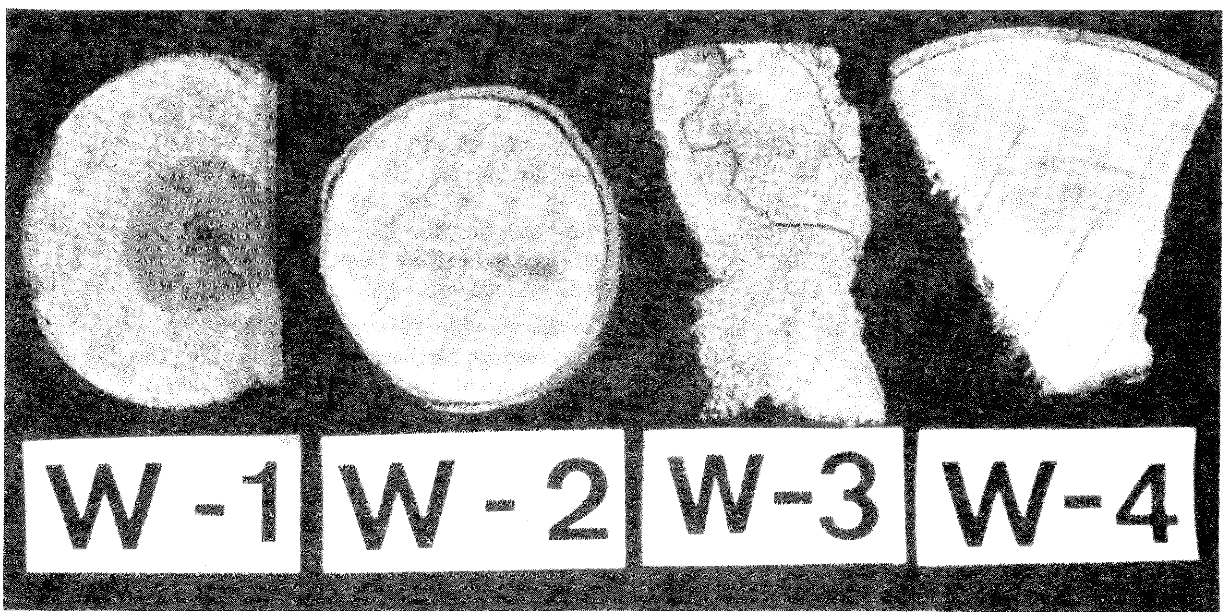


Figure 2.—Schematic of conventional, wood-fired, open-pan evaporator.

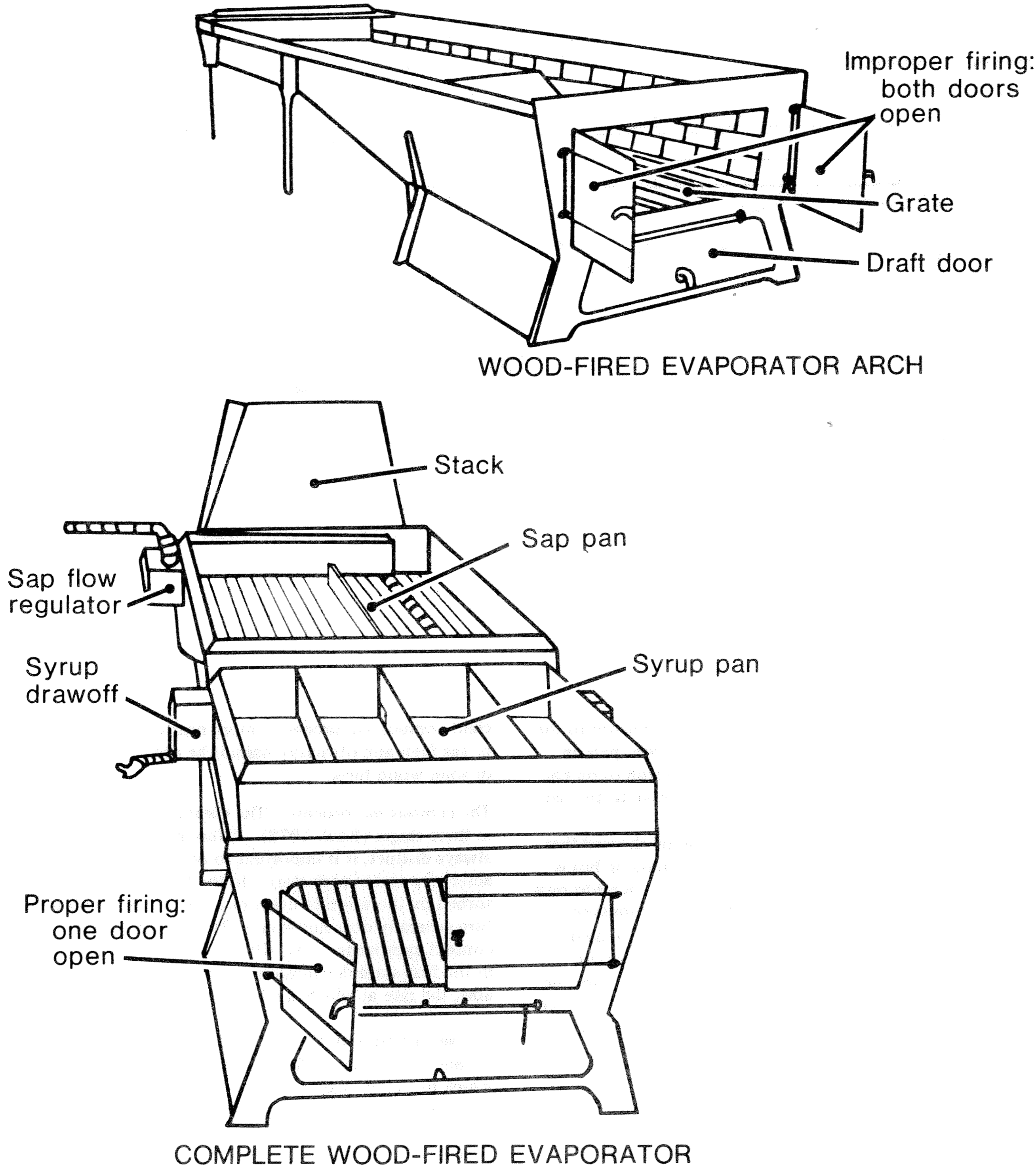
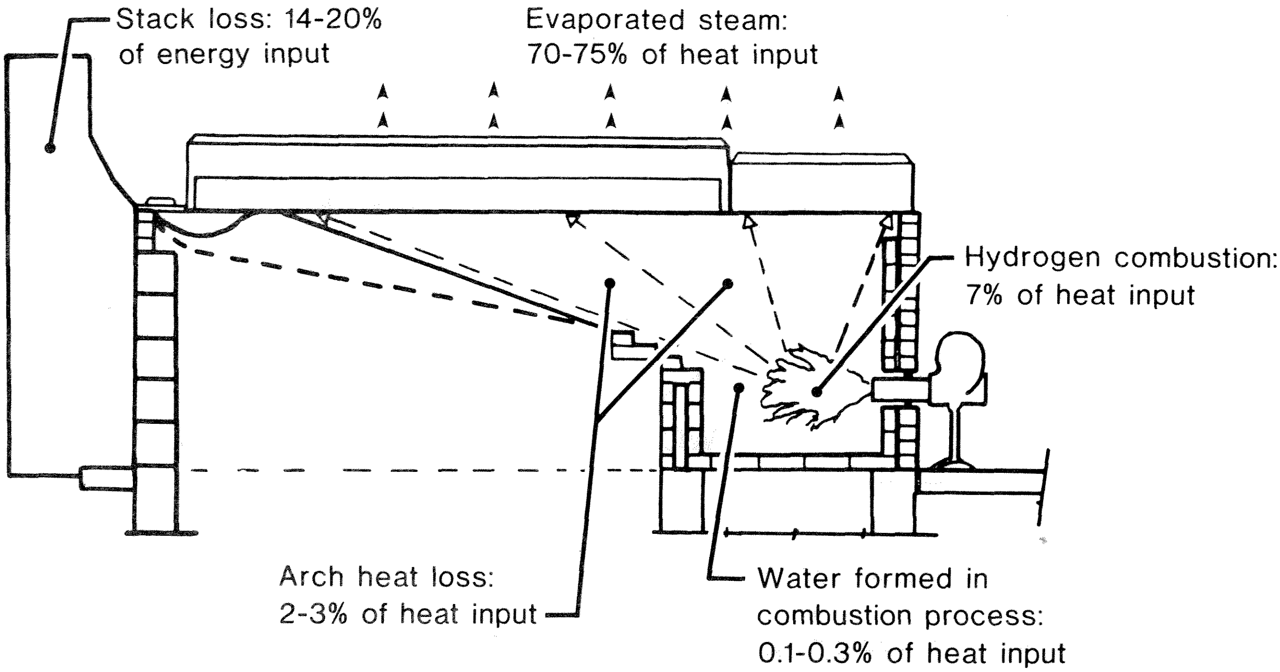


Figure 3.—Schematic of conventional, oil-fired, open-pan evaporator showing efficiency losses.



$$\text{Evaporator efficiency} = 100 - [16 + 2.5 + 7.0 + 0.2] = 100 - 25.7 = 74.3$$

arch are important in ensuring maximum heat transfer to the underpan surfaces (Strolle et al. 1956). The front pan on many wood evaporators that have been converted to oil has been damaged because the oil fireball is too close to the pan.

Evaluation of evaporators operating on fuel oil showed that 14 to 20 percent of the direct input of heat units or Btu is lost to gases exiting through the stack (Fig. 3). An additional loss of 7 percent results from poor hydrogen combustion in the firebox (Garrett et al. 1977). It is realistic to assume that similar evaporators that use solid wood fuels would have lower efficiencies. Since the fire doors must be opened continually to fire the evaporator, cold-air drafts are created over the fuel bed, cooling down the hot gases and reducing heat transfer to the evaporator pans.

The fuel effect

The amount of heat energy produced from a fuel depends on the combustion process, wood moisture, and type of fuel consumed. The greatest heat is generated by atomizing a fuel so that a rapid, complete burn is obtained. This efficient combustion process is more nearly attained with liquid or gas fuels and obviously cannot be obtained with split or solid wood fuels.

The combustion process. The combustion of wood occurs in three stages (Koch 1972). Although the stages are not always distinct, it is important to define the general character of wood in each stage. In the first stage, heat is absorbed by the wood to evaporate water. The wood temperature generally does not exceed 212°F until the moisture content approaches zero. The length of time wood remains in the first stage depends on the total amount of heat available, the rate at which it is applied, and the MC of the wood.

The second stage of the combustion process includes driving off and burning gas volatiles other than water. The rate at which this takes place also depends on the rate at which heat is applied. Most volatiles ignite and burn at temperatures above 1,000°F. This is where 65 to 80 percent of energy from wood burning is derived.

The third stage of combustion is the actual burning of residual charcoal matter. The surface of the charcoal reaches a glowing temperature and burns as external oxygen is brought into contact with it.

Wood moisture. Fuel moisture does not reduce the total heat produced during combustion. However, its presence in the flue gases, together with the water formed as the hydrogen in the fuel is burned, reduces recoverable heat. Heat is required to raise the water in the wood from an ambient temperature (65°F, for example) to 212°F. In addition, evaporation of the water (212°F) to steam (at 212°F) requires a large heat input (970 Btu per pound). The steam temperature is then raised from 212°F to a flue temperature of about 400°F, and the steam is released through the stack. In total, each pound of steam carries up the flue approximately 1,210 Btu.

Typically, green sapwood (50 percent MC, wet basis) of northern hardwoods contains approximately 1 pound of water for each pound of wood. One pound of dry wood contains approximately 8,600 Btu. Since there is 1/2 pound of dry wood and 1/2 pound of water in each pound of freshly cut wood, the heat value is only 4,300 Btu (8,600/2). So 2 pounds of wet wood would be required to obtain 8,600 available Btu.

Approximately 0.55 pound of water is formed during the combustion process. This causes an additional loss of about 726 Btu. Also, for each 1 pound of wood burned, an additional 690 Btu may be lost through the stack in other hot flue gases (carbon dioxide, nitrogen, and excess air).

Therefore, the net heat value normally recovered from 2 pounds of green sapwood (1 pound wood and 1 pound water) is:

Heat of combustion of 2 pounds of wet wood	8,600
Less	
Heat loss associated with water content	-1,210
Heat loss associated with hydrogen combustion	-726
Heat loss in other flue gases	-690
Net usable heat	5,974

The recoverable heat from 1 pound of wet fuel would be only 2,987 Btu (5,974/2), i.e., about 70 percent of the 4,300 Btu (8,600/2) input.

The recoverable heat value from air-dried wood (20 percent MC wet basis) is significantly larger. Using 1 pound of air-dried wood at 20 percent MC gives 0.8 pound of wood or 6,880 Btu (8,600 x 0.8). Only 1,300 Btu are lost to moisture, water vapor formed, and dry flue gas, leaving a net for evaporation of approximately 5,580 Btu.

Type of wood. For practical purposes, 1 pound of oven-dried wood of any species has the same energy component —approximately 8,600 Btu per pound. However, ignition and burning characteristics and the weight of a given volume of wood can confuse the user of wood fuels as to the efficiency of one wood versus another.

Certain woods have greater concentrations of lignin than others. Some of these include sassafras, wood from fruit trees, white oak, and locusts. These concentrations increase the Btu yield slightly above the normal yield from species with little or no lignin deposits. Also, certain pines have greater resin levels which increases the Btu yield per pound. Resins have a higher Btu yield per unit weight than cellulose fiber. Yet, Btu yield per pound is fairly consistent among the species normally used (Table 1).

The confusion concerning heat yield from different species relates to wood being sold on a unit volume or cord basis rather than on a weight basis. The dimensions of a cord of wood (4 x 4 x 8 feet) produce a volume of 128 cubic feet (ft^3). In reality, a cord contains between 80 and 100 ft^3 of solid wood with approximately 30 to 50 ft^3 taken up in air space. The amount of energy that the maple producer obtains from a cord will depend on the species used, since equal volumes (1 cord) have different densities and/or weights.

A producer would need almost 2 cords of white pine, balsam fir, hemlock, or basswood (12.1 MM Btu/cord) to equal the Btu yield from 1 cord of locust, red oak, white oak, or hard maple (22.5 MM Btu/cord). Table 1 shows the specific gravity (density) and Btu heat yields per cord for typical Northeastern and North Central woods.

Results

This study documents the major cause of wood-fired evaporator efficiency to be related to characteristics of the wood fuel and secondly, to evaporator design. Further, it characterizes expected evaporator efficiency to fall between 35 percent and 50 percent. These findings support research by Huyler and Garrett (1979).

Wood fuel effect

In this study, no attempt was made to define the effect of different wood species used most often—beech, birch, and maple. Lower density hardwoods and softwoods made up 20 percent of the weight of the test fuelwood. Test fuels composed of deteriorated wood were used to represent wood that normally is recovered from sugarbush improvement and used in evaporators.

Wood moisture was identified as the primary wood fuel variable for evaluation. The average MC (wet basis) of wood

Table 1.—Greater heat values of wood and heat equivalents in coal, fuel oil, and natural gas

Species (1 standard cord)[a]	Specific gravity	Available heat of 1 cord wood (Btu)[b]	Anthracite coal (tons)[c]	No. 2 fuel oil (gallons)[d]	Natural gas (100 ft^3)[e]
Shagback hickory	0.72	24,600,000	1.12	251	308
Black locust	.69	24,600,000	1.12	251	307
Rock elm	.63	23,488,000	1.07	240	294
White oak	.68	22,700,000	1.04	232	284
American beech	.64	21,800,000	.99	222	273
Yellow birch	.62	21,300,000	.97	217	286
Sugar maple	.63	21,300,000	.97	217	286
Red oak	.63	21,300,000	.97	217	286
White ash	.60	20,000,000	.91	204	250
Black walnut	.55	19,500,000	.89	198	244
White birch	.55	18,900,000	.86	193	236
Black cherry	.50	18,770,000	.85	191	235
Tamarack (eastern larch)	.53	18,650,000	.85	190	233
Red maple	.54	18,600,000	.84	190	232
Green ash	.56	18,360,000	.83	187	229
Pitch pine	.52	17,970,000	.82	183	225
American sycamore	.49	17,950,000	.82	183	224
Black ash	.49	17,300,000	.79	177	216
American elm	.50	17,200,000	.78	176	215
Silver maple	.47	17,000,000	.77	173	213
Red spruce	.41	13,632,000	.62	139	170
Hemlock	.40	13,500,000	.61	138	169
Black willow	.39	13,206,000	.60	135	165
Red pine	.46	12,765,000	.58	130	160
Aspen (poplar)	.38	12,500,000	.57	128	156
White pine	.35	12,022,000	.55	123	150
Basswood	.37	11,700,000	.53	119	146
Balsam fir	.36	11,282,000	.51	115	141

[a] 1 standard cord = 128 ft^3 of wood and air; 80 ft^3 solid wood; 20% MC; 1 lb of this wood contains approximately 5,580 Btu.
[b] It is assumed that available heat of wood is oven-dry, or calorific value, minus loss due to moisture, minus loss due to water vapor formed, minus loss due to heat carried away in dry chimney gas. Stack temperature 450° F. No excess air. Efficiency of burning unit = 50 to 60 percent.
[c] Contains 28 million Btu per ton, but available heat is only 22 million Btu per ton; 1 lb of coal contains 11,000 available Btu. Coal burned under similar conditions to wood.
[d] 1 gallon contains 140,000 Btu, but is burned at 70 percent efficiency, providing 98,000 available Btu.
[e] 100 ft^3 = 1 therm = 100,000 Btu, but is burned at 80 percent efficiency, providing 80,000 available Btu.

fuels used in the 12 tests ranged from 19.3 to 41.8 percent. The average MC for the three tests run with fuel type 1 was 21.9 percent. The average for wood fuel type 4 was 40.3 (Table 2).

The number of pounds of wet fuel used per hour ranged from 551 to 685 for the four fuel types. Actual dry fuel consumed for the four fuels ranged from 409 to 466 pounds per hour (Table 2).

The average amount of water evaporated per hour from the various woods for the three operators was greatest (1,844.8 pounds) with relatively dry wood (21.9 percent MC) and lowest (1,194.8 pounds) with wet woods (40.3 percent MC) (Table 2).

Wood moisture was critical in reducing evaporator efficiency. For each operator, efficiency dropped significantly when the wood fuel used was changed from a relatively dry to a very wet one (Table 3). For the three operators, the average efficiency was 52.8 percent when wood fuels with an average MC of 21.9 percent were used. As the MC of the wood fuels increased to 40.3 percent, evaporator efficiency dropped to 27.7 percent.

Fuel type 3 was used in the study because producers remove deteriorated wood from their sugarbushes for use in evaporation. It can be concluded from the results of this study that the MC of the deteriorated wood was much more critical in determining evaporator efficiency than the deteriorated state of the wood. On a comparative dry-pound basis, fuel type 3 performed as effectively as the nondeteriorated woods.

Table 2.—Relationship of wood moisture content to wood use and water evaporated per hour

Item	Wood fuel			
	1	2	3	4
Average wood MC (%) wet basis	21.9	26.1	32.6	40.3
Pounds of wood per hour				
Dry	430.6	466.4	447.5	409.4
Wet	551.2	631.5	664.1	685.3
Pounds of water evaporated	1844.8	1630.4	1431.8	1194.8

A word of caution is important concerning this analysis. Efficiency evaluations are computed on pounds of dry fuel consumed. As such, deteriorated wood is evaluated purely on the weight of the remaining tissue, which naturally would be less than an equal volume of solid wood. Stated another way, the deteriorated condition of the wood results in lower specific gravity or weight per unit volume and also in a reduction in some energy chemicals. Its Btu yield per pound is only slightly less than that of oak, pine, or balsa wood. But the number of pounds of wood remaining per unit volume or cord has been reduced by rot. The primary objective was to see if the deteriorated wood produced an efficient flame for effective evaporation. The conclusion is that it did.

Evaluating equipment effect

In addition to the obvious fuel effect of higher MC on evaporator efficiency, an equipment effect was also important. The continual opening of the evaporator doors produced high infusions of cold draft air, which created a buffer of cold air that reduced the coefficient of heat exchange to the underside pan surfaces. Also, the cold air mixed with the hot gases to produce a lower average gas temperature, which further reduced net heat transfer.

Operators of wood-fueled evaporators can control the efficiency of their evaporator through an effective firing method. The best method for firing a solid wood-fueled, open-pan evaporator is to open one fire door at a time, as illustrated in Figure 2. By firing one-half of the burning surface at a time, the operator can maintain an effective fire in the evaporator with minimal door opening time.

Table 3.—Relative efficiencies using solid wood fuels in maple syrup evaporators, in percent

Operator	Evaporator efficiency using:				
	Dry hardwood <25% H_2O	Partially dry hardwood <30% H_2O	Deteriorated wet hardwood <35% H_2O	Green hardwood >35% H_2O	Average efficiency
A	66.3	45.4	38.2	30.4	45.1
B	49.5	43.6	32.5	28.4	38.5
C	42.7	33.2	32.1	24.4	33.1
Average efficiency	52.8	40.7	34.3	27.7	38.9

Table 4 shows the relationship of required fueling time to evaporator efficiency. For the most efficient operator (A), the average time in which one of the fire doors was open was 16.6 minutes per hour. The average efficiency of operator A's evaporator was 45.1 percent. For the next most efficient operator (B), the average fire door opening time was 19.9 minutes per hour, and the average evaporator efficiency was 38.5 percent.

Wood Fuel Economics

The type of wood burned by maple producers has little alternate use except as pulpwood. It consists of stems and tops of cull, small-diameter, rough and rotten, and dead standing timber, and upper stems and tops of sawtimber. It usually represents cleanings from the producer's sugarbush and tops and culls from logging operations and timber stand improvement.

Generally, fuelwood is cut by the maple producer from his woodlot (Acker et al. 1970, Kearl 1970, Morrow 1959). As such, the producer must assign costs to his procurement activities to derive a real cost of the wood fuel. These costs will include:

1. $5 to $10 per cord for standing or down wood resources.
2. $3 to $5 per cord for chainsaw, splitting mall, axe, wedges, and accessories used in cutting and splitting operations.
3. $2 to $3 per cord annual maintenance cost for worn and damaged equipment.
4. $4 to $6 per cord annual operating cost for gloves, gas, plugs, and oil products.
5. $2 to $4 per cord for transportation associated with moving the wood to the sugarhouse.

A purchaser will incur out-of-pocket costs between $20 and $30 for each cord obtained (Frick 1978). If labor is included, the cost would be between $3 and $5 per hour and 3 to 5 hours per cord would be required. In our example, the total price of a cord would be $34. If the producer buys wood from other producers or on the open market in maple-producing regions, he will incur a cost of $60 to $80 per cord for air-dried wood.

The price of $34 to $80 per cord does not necessarily reflect the value of energy received. If the maple producer ignores the effect of wood volume, species differences, and MC on realized net heat yield from wood, he could be paying a much higher price for fuel than he realizes.

Nominal fuel volume

When wood is obtained by the cord in a 4-foot or longer length, one can expect significantly less than the actual cubic-foot measure of the truck body in which it is hauled. Anything that causes cordwood sticks to vary from perfect cylinders, such as limbs, knots, crook, and sweep, will increase the air space in a stacked cord. In general, the smaller, longer, and more crooked the material, the lower the cubic-foot yield and the higher the real energy cost (Tables 5-6).

Fuel type

As noted, 1 pound of oven-dried wood of any species has the same energy component, approximately 8,600 Btu per pound. However, Btu content varies greatly for a given volume of wood such as a cord (Table 1). The variable heat yield relates to specific gravity or weight per unit volume of the wood.

Table 7 relates the effect of specific gravity or wood density to the true cost of energy received from purchased wood fuels. If beech and fir each cost $60 a cord, the real cost of fir becomes $102.60, because 1.7 cords of fir are required to equal the heat yield of 1 cord of beech.

Fuel moisture content

A third factor directly affecting the energy cost of wood fuels is fuel moisture content. Typically, green sapwood of northern hardwoods contains approximately 0.5 to 0.7 of a pound of water for each pound of wood, or is said to have 30 to 40 percent MC measured on a wet basis. As related earlier, maple producers using low moisture fuels (20 to 30 percent) obtained evaporator efficiencies above 50 percent. As MC increased to 40 percent, efficiency dropped to 30 percent.

The primary economic question posed by wet fuels is: how many pounds of water can be evaporated per dollar of fuel input? In the food processing industry, this is expressed as a fuel cost per 1,000 pounds of water removed, and it is the guiding factor in determining an evaporator's economic effectiveness.

A conventional 5 x 16 foot evaporator using seasoned wood of 20 to 30 percent MC (dry basis) can evaporate 208 pounds or 25 gallons of water with about 72 pounds of wood. Seventy-two pounds of wood is .025 of the weight of 1 cord of medium density hardwood at 25 percent moisture (72 lb/2,900 lb = .025).

Table 4.—Relationship of fire door opening time to evaporator efficiency for three commercial operators

Operator	Time fire door open: Fuel type 1	Fuel type 2	Fuel type 3	Fuel type 4	Average	Evaporator efficiency
	Minutes/hour					*Percent*
A	15.9	16.1	13.7	20.9	16.6	45.1
B	16.1	19.1	21.7	22.6	19.9	38.5
C	21.9	29.9	24.9	19.6	24.0	33.1
Average	17.9	21.7	20.1	21.0	20.2	

Table 5.—Solid content[a] of stacked roundwood cord[b], by dimension and type of wood, in ft^3

Wood type	6-inch or less diameter		6- to 12-inch diameter		12-inch diameter	
	4 feet	8 feet	4 feet	8 feet	4 feet	8 feet
Softwood						
Straight	87	84	92	90	98	96
Crooked	75	71	84	79	88	86
Tops and branches	67	60	—	—	—	—
Hardwood						
Straight	79	78	88	85	95	92
Crooked	70	65	78	74	84	81
Tops and branches	58	50	—	—	—	—

[a]Source: USDA Forest Service, Lake States For. Exp. Stn., For. Res. Dig., May 1935.
[b]Stacked cord dimension 4 x 4 x 8 feet.

Table 6.—Cost of obtaining less than 1 cord of wood (80 ft^3) in a purchase agreement

Purchase price (dollars/cord)	Amount of wood paid for	Wood actually received	Conversion value (cords)	Actual cost of wood purchased
	ft^3			*Dollars*
60	80	75	1.07	64.20
60	80	70	1.14	68.40
60	80	65	1.23	73.80
60	80	60	1.33	79.80
60	80	55	1.45	87.00

Table 7.—Relationship of wood density to cost per Btu when buying on volume basis

Species class	Specific gravity	Purchase price	Conversion value (cords)	Real cost for equivalent heat value[b]
		Dollars/cord[a]		*Dollars*
Red and white oak, hard maple, pecan, beech	0.60—0.65	60.00	1.00	60.00
Soft maple, cherry	.50—.55	60.00	1.20	72.00
Cottonwood, aspen	.40—.45	60.00	1.50	90.00
Pines, true firs, spruce	.35—.40	60.00	1.71	102.60

[a] Assumes 80 ft^3 of solid wood.
[b] Assumes oak and maple heat yield as base or equal 100 percent.

For the operators studied, $1.25 worth of wood (at $50 per cord) would be required to produce 1 gallon of syrup (.025 x 50). At $70, $100, and $130 per cord, the cost of wood fuel per gallon of syrup produced would be $1.75, $2.50 and $3.25, respectively. By contrast, 3.5 gallons of oil are required to produce the same gallon of syrup. Thus, at $0.50 per gallon of oil, $1.75 worth of oil would be needed to yield 1 gallon of syrup (3.5 x 50). At $0.90, $1.20, and $1.50 per gallon, the cost of oil per gallon of syrup produced would be $3.15, $4.20 and $5.25, respectively.

Even at $90 per cord, wood will be much more competitive than oil if the price per gallon of oil ranges from $0.90 to $1.20. At $90 per cord versus $1.20 per gallon of oil, an operator using wood would achieve a fuel cost advantage of $1.95 for each gallon of syrup produced.

Summary

The operator who chooses wood over oil or gas must deal with several factors that contribute to the efficiency and economics of using wood in a conventional evaporator. First, he must remember that when buying on a volume basis, such as cord measure, less of a denser wood is required for the same heat value. Second, if the operator keeps his evaporator in good repair and uses good firing techniques, he still must be concerned with the MC of the wood that he is using. For any given wood, the evaporator efficiency can drop from a level of about 50 percent to less than 30 percent when the MC of wood is increased from 20 to 40 percent on a wet basis. His fuel cost will increase significantly, diminishing the cost advantage of wood over oil or gas.

The use of dry dense hardwoods with proper operating procedures can ensure significant reductions in fuel costs over oil and gas. Further, wood is expected to maintain its economic advantage over alternate fuels such as oil and gas over an investment period of 5 to 10 years.

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A study of commercial, wood-fired evaporators revealed that normal expected thermal efficiencies are between 35 to 50 percent. The moisture content and quality of wood fuels used and the design and method of firing the evaporator are critical in determining evaporator efficiency and the economic implications of using wood.

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