AN ABSTRACT OF THE THESIS OF

KEITH MASTERS for the degree of Master of Science

in Forest Products presented on May 23, 1979

Title: Steam-Jet Heat Recovery in a Lumber Dry Kiln

Abstract approved: Signature redacted for privacy.

Robert L. Krahmer

Lumber drying accounts for about 70 percent of sawmill energy requirements. Significant recovery of energy used to dry lumber would result in significant energy recovery for the mill. This is desirable because of today's high cost of energy. The objective of this study was to recover some of the energy required to dry Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco] with a superheated steam schedule by compressing kiln exhaust in a steam-jet thermocompressor and condensing this compressed steam in the kiln steam heating coils. Once the steam recovery was determined, an economic sensitivity analysis was performed.

The recovery system resulted in approximately 20 percent recovery of the steam required to dry the charge of lumber. The economic sensitivity analysis showed that the recovery system is sensitive to the size of the kiln on which it is used, and steam value factors

which include the fuel cost to produce steam, steam recovery, and the steam flow requirement of the kiln.

Steam-Jet Heat Recovery in a Lumber Dry Kiln

by

Keith R. W. Masters

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed May 23, 1979

Commencement June 1980

APPROVED:

Signature redacted for privacy.

Professor of Forest Products
in charge of major

Signature redacted for privacy.

Head of Department of Forest Products

Signature redacted for privacy.

Dean of Graduate School

Date thesis is presented May 23, 1979

Typed by Linda S. Crooks for Keith R. W. Masters

COMMITTEE MEMBERS

Signature redacted for privacy.

Robert L. Krahmer (Major Professor)

Signature redacted for privacy.

Earl Smith (Graduate Representative)

Signature redacted for privacy.

Charles Kozlik

Signature redacted for privacy.

~~Joseph~~ Stevens
Joe B.

ACKNOWLEDGEMENTS

At this time I wish to thank Charles Kozlik for his assistance in all phases of this project and Robert Krahmer for his critical review of the thesis paper.

A very special thanks to the late Stanley Corder, the project leader at the start of this study, whose assistance and support were invaluable to the successful completion of this project.

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INTRODUCTION

The United States of America is in an energy crisis, and all industries that rely on energy are affected. Between October 1, 1973 and April 1, 1979 the price of crude oil has increased from $2.80/barrel to $14.54/barrel (U.S. News, 1979). The supply of petroleum products has also been affected. The recent political revolution in Iran caused a supply crunch in the world petroleum market. The combined effect of increased prices and decreased supply has caused uncertainty with respect to use of petroleum products.

The increased cost of energy encourages the development of energy reducing systems. In a sawmill operation, drying accounts for 70 percent of the energy requirement to produce lumber (Szymani, 1979). If the energy requirement for drying lumber is significantly reduced, the energy requirement for the sawmill will be significantly reduced.

Comstock (1975) reports that a significant portion of the energy used to dry lumber is the heat of vaporization needed to evaporate moisture from the lumber. Once the moisture has been evaporated, it is typically exhausted to the atmosphere and the heat of vaporization is lost. If the heat of vaporization can be recovered, energy can be saved.

One method of drying is in a superheated steam environment. In this drying process, superheated steam with the absence of air is the drying medium used to dry the lumber, and after it is saturated with moisture, it is exhausted to the atmosphere. If the exhausted steam is recovered and condensed, the heat of vaporization is recovered. Exhaust steam can be recovered by piping it into the kiln steam coils. However, the pressure of the exhaust steam must be increased to set up a temperature gradient in the steam coils. There are two methods available for increasing exhaust steam pressure; mechanical and steam-jet compressors. Miller (1977) has looked at the feasibility of mechanical compression and suggests that it is a possible recovery method. No published information was found on the feasibility of utilizing a steam-jet compressor for a lumber dry kiln evaporation system which is the objective of this study.

OBJECTIVE

The objective of this study was to use a steam-jet heat recovery device in conjunction with a superheated steam lumber dry kiln so that part of the moisture evaporated from the lumber was condensed and the resulting energy recovered. To accomplish this, the technical and economic feasibility of this recovery system was investigated, and a test system was constructed to determine operational performance and define operational problems associated with the system.

LITERATURE REVIEW

The literature review for this study consisted of three phases. The first phase was a review of lumber drying systems with emphasis on superheated steam drying systems. The second phase was a review of compressor recovery systems with emphasis on recovery systems using a steam-jet thermocompressor. The third phase was a review of methods for economic analysis with emphasis on those methods used in this study.

Phase One

Lumber drying systems. The method by which lumber dries is known and is summarized in a number of manuals. Reference to manuals by Rasmussen (1961), and Hildebrand (1970), and papers by Kozlik (1967, 1973), Ladell (1953), and Mathewson (1954) were used to develop this discussion of lumber drying.

The lumber dry kiln is typically a physical structure equipped with heat, humidification, circulation, and ventilation capacity to control the lumber drying process. The kiln can be heated with steam coils, direct-fire heaters, or some other heat source; humidification is typically accomplished through moisture evaporating from the lumber and with the use of a steam spray line; circulation is provided by a fan system; and ventilation is accomplished through vents and leaks in the kiln structure. In conventional drying, air is brought into the kiln through a vent, heated by the coils, humidified by the spray line, circulated through the charge of lumber, and exhausted through another vent. In superheated steam drying, no air enters the kiln. Steam above saturation temperature has the ability to absorb moisture so it acts as a drying medium, and it is steam that is circulated through the charge and exhausted.

To control the drying process, wet and dry bulb temperatures are used to monitor the drying environment. The dry bulb temperature and the wet bulb depression define the equilibrium moisture content (EMC) and the relative humidity (RH) of the drying environment. The EMC is the moisture content the lumber would assume if it were in equilibrium with its environment, and RH is the ratio of the partial vapor pressure of the air to the saturated vapor pressure at a given temperature. Both EMC and RH are expressed mathematically as a percentage. It is the EMC and the RH of the drying medium which set up forces responsible for moisture movement through wood and lumber drying.

Other factors affecting moisture removal are the temperature in the kiln and the circulation rate of the drying medium. As temperature increases, the kinetic energy of the water molecules increases and moisture movement increases. As circulation increases, the moisture evaporated from the lumber is removed faster and drying rate increases.

To dry lumber in a superheated steam system at atmospheric pressure, the wet bulb temperature will be 212°F and the dry bulb temperature must be above 212°F. Psychrometric charts define EMC and RH of a drying environment for a given dry bulb temperature and wet bulb depression. A psychrometric chart for superheated steam conditions was used to find the associated EMC and RH (Table 1) as developed from charts published by Hildebrand (1970), Kauman (1956), and Mathewson (1954).

TABLE 1. PSYCHROMETRIC CHART FOR SUPERHEATED STEAM

Temperature Dry Bulb °F	Temperature Wet Bulb °F	EMC %	Relative Humidity %
212	212	19.5	100
215	212	15.5	94
220	212	11.3	85
225	212	8.7	77
230	212	6.9	70
235	212	5.8	65

If the moisture content of the lumber is greater than the EMC in the kiln, a moisture content gradient is set up between the interior of a piece of lumber and its surface. A steep gradient may cause degrade and a flat gradient retards drying. Therefore, an optimum gradient must be found. Since susceptibility to degrade is species dependent, the moisture content gradient should be adjusted for each species. This can be accomplished by varying the EMC in the kiln with the wet and dry bulb temperatures in conventional drying and with the dry bulb temperature in superheated steam drying.

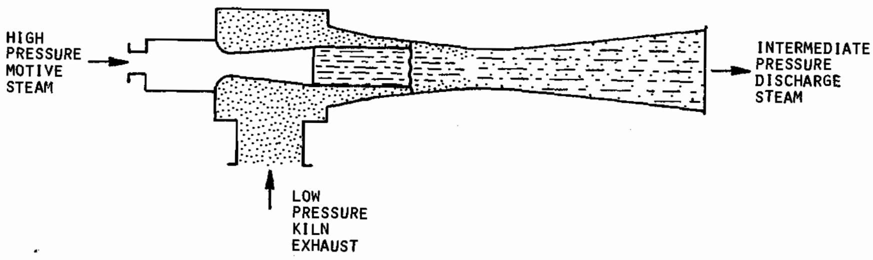
Optimum kiln performance is obtained when drying time and degrade are minimized. Since drying time is minimized as EMC is minimized, high kiln temperatures are desirable. However, degrade can be expected to increase with lower initial EMC conditions in the kiln.

Phase Two

Compressor recovery system. If a superheated steam environment is established in the kiln, the potential for utilizing the latent heat of vaporization in the exhausted steam is created. Miller (1977) reports that mechanical compression of dry kiln steam exhaust and subsequent condensation in the steam coils is a practical heat recovery method. His system required a 614 HP electric motor to compress the steam. The large electric motor required electric power to operate; this may be undesirable. The alternative to mechanical compression is steam-jet compression. Bruns (1951) reports that steam-jet compression is feasible for a sea water purification system. Blatchley and Stratton (1964) report that steam-jet thermocompressors perform well in dryer drainage systems in paper manufacture. Both evaporation systems use steam-jet thermocompressors to compress moisture evaporating from the system and recover the latent heat of vaporization by condensing the compressed vapor in coils used to heat the system. The principle has not been applied to lumber drying systems, but it could be because a steam drying system for lumber is similar to a sea water purification system or a dryer drainage system in that all three exhaust steam from the drying system.

Dodge (1944) explains the theoretical operating principles of a steam-jet thermocompressor, and Figure 1 shows a schematic of a steam-jet. The high pressure, motive steam is expanded in nozzle "A" to a high velocity and exits into chamber "C." The momentum of the motive steam pulls the kiln exhaust through "B" and mixes or "entrains" it. A mixture of steam at "C" is diffused through nozzle "D" to a discharge pressure at "E" which is between the high pressure, motive steam at "A" and the atmospheric pressure, kiln exhaust at "B."

Figure 1. Steam-jet thermocompressor schematic diagram



Steam-jet efficiency is defined as the ratio of steam entrained to the total flow of steam through the steam-jet. Entrainment ratios are measures of performance and are used to determine compressor efficiencies. The entrainment ratio (Equation 1) is the ratio of steam entrained to the motive steam used and is dependent on isentropic expansion in nozzle "A," isentropic mixing in chamber "C," and isentropic compression in diffuser "D" and the efficiencies of expansion, mixing, and compression.

$$\frac{M_2}{M_1} = \frac{(H_1 - H_2) \quad e_1 e_2 e_3 \quad - \quad (H_4 - H_3)}{H_4 - H_3} \qquad \text{Equation 1}$$

M_1 = mass of motive steam, "A" Figure 1 (lbs)

M_2 = mass of entrained steam, "B" Figure 1 (lbs)

H_1 = enthalpy of motive steam, "A" Figure 1 (BTU/lb)

H_2 = enthalpy of motive steam after reversible, adiabatic expansion in nozzle "A" to the pressure in chamber "C" (BTU/lb)

H_3 = enthalpy of mixed steam at the start of compression in diffuser "D" (BTU/lb)

H_4 = enthalpy of compressed steam after reversible, adiabatic compression to the discharge pressure at "E" (BTU/lb)

e_1 = efficiency of nozzle "A" (-)

e_2 = efficiency of diffuser "D" (-)

e_3 = efficiency of mixing in chamber "C" (-)

Bruns (1951) reports that e_1 ranges between 0.85 and 0.95, e_2 is about 0.80, and e_3 ranges between 0.50 and 0.65. Equation 1 requires a trial and error solution because H_3 is unknown and depends on M_1 and M_2, however, a simplified solution is available. Ametek (1976) developed a set of performance curves (Figure 2) that correlate the entrainment ratio, M_2/M_1, to the discharge pressure from the steam-jet.

Efficiency is found from the entrainment ratio by the following method:

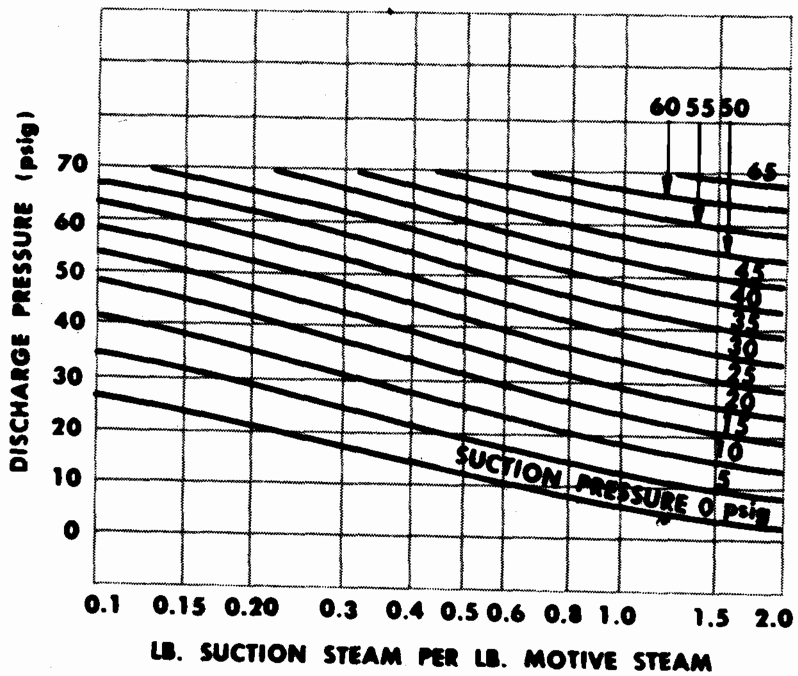
1. Let "x" equal the amount of motive steam, M_1, used (lb)
2. Pick the desired discharge pressure, P_d (Figure 2)(psig)
3. Find the associated Entrainment ratio, E_r (Figure 2)
4. The amount of entrained steam equals E_r times "x" (lb) and "x" equals 1
5. Total flow equals "x" + $E_r \cdot$"x" or $1 + E_r$ (lb)
6. Efficiency equals $E_r/(1 + E_r) \cdot 100$ (%)

Optimum thermocompressor performance depends on three parameters; the compression ratio, the discharge pressure, and the total flow rate through the thermocompressor (Ametek, 1976).

The compression ratio is the ratio of discharge pressure to entrainment pressure on the absolute scale. When the compression ratio exceeds 2:1, the steam exceeds the velocity of sound in the diffuser (Blatchley and Stratton, 1964) and shock waves can develop which produce pressure losses (Shames, 1962). Performance may be affected when the compression ratio exceeds 1.7:1 (Stratton, 1978). Since the pressure of the entrained steam is atmospheric for this study, the maximum discharge pressure is 10 psig.

The discharge pressure is correlated to entrainment ratio. Lower discharge pressures correspond to higher entrainment ratios

Figure 2. Performance chart for a steam-jet thermocompressor.



(Figure 2). Thermocompressor efficiency increases with decreased discharge pressures.

The total flow rate through the compressor is used to size the compressor to the system (Figure 3). Stratton (1978) reports that larger compressors are generally more efficient than smaller ones.

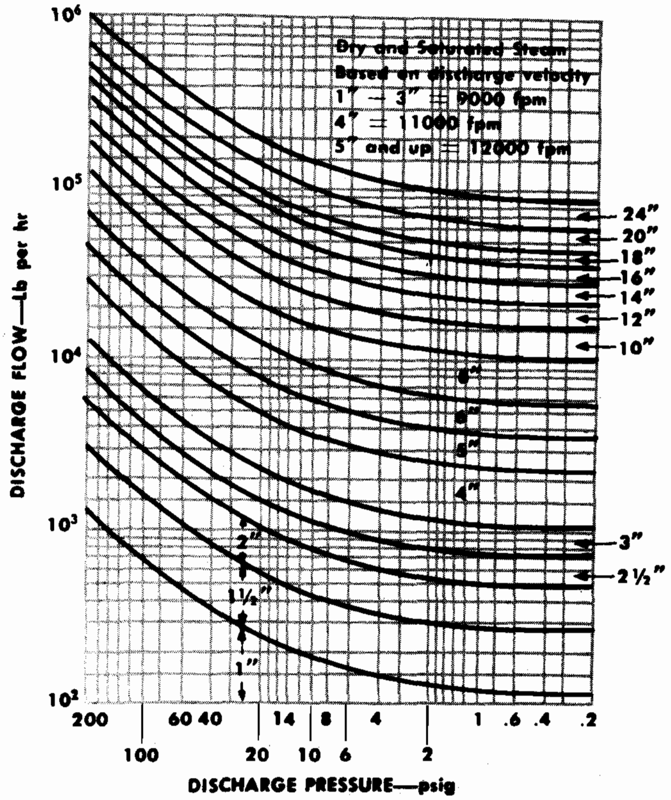
Optimum performance of the heat recovery system involves the interaction of the steam-jet thermocompressor with the dry kiln. An optimum must be found since efficient thermocompressor operation results in inefficient kiln operation.

Expected steam-jet efficiency depends on the discharge pressure. Since the steam discharged from the steam-jet is condensed in the kiln steam coils, it is advantageous to have the highest possible steam temperature for efficient steam coil performance. However, high steam temperature requires high steam pressure (Combustion Engineering, 1967) which reduces thermocompressor performance (Figure 2). Optimum recovery system performance occurs when the thermocompressor is operated at the lowest discharge pressure required to maintain desired kiln temperatures.

Phase Three

Economics. There are a number of methods available for making economic comparisons. Payback, net present value (NPV), internal rate of return (IRR), and equivalent uniform annual worth (EUAW) are some of the more common methods used by decision makers (Riggs, 1974). Each has its own advantages and disadvantages for use with

Figure 3. Size chart for a steam-jet thermocompressor.



various types of analysis. Decision makers typically use a method which they think best suits the analysis; this frequently depends on the relative ease by which results may be communicated (Riggs, 1974). Since payback and NPV methods are commonly used by the forest products industry (Harpole, 1978; Schutte, 1978; Try, 1978; and Rice, 1979), they will be used for this study so that results are easily communicated.

The payback method determines the number of years it takes to recover the initial investment if the time value of money is ignored. It is equal to the initial outlay divided by the net, after-tax annual savings.

The NPV method finds the net of cash inflows minus outflows. All cash flows are discounted to a present value at an appropriate interest rate for the economic life of the project. It is equal to the present value of the discounted cash flows minus the initial outlay.

Since economic data must be estimated into the future, uncertainty with respect to future cash flows becomes a consideration. Sensitivity analysis is therefore used to analyze the effect on NPV of variability in the economic factors which affect NPV (Riggs, 1974).

EXPERIMENTAL PROCEDURES

The experimental procedure for this study involved four phases. Phase One included (a) calculating the theoretical heat requirement for the experimental kiln at the Oregon State University, Forest Research Laboratory using a conventional schedule and a superheated steam schedule, (b) sizing the steam-jet thermocompressor to the steam requirement for the superheated steam schedule, and (c) determining the theoretical recovery for the steam-jet heat recovery system used with the superheated steam schedule. Phase Two included the design and construction of a system for steam recovery and data collection to determine (a) actual performance and define operational problems of the recovery system, and (b) the heat loss from the kiln. Phase Three included the experimental sample preparation and drying procedure used for this study. Phase Four included the economic analysis used for this study.

Phase One

Theoretical heat requirements. Theoretical heat requirements were determined for the experimental kiln using a conventional and a superheated steam schedule. The heat requirements were calculated for a full charge, 107.3 ft^3, of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] dimension lumber, 2 by 6-inch nominal size, dried from an initial average moisture content of 50 percent to a final average moisture content of 15 percent. The steam-jet was sized to the steam requirement for the superheated steam schedule. The theoretical recovery was determined for the steam-jet heat recovery system used with the superheated steam schedule. The net heat used by a superheated steam dry kiln with heat recovery was compared to the heat used in a conventional drying process and a superheated steam drying process without a heat recovery system.

The method used for determining the energy requirements for drying is described by Shottafer and Shuler (1974). By this method the total heat requirement, H_t, is equal to the sum of six individual heat requirements. This relationship is described by Equation 2, and supporting information is found in Appendix 1.

$$H_t = H_1 + H_2 + H_3 + H_4 + H_5 + H_6 \qquad \text{Equation 2}$$

H_t = total heat requirement (BTU)

H_1 = heat used to raise the temperature of the wood substance to kiln operating temperature (BTU)

H_2 = heat required to overcome hygroscopic forces (BTU)

H_3 = heat required to raise the temperature of the water remaining in the wood at the end of drying (BTU)

H_4 = heat required to raise the temperature of and evaporate the water removed from the wood (BTU)

H_5 = heat required to raise the temperature and humidify the incoming vent air (BTU)

H_6 = heat used to replace the heat loss through the kiln walls (BTU)

Steam-jet thermocompressors are sized according to the steam flow rate through them (Figure 3). The steam requirement for the kiln equals the total heat requirement, H_t, divided by the heat of vaporization, H_{fg}, of water. At 10 psig the heat of vaporization equals 952 BTU/lb. The steam requirement equals $H_t/952$. Figure 3 relates discharge pressure and discharge flow to thermocompressor size.

The theoretical recovery for the steam-jet heat recovery system is the calculated amount of steam recovered divided by the total steam requirement for the kiln expressed in percent. The amount of steam recovered depends on the entrainment ratio (Figure 2), and the total steam requirement, S_t, for the kiln equals the total steam flow through the steam-jet thermocompressor. For theoretical recovery calculation procedure, the method is very similar to the thermocompressor efficiency calculation procedure described in the Literature Review, and it is shown below.

Recovery calculation procedure

1. let "x" equal the amount of motive steam used by the steam-jet, M_1; "x" = 1 when entrainment ratio is used
2. determine the range of expected discharge pressures, P_d
3. find the associated entrainment ratios, E_r, Figure 2

4. calculate the amount of entrained, recovered steam; recovered steam = "x" times E_r, $(x \cdot E_r) = E_r$ when "x" = 1
5. determine the total flow through the steam-jet when "x" = 1, total flow = $E_r + 1$
6. determine recovery, R, $R = E_r/(E_r + 1) \cdot 100$ (%)

Phase Two

Steam recovery and data collection system. A system was designed using a steam-jet thermocompressor to recover the steam typically exhausted to the atmosphere from the experimental dry kiln and to collect data so that operational performance of the system could be determined. The mass balance concept was used to develop the data collection system (Van Wylan, 1976).

The recovery system captured the steam typically exhausted to the atmosphere through the kiln vent and piped it to the steam-jet thermocompressor (Figure 8) where motive boiler steam at 60 psig was used to entrain and compress the steam from the kiln exhaust. The compressed steam was then piped to the steam coils, trapped and condensate measured. Heat is recovered because the steam from the kiln exhaust is condensed in the kiln coils, releasing heat to the kiln.

Operational performance of the heat recovery system is defined by steam and energy recovery (Table 4). Steam recovery is the amount of steam recovered divided by the amount of steam used by the kiln.

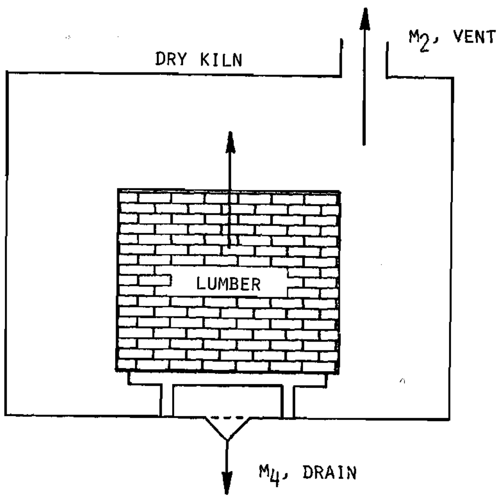
Energy recovery is the energy in the recovered steam liberated to the kiln divided by the total energy used by the kiln.

The data collection system used to determine the operational performance of the heat recovery system was based on the mass balance concept. The mass balance concept states that the mass into a system equals the mass out of a system (Equation 3).

$$\text{Mass}_{in} = \text{Mass}_{out} \qquad \text{Equation 3}$$

For the kiln structure illustrated in Figure 4, steam enters and leaves the kiln. In this case the mass in equals the moisture evaporating from the lumber*, M_7 (Figure 7), and the mass out equals the sum of the steam leaving the kiln through the vent, M_2, and through the drain, M_4.

Figure 4. Dry kiln schematic diagram



$$\text{Mass}_{in} = \text{Mass}_{out}$$

$$M_7 = M_2 + M_4$$

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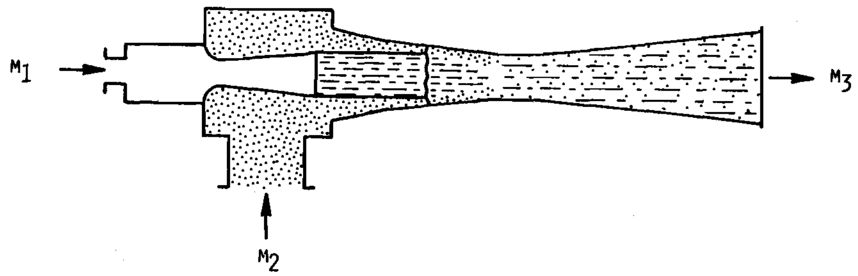
*Simpson EKS plastic stickers were used so that mass loss was moisture loss from the charge and not the stickers.

For the thermocompressor (Figure 5), steam also enters and leaves. The mass in equals the sum of the motive, M_1, and entrained, M_2, steam, and the mass out equals the mass of discharge, M_3, steam from the thermocompressor.

Figure 5. Steam-jet thermocompressor schematic diagram.



$$Mass_{in} = Mass_{out}$$

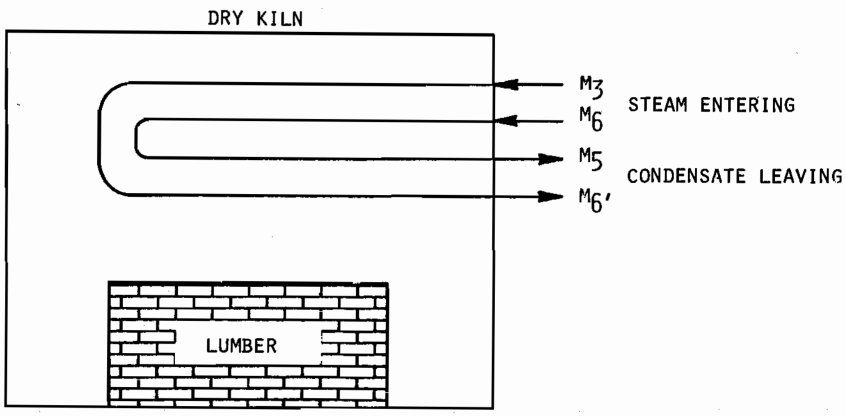
$$M_1 + M_2 = M_3$$

For the steam coils (Figure 6), steam enters but condensate leaves the coils. The steam coils consist of a primary and an auxiliary component.* The mass in equals the sum of the steam entering, M_3 and M_6, and the mass out equals the sum of the condensate leaving, M_5 and $M_{6'}$.

The data collection system shown in Figure 7 and Figure 10 using the equipment summarized in Table 3 was composed of the dry

*Reason for primary and auxiliary heat discussed in Appendix 2.

Figure 6. Steam coil schematic diagram.



$$\text{Mass}_{in} = \text{Mass}_{out}$$

$$M_3 + M_6 = M_5 + M_{6'}$$

kiln, the steam-jet thermocompressor, and the steam coils. Figure 7 schematically illustrates the data collection points and the heat recovery system, and Table 2 is the key for Figure 7. Energy recovery was determined from the mass data collected and the estimated heat of vaporization, H_{fg}, of the steam condensing in the coils. The steam condenses in the coils at the pressure entering the coils (Babcock and Wilcox, 1975). Steam traps allow condensate to pass but not steam. Once the condensate passes the trap, it comes to equilibrium with its new environment (Van Wylen, 1976). Since the pressure is lower past the trap, the steam will flash and the temperature will drop as the steam passes the trap (Babcock and Wilcox, 1975). To determine the heat used by the kiln, pressure and temperature of the steam were monitored entering the coils ("3" and "6",

Figure 7) to estimate the enthalpy of the steam. The heat liberated to the kiln is the heat of vaporization of the steam condensing in the coils plus any superheat attributed to the steam (Babcock and Wilcox, 1975). The temperature of the condensate was monitored as it left the kiln (T_5 and $T_{6'}$, Figure 7) to insure condensation had occurred. If condensation is complete, the temperature at points T_5 and $T_{6'}$ should be approximately equal (Figure 7), and will be lower than the temperature at points T_3 and T_6 (Van Wylan, 1976, and Babcock and Wilcox, 1975).

Operational performance was determined from the data collection system by measuring the mass of condensate at points M_4, M_5, $M_{6'}$, and weight loss from the charge at point M_7; temperature at points T_1, T_2, T_3, T_5, T_6, and $T_{6'}$; the pressure at points P_1, P_2, P_3, and $P_{6'}$, and with the performance relationships summarized in Table 3. In addition to determining thermocompressor operational performance, the data collection system was used to determine the heat loss through the kiln walls.

Data were monitored periodically, every two to four hours, to determine operational performance of the heat recovery system and the steam-jet thermocompressor according to the measures represented in Table 4. Because fan operation causes error in measurement at points M_7 and P_2, the fans were shut off prior to data recording. Data were monitored at points M_4, M_5, $M_{6'}$, M_7, P_1, P_2, P_3, and P_6 periodically by visual observation and manually recorded. The

Esterline Angus pyrometer was used to continuously record all of the temperatures and the pressure at points P_1, P_3, and P_6.

The general heat transfer equation, shown below by Equation 4, was used to determine the heat loss through the kiln walls (Babcock and Wilcox, 1975). Data were collected for four separate, one hour periods of kiln operation without lumber in the kiln. The mass of condensate collected at points M_5 and M_6', the pressure of the steam entering the steam coils, the temperature inside the kiln, T_d and T_w, and the temperature outside the kiln were recorded for each one hour period. Prior to data collection, the kiln was brought to and held at operating temperature for 15 minutes. The steam spray line was used to bring the wet bulb up to 212°F so that actual operating conditions were simulated as closely as possible.

$$Q = UAdTt \qquad \text{Equation 4}$$

Q = heat transferred (BTU)

A = heat transfer surface area (ft^2)

dT = temperature difference between the inside and the outside of kiln (°F)

U = overall heat transfer coefficient ($BTU/hr\text{-}°F\text{-}ft^2$)

Three modifications were made to the kiln for this study; addition of steam coils, installation of vapor seals, and installation of the steam recovery system.

Figure 7. Data collection system schematic.

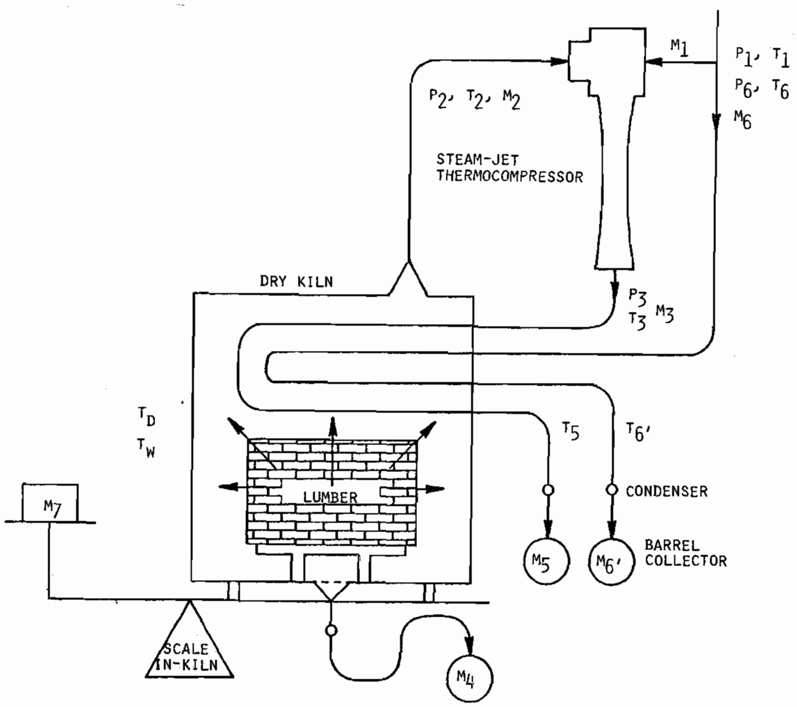


TABLE 2. KEY FOR FIGURE 7: DATA COLLECTION SYSTEM SCHEMATIC

Data Point	Description	Measurement and[1] Equipment Used
1	motive steam used to compress exhaust steam pressure and temperature measured at same place as "6"	M - Determined P - Transducer Gauge (psig) T - Thermocouple
2	entrained vapor pressure in inches of water pressure same as "4"	M - Determined P - Water Manometer T - Thermocouple
3	discharged steam from steam-jet used as primary kiln heat	M - Determined P - Transducer Gauge (psig) T - Thermocouple
4	condensate collected at drain pressure in inches of water pressure same as "2"	M - scale P - Water Manometer T - Dry bulb sensor
5	condensate discharged from primary steam coil	M - Scale T - Thermocouple
6	steam used as auxiliary heat pressure and temperature measured at same place as "1"	M - Determined P - Transducer Gauge (psig) T - Thermocouple
6'	condensate discharged from auxiliary heat coil	M - Scale T - Thermocouple
7	moisture loss from charge	M - Scale T - Dry bulb, T_d Wet bulb, T_w

[1]M = Mass (lb); P = Pressure (psig) or (inches water); T = Temperature (°F)

TABLE 3. DATA COLLECTION EQUIPMENT USED FOR THIS STUDY

Item	Quantity Used	Manufacturer or Type	Range	Precision (divisions)
thermocouples	5	iron-constantan	0 - 600°F	3°F
pressure transducer	1	BLH electronics	0 - 50 psia	1/3 psia
pressure transducer	1	BLH electronics	0 - 200 psia	1 psia
pressure gauge	1	Duragauge	0 - 15 psig	3 psig
pressure gauge	1	Duragauge	0 - 100 psig	1 psig
water manometer	1	Vehling	-5 to +5 inches water	1/10 inch water
scale	1	Fairbanks Morse	0 - 1000 lbs	1/2 lb
scale	1	Fairbanks Morse	0 - 500 lbs	1/4 lb
scale	1	Fairbanks Morse	0 - 200 lbs	1/10 lb
scale	1	Fairbanks Morse	0 - 9800 lbs	1 lb
pyrometer	1	Esterline Angus	24 channel	not applicable

TABLE 4. SUMMARY OF HEAT RECOVERY SYSTEM PERFORMANCE INFORMATION

Performance Measure	Theoretical Formula	Measurable Formula
Steam Recovery	$M_2/(M_3 + M_6)$	$(M_7 - M_4)/(M_5 + M_{6'})$
Heat Recovery	H_r/H_t	$\dfrac{(M_7 - M_4) \cdot H_{fg3}}{(M_5 \cdot H_{fg3}) + (M_{6'} \cdot H_{fg6})}$
Entrainment Ratio	M_2/M_1	$(M_7 - M_4)/(M_5 + M_4 - M_7)$

Calculations shown in Appendix 2 indicated that the existing steam coil capacity was insufficient to transfer necessary heat to the kiln for this study. Therefore, additional steam coil was added. Due to space constraints in the plenum chamber, coil addition was limited to twice the existing length, but the heat transfer capacity of the steam coils was still insufficient to maintain desired kiln temperatures (Appendix 2). To rectify this problem, 16 lineal feet of coil on each side of the kiln was supplied with high pressure, 60 psig steam as an auxiliary heat source. The primary steam coils were connected to the steam-jet and supplied with 10 psig steam and were operated during the entire drying run. The auxiliary steam coils were connected to a pneumatic valve operated by a controller sensing the dry bulb temperature in the kiln to maintain desired dry bulb temperatures.

The mass balance analysis used for data collection required that no vapor leak in or out of the kiln. The conventional vents were sealed with plywood and silicon sealant, and the door was sealed with neoprene weatherstripping material. The kiln was able to hold a positive pressure of five inches of water with these seals before a leak was detected around the door frame.

The steam recovery system included the steam-jet thermocompressor, two 55 gallon barrels, one ten gallon bucket, three condensers, and pipe valves, fittings, etc. as needed to construct the system. One vent was fitted with a funnel (eight inches to two inches) to exhaust steam from the kiln. This atmospheric pressure steam was piped through a two-inch, schedule 40, black pipe to the steam-jet thermocompressor and compressed with the 60 psig, motive steam piped to the steam-jet thermocompressor high pressure inlet. The discharge from the steam-jet at 10 psig was piped to the steam coils, trapped, and the condensate from the coils was piped through a condenser to prevent flashing. Upon leaving the condenser, the cool condensate was collected in a barrel and weighed on a scale. The auxiliary steam at 60 psig was piped through the pneumatic valve into the auxiliary steam coils, trapped, and the hot condensate was cooled in a condenser, collected in a barrel, and weighed on a scale.

Figure 4 shows steam exhausted through a drain in the kiln floor. A condenser was attached to this drain, and the condensate was collected in a ten gallon bucket. Between the condenser and the bucket, a water manometer was constructed out of plastic tubing (Figure 9). The water height was varied to control pressure in the kiln (P_2, Figure 7). Pressure in the kiln was monitored with a water manometer at P_2 attached to the static pressure jack adjacent to the kiln exhaust. The system was completed by installing thermocouples, pressure transducers, and pressure gauges according to Figure 7.

Phase Three

Sample preparation. Mill-run, Douglas-fir dimension lumber, 2 by 6-inch nominal size, was selected for this study because it is a major timber species in the Pacific Northwest and is commercially dried at temperatures above 212°F. Prior to drying, each board was surfaced to 1.75 inches, cut to a maximum length of 97 inches, weighed, numbered, the heartwood to sapwood ratio estimated, and the length measured. Each board was weighed after drying, final moisture content was measured with a Delmhorst resistance meter (model RC - 1, with one-inch insulated electrodes, model 26E), and degrade was visually estimated.

One moisture content sample was cut from each of ten boards. The sample was sawn one inch along the grain, at least 15 inches from the end, and contained clear wood. The current weight, ovendry weight, green volume, sample width, and number of rings per inch were measured from each sample. The dry basis moisture content and the dry mass-green volume specific gravity were determined from the measurements. The board thickness, average length, average width, and number of boards per charge were used to determine the size of the charge in cubic feet (ft^3). The final average moisture

Figure 8. Steam-jet thermocompressor, showing discharge pressure, P_3, transducer and gauge, discharge temperature, T_3, thermocouple, and recovered temperature, T_2, thermocouple; 2-inch schedule 40 steam line from kiln vent to steam-jet.

Figure 9. Condenser at kiln drain, M_4, and water manometer.

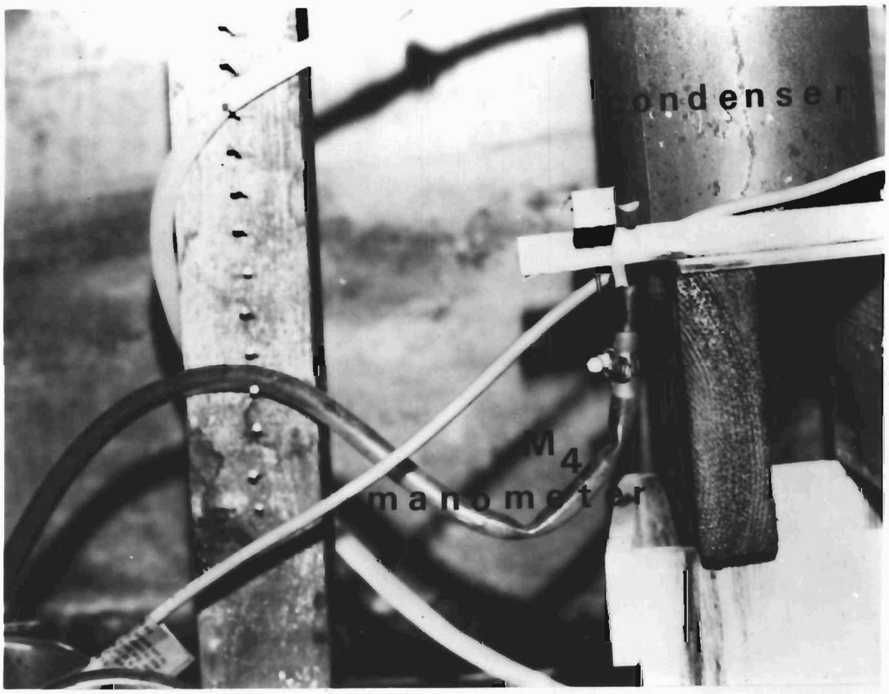
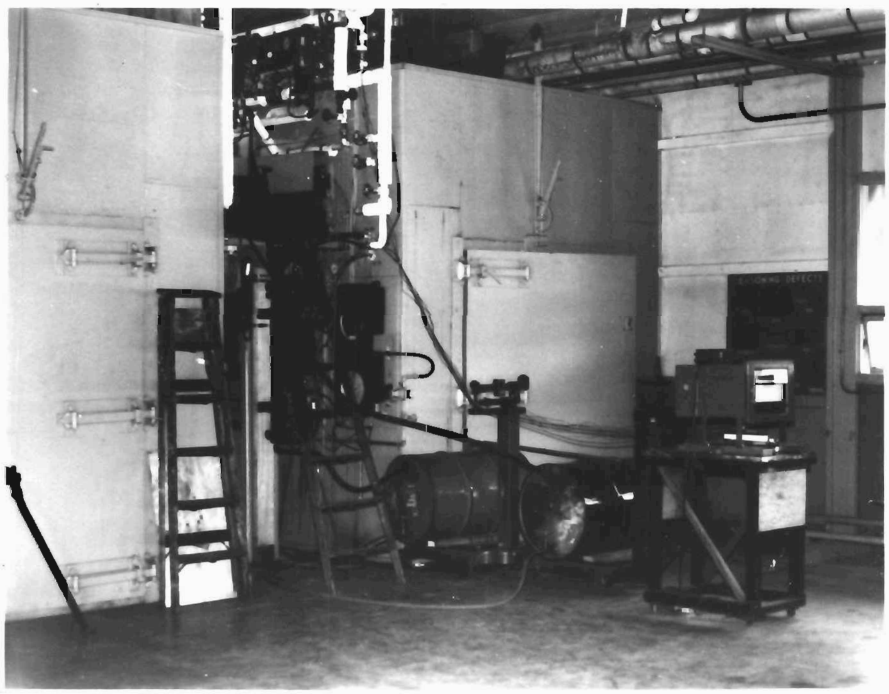


Figure 10. Data collection system showing barrel collectors, esterline angus, and wires for pressure and temperature data to esterline angus.



content and the final weight of the charge were used with the dry basis moisture content equation and the weight of the charge, M_7, during the drying run to estimate the average moisture content of the charge at any time during the drying run. The heartwood to sapwood ratio and the number of rings per inch were measured for general information, and Table 5 represents the drying schedule used.

TABLE 5. SUPERHEATED STEAM DRYING SCHEDULE FOR DOUGLAS-FIR.

Time Period (hours)	Process	Dry Bulb (°F)	Wet Bulb (°F)	EMC (%)
0 - 4	warm up	0 - 225	0 - 212	-
4 - 38	drying	225 - 230	212	9 - 7
38 - 42	equalize	212 - 220	212	20 - 11

The following data were recorded periodically, every two to four hours, during each drying run: dry bulb temperature, wet bulb temperature, EMC in the kiln, average moisture content of the charge, and description of the process (warm up, drying period, recovery system operation, auxiliary heat use, steam spray use, etc.).

Phase Four

Economic analysis. After-tax payback and net present value (NPV) methods of economic analysis were both used to evaluate two drying systems which were (1) the OSU experimental kiln used in this study, and (2) a hypothetical investment in a 104', double track kiln commonly used in the forest products industry (Try, 1978). Both analyses required an estimate of the initial cost to install the recovery system, annual expenses associated with recovery system operation, annual savings resulting from recovery system operation, and salvage value of the recovery system. The forest products industry typically uses a ten year economic life and a 20 percent interest rate; both of these figures were used in this analysis.

Economic data (costs and savings) were estimated for both the experimental kiln and the industrial kiln. It was not possible to obtain perfect economic data so the best estimate for all cost factors formed the set of base data, and the sensitivity of NPV to ceteris paribus changes in each factor was determined for the 104' kiln.

Actual labor and material costs were the initial cost of the recovery system for the experimental kiln. Annual expenses were estimated by assuming the system required a one-week overhaul twice each year. Annual savings depend on the cost of steam generated by oil and were estimated according to calculations in Appendix 3. Salvage value was based on the estimated value of the recovery system after ten years and was estimated by forest industry personnel (Try, 1978; Schutte, 1978; and Rice, 1979).

The initial cost of the recovery system used with a 104' kiln would be composed of three factors: (1) the construction costs to build a kiln capable of maintaining 212°F wet bulb temperature as compared to the cost of a conventional kiln, (2) the cost of duct work to pipe the recovered steam to the steam-jet thermocompressor, and (3) the cost of the steam-jet thermocompressor. Annual expenses would be the cost to maintain the recovery system and kiln seals. Kiln manufacturers were solicited for kiln construction, duct work, and maintenance costs, and steam-jet thermocompressor suppliers were solicited for thermocompressor costs.

Annual savings depend on the cost of steam, and for this analysis the cost of steam is assumed to be the fuel cost to produce steam. Amortization of the boiler, labor costs, and maintenance costs associated with power plant operation are not considered in this study. This study looks at a reduction in steam required by the dry kiln. Steam still needs to be generated so the cost of maintaining a power house is not changed. If the mill has a co-generation facility, the steam not used by the kiln would be diverted to the generator and the steam production would not be reduced (Rice, 1979). Since a detailed economic analysis of power plant cost operation is out of the scope of this study, steam costs are limited to fuel costs to generate steam (Appendix 4), and depend on the type of fuel used to generate steam. Wood residue, Bunker C oil, and natural gas are the fuel types used for this analysis, and price information for these fuels was obtained from local suppliers.

Riggs (1974) reports that sensitivity analysis should include the effect on NPV of ± 50 percent change in each cost factor. This was done for all factors except the price of Bunker C oil and natural gas which was known with greater certainty. The effect of annual growth in maintenance costs and fuel prices was also evaluated. The sensitivity analysis included the effect on NPV of changes in interest rate, economic life, initial cost, maintenance cost, fuel price, steam flow, and recovery; and the effect on NPV of growth in maintenance or fuel prices.

RESULTS AND DISCUSSION

The results and discussion section for this paper involved four phases. Phase One includes (a) the theoretical heat requirement for the Oregon State University experimental dry kiln using a conventional schedule and a superheated steam schedule; (b) the thermocompressor sized for use with this recovery system; and (c) the theoretical recovery for the steam-jet heat recovery system used with the superheated steam schedule. Phase Two includes (a) experimental results, operational problems and performance of the recovery system, and (b) heat loss from the kiln. Phase Three reported the lumber drying results. Phase Four reports the economic results for this study.

Phase One

Theoretical heat requirement. The theoretical heat requirements were determined for drying a full charge, 107.33 ft^3, of Douglas-fir dimension lumber, 2 by 6-inch nominal size, in the experimental dry kiln. The results are presented in Table 6, and supporting information is found in Appendix 1.

The theoretical heat requirement (Table 6) shows that the heat requirement to dry lumber by a superheated schedule (1,572,186 BTU) was less than the heat requirement to dry lumber by a conventional schedule (1,898,157 BTU). Steam-jet heat recovery reduces the heat requirement to dry by a superheated steam schedule by 46 percent (731,066/1,572,186).

Kiln drying lumber in the Pacific Northwest is an important phase of the sawmill production process. Superheated steam drying takes less time than conventional drying (Appendix 1) and this is advantageous for production scheduling and energy requirements. Short drying times associated with superheated steam schedules increase production through the kilns compared to longer drying times associated with conventional schedules. Superheated steam drying does not require energy to heat and humidify incoming vent air (H_5, Equation 2) that is required in a conventional drying process.

TABLE 6. THEORETICAL HEAT REQUIREMENT TO DRY LUMBER BY CONVENTIONAL, SUPERHEATED STEAM, AND SUPERHEATED STEAM WITH STEAM-JET RECOVERY METHOD.

	Schedule					
	Conventional		Superheated		Superheated with steam-jet heat recovery	
Heat type	Amount (BTU)	% of total	Amount (BTU)	% of total	Amount (BTU)	% of total
H_1	108,120.4	5.70	159,125.5	10.12	159,125.5	10.12
H_2	22,620.6	1.19	22,620.6	1.44	22,620.6	1.44
H_3	49,764	2.62	64,240.8	4.09	64,240.8	4.09
H_4	1,161,160	61.17	1,180,545.8	75.09	1,180,545.8	75.09
H_5	210,329.8	14.20	ϕ	ϕ	ϕ	ϕ
H_6	286,879.3	15.12	145,653	9.26	145,653	9.26
H_T	1,898,157	100.00	1,572,185.7	100.00	1,572,185.7	100.00
Less heat recovered	ϕ		ϕ		731,066	
Net heat used to dry lumber	1,898,157		1,572,185.7		841,119	

The compressor chosen for this project was the Ametek model 431, 1/2", bronze steam-jet thermocompressor with manual control spindle. This model was chosen because the total flow rate for this thermocompressor ranged between 44 lb/hr and 65 lb/hr (Stratton, July 21, 1978), and the steam requirement for the kiln was 44 lb/hr [1,572,186/(952 · 38)].

The theoretical recovery for the steam-jet heat recovery system is expected to range between 38 and 55 percent since the discharge pressure from the steam-jet is expected to range between ten and five psig. If the discharge pressure is ten psig, the associated entrainment ratio (Figure 2) is 0.6, the total steam flow rate is 1.6 lb/hr (0.6 + 1), and recovery is 38 percent (0.6/1.6). In like manner, if the discharge pressure is five psig, the entrainment ratio is 1.2, the total flow rate is 2.2 lb/hr, and recovery is 55 percent.

Phase Two

Experimental results. Four charges of lumber were dried in the modified dry kiln at Oregon State University's Forest Research Laboratory. Charges 1 and 2 were used to "shake-down" the data collection system and determine operational problems associated with the system. Charges 3 and 4 were used to determine operational performance associated with the recovery system.

Operational problems encountered in the "shake-down" period were identified as follows:

(1) A 0.5-inch, schedule 40, black steam line was installed to pipe the kiln exhaust to the steam-jet thermocompressor. Apparently there was too much resistance in this pipe, and little steam was getting to the steam-jet. Between charges 1 and 2, a two-inch, schedule 40, black steam line was installed to replace the 0.5-inch nominal line so that frictional resistance would be reduced

(2) The swing check valve called for in the Ametek (1976) literature was overlooked initially and was installed in the two-inch nominal line

(3) Control of the steam loss through the kiln drain was established while charge 2 was drying. Steam loss through the drain was controlled with the water manometer constructed out of plastic tubing and installed between the condenser and the bucket collector (Figure 9)

(4) A steam flow metering device was in the original data collection design to measure steam flow from the boiler (M_1 plus M_6, Figure 7). The device failed repeatedly during calibration despite suggestions from the manufacturer's engineers so it was not used

Charges 3 and 4 were used for data analysis. Table 7 summarizes the results obtained, and raw data and supporting information is found in Table 16 and Figure 14 (charge 3), and Table 17 and Figure 15 (charge 4) in Appendix 3.

TABLE 7. EXPERIMENTAL RESULTS FOR THE RECOVERY SYSTEM.

		Charge	
		3	4
Steam requirements	(lb)	1,004	1,253
Auxiliary heat	(lb)	858	749
Warm up	(lb)	649	218
Total	(lb)	2,511	2,220
Less: Steam recovered	(lb)	386	507
Net steam used	(lb)	2,125	1,713
Steam recovery			
Overall operation	(%)	16	23
During steam-jet operation	(%)	21	25
Heat requirements			
Primary heat	(BTU)	959,824	1,195,362
Auxiliary heat	(BTU)	779,064	680,092
Warm up	(BTU)	589,292	197,944
Total	(BTU)	2,328,888	2,073,398
Less: Heat recovered	(BTU)	369,016	483,678
Net heat used	(BTU)	1,959,164	1,589,720
Heat recovery			
Overall operation	(%)	16	23
During steam-jet operation	(%)	21	25
Entrainment			
Motive steam used	(lb)	618	746
Entrainment ratio		0.6	0.7
Size of charge	(ft^3)	69.1	67.9

Table 7 shows some experimental differences between charges 3 and 4. Charge 3 required more auxiliary, warm up, total, and net steam (heat) than charge 4, and charge 4 required more primary steam (heat), recovered more steam (heat), and showed higher recovery than charge 3. There were some operational differences between charges 3 and 4 that may offer an explanation for the different values.

One of the objectives of this project was to determine the limits of operational performance for the recovery system. Since time and material constraints limited the study to four charges and the first two charges were used to "shake down" the data collection system, charge 4 was dried with different procedures than charge 3 in an attempt to increase actual recovery.

Charge 3 was dried according to the schedule shown in Figure 14 (Appendix 3). The schedule consisted of a ten hour warm up period followed by 36 hours of drying and recovery system operation. The recovery system could not be operated until the kiln was purged of air, or a steam environment with a 212°F wet bulb temperature was reached. The 212°F wet bulb temperature was reached in ten hours without any assistance from the steam spray line (Figure 14, Appendix 3), and the steam-jet heat recovery device was turned on. During its operation, the discharge pressure from the steam-jet varied between 8.2 and 9.5 psig (Table 16, Appendix 3). The expected entrainment ratio was 0.6 (Figure 2), which was the same as the experimental entrainment ratio obtained for charge 3

(Table 7). Recovery for the 36 hour drying period was 21 percent of the energy required for that period, and recovery for the entire drying run of 46 hours was 16 percent of the energy required to dry the lumber (Table 7).

Figure 14 (Appendix 3) shows that the dry bulb temperature varied between 224°F and 229°F, and the wet bulb temperature varied between 212°F and 213°F. The dry bulb temperature was controlled by the kiln temperature control mechanism connected to the auxiliary heat source. The change in wet bulb temperature is explained by the kiln pressure (P_2, Figure 7). The kiln pressure, P_2, varied between +0.5 and +1.5 inches of water (Table 16, Appendix 3), and one inch of water pressure corresponds to a 1°F change in wet bulb temperature. Therefore, the 213°F wet bulb temperature was expected.

Charge 4 was dried according to the schedule in Figure 15 (Appendix 3). There were two drying procedure differences between charge 3 and 4. First, the recovery system was operated without the auxiliary heat for part of the drying run to determine the temperature the kiln would maintain without auxiliary heat. The auxiliary heat was shut off at hour 19 of the drying run. The kiln temperature dropped from 225°F to 219°F and remained there until the auxiliary heat was turned on again at hour 31. The drying rate decreased during this period (Figure 15, Appendix 3). Second, a problem arose that required another procedure change. A leak was detected in the kiln vent at the end of the warm up period so the kiln was shut down, cooled off, repairs made, and restarted. The moisture content of the charge dropped from 58 to 49 percent between the beginning of the initial warm up period and the time the kiln was restarted. To minimize additional moisture loss from the charge without recovery during the second warm up period, a spray steam line was utilized in conjunction with the steam coils to bring the kiln to operation temperature. The warm up time was 3.5 hours, and the moisture content dropped four percent during the second warm up period (Figure 13).

The energy used by the kiln and the moisture lost from the charge during the initial warm up period was not counted because the charge was completely cooled off between the time the leak was detected and the kiln was restarted. The energy used by the kiln from the steam spray line was not counted either because it could not be measured with the data collection system used for this study. Therefore, energy requirements were measured for charge 4 from the restart time to completion neglecting the steam spray used in the warm up period.

Operational performance was higher for charge 4 than charge 3. During steam-jet operation, the discharge pressure varied between 7.8 and 8.9 psig (Table 17, Appendix 3). The expected entrainment ratio was 0.7 (Figure 2) which was the same as the actual entrainment ratio obtained for charge 4 (Table 7). Since the entrainment ratio was higher for charge 4 than charge 3, recovery was expected to be higher for charge 4. The recovery for the 36.5 hour drying period was 25 percent of the energy required for that period (Table 7).

The discharge pressure was not easily controlled, and no reason is offered for the lower discharge pressures for charge 4.

Table 8 summarizes the heat transfer data collected to determine the heat loss through the kiln wall.

TABLE 8. HEAT TRANSFER DATA FOR THE EXPERIMENTAL KILN.

Repetition Number	Steam Used (lb)	Steam Pressure (psig)	Heat of Vaporization (BTU/lb)	Heat Transfer (BTU)	Temperature Gradient (°F)	Heat transfer Coefficient (BTU/hr-°F-ft^2)
				Q	dT	U
1	55	55	907.86	49,932	171	0.471
2	42	10	952.08	39,987	147	0.439
3	55.5	55	907.86	50,386	177	0.459
4	51	55	907.86	46,301	180	0.415

Heat loss calculation for superheated steam drying:

$$Q = U \cdot A \cdot dT \cdot t$$

U: $\bar{x} = 0.456$; $s = 0.016$ BTU/hr-°F-ft^2

A: $A = 620$ ft^2 (Appendix 1)

dT: $dT = 155$°F (Appendix 1)

t: $t = 42$ hours (Appendix 1)

$Q = 1{,}840{,}507$ BTU

Theoretical heat loss through the walls (H_6, Equation 2) was 145,653 BTU, and the experimentally determined heat loss through the walls was 1,840,507 BTU for the superheated steam dry kiln. The difference between the theoretical heat loss and the experimental heat loss explains the difference between the theoretical and experimental heat requirements. The calculated theoretical heat requirement for a superheated steam schedule was 418.3 BTU/ft^3-MC* (Appendix 1), and the experimentally determined heat requirements were 710.3 BTU/ft^3-MC and 847 BTU/ft^3-MC for charges 3 and 4, respectively. If the theoretical heat loss (H_6, Equation 2) is replaced by the experimentally determined heat loss, the theoretical heat requirement becomes 869.4 BTU/ft^3-MC which is comparable with the experimentally determined heat requirement.

Phase Three

Drying data results. Drying data are presented for charges 3 and 4 in Table 9, and moisture content sample data are presented in Table 10.

The final average moisture content shown in Table 9 was lower than the target one of 15 percent for both charges. Operator inexperience is the reason given for overdrying the charge. The calculated moisture loss from the charge was 973 lb and 911 lb for charges 3 and 4, respectively, and the measured moisture loss (M_7, Figure 7) was 974 lb and 912 lb for charge 3 and 4, respectively, indicating that the in kiln balance was accurate. Degrade was visually estimated. There was very little warp (Figure 11) or checking in the wood surface, but many of the knots had "star" checking which is typical for Douglas-fir.

*Heat requirements on an equivalent BTU per ft^3- change in moisture content, MC, basis

TABLE 9. DRYING DATA.

		Charge	
		3	4
Initial weight/board - IW			
$\bar{x}$	(lb)	25.98	25.34
s	(lb)	3.31	3.57
Final weight/board - FW			
$\bar{x}$	(lb)	18.34	18.22
s	(lb)	2.24	2.54
Initial moisture content/board			
$\bar{x}$	(%)	59.15	57.88
s	(%)	19.50	22.78
Final moisture content/board			
$\bar{x}$	(%)	11.69	12.97
s	(%)	3.27	2.54
Length/board - L			
$\bar{x}$	(in)	95.42	95.23
s	(in)	4.86	4.92
Heartwood to sapwood ratio H:S	(-)	3:1	2.5:1
Thickness/board - T	(in)	1.75	1.75
Number of boards - N	(#)	130.0	128.0
Charge capacity (N · L/12 · W/12 · T/12)	(ft^3)	70.9	69.6
Total moisture loss from charge [N · (IW - FW)]	(lb)	973.0	911.0
Measured moisture loss in kiln			
Recovery system operating	(lb)	667.0	704.0
Recovery system not operating	(lb)	307.0	208.0
Total	(lb)	974.0	912.0
Drying time			
Warm up	(hr)	10.0	3.5
Drying	(hr)	36.0	36.5
Total	(hr)	46.0	40.0

TABLE 10. MOISTURE CONTENT SAMPLE DATA.

Data		Charge 3	Charge 4
Green mass - G			
$\bar{x}$	(gm)	114.49	136.91
s	(gm)	21.85	31.93
Dry mass - D			
$\bar{x}$	(gm)	72.64	87.71
s	(gm)	16.25	19.56
Moisture content - MC (G - D)/D			
$\bar{x}$	(%)	59.92	57.44
s	(%)	24.19	26.35
Mass - water displaced - M_d			
$\bar{x}$	(gm)	51.55	48.35
s	(gm)	12.99	23.81
Specific gravity $[D/(D + M_d)]$			
$\bar{x}$	(-)	0.58	0.66
s	(-)	0.07	0.19
Sample width - W			
$\bar{x}$	(in)	5.64	5.64
s	(in)	0.07	0.06
Rings per inch			
$\bar{x}$	(in^{-1})	9.08	12.68
s	(in^{-1})	5.22	7.52

Figure 11. Charge after drying showing little warp.

Since drying was not the emphasis of this study, the remainder of the information in Tables 9 and 10 are not discussed but are presented for the reader's reference.

Phase Four

Economic analysis results. The economic analysis involved estimating costs and savings associated with the recovery system and determining the after-tax payback and NPV associated with recovery system operation in conjunction with the OSU experimental dry kiln and a 104', double track industrial kiln.

The costs, savings, payback, and NPV are reported in Table 11.

TABLE 11. ECONOMIC DATA SHOWING COSTS, SAVINGS, PAYBACK, AND NPV FOR THE EXPERIMENTAL AND THE INDUSTRIAL KILN.

Factor	OSU kiln	104', Double track kiln		
		Wood Residue	Bunker C oil	Natural gas
Initial cost				
Kiln Modifications	3,433	55,000	55,000	55,000
Duct Work	---	2,000	2,000	2,000
Steam-Jet	141	700	700	700
Total	3,574	57,700	57,700	57,700
Annual Maintenance	800	4,000	4,000	4,000
Annual Savings	278	4,636	37,181	54,092
Salvage Value	ϕ	ϕ	ϕ	ϕ
Payback (years)	∞	18.0	2.96	2.07
NPV	-5,762	-44,272	23,951	59,397

Base data calculations for payback and NPV are found in Appendix 5. For the industrial kiln, Table 12 presents the sensitivity of NPV to changes in the cost factors, and Table 13 presents the sensitivity index as associated with data in Table 12.

The economic data presented in Table 11 showed that the small experimental kiln was not economically feasible (infinite payback and -5762 NPV). The 104', double track kiln was economically feasible if Bunker C oil or natural gas was used to generate steam, but it was not economically feasible if wood residue was used to generate steam (Table 11).

The 104', double track kiln was economically sensitive to the fuel used to generate steam (Table 12 and 13). If the cost of steam was high due to use of Bunker C oil or natural gas, the NPV was sensitive to steam value factors; i.e. fuel price, steam flow, and recovery. If the cost of steam was low, the NPV was sensitive to cost factors; i.e. initial cost and maintenance cost growth. The overall sensitivity decreased with decrease in steam costs (Table 13). The wood system was less sensitive than Bunker C oil, and Bunker C oil was less sensitive than natural gas.

The purpose of the economic analysis was not to determine the absolute economic feasibility of the recovery system, but to discuss the economic factors entering the analysis and estimate the amount of each. In a real situation, the economic analysis would be done according to company policy and may include some additional factors not included in this discussion.

TABLE 12. SENSITIVITY DATA FOR THE INDUSTRIAL KILN

Kiln Size <u>DT 104</u>; Fuel Type <u>Oil</u>

Interest Rate deviation		Economic Life deviation		Costs: Initial deviation		Costs: Maintenance deviation		Costs: Maintenance growth		Savings: Fuel Price deviation		Savings: Fuel Price growth		Savings: Steam Flow deviation		Savings: Recovery deviation	
%Δ	NPV	%Δ	NPV	%Δ	NPV	%Δ	NPV	%	NPV	%Δ	NPV	%	NPV	%Δ	NPV	%Δ	NPV
+50	2,666	+50	31,958	+50	1,149	+50	19,759			+25	43,436			+50	62,921	+50	62,921
+25	13,308	+20	28,042	+25	12,550	+25	21,855	5	22,662	+12.5	33,693	5	35,930	+25	43,436	+25	43,436
0	23,951	0	23,951	0	23,951	0	23,951	10	21,374	0	23,951	10	47,908	0	23,951	0	23,951
-25	40,644	-30	15,989	-25	35,352	-25	26,047	15	20,085	-12.5	14,208	15	59,887	-25	4,466	-25	4,466
-50	61,980	-50	6,350	-50	46,754	-50	28,144	20	18,796	-25	4,466	20	71,866	-50	-15,019	-50	-15,019

Kiln Size <u>DT 104</u>; Fuel Type <u>Gas</u>

Interest Rate deviation		Economic Life deviation		Costs: Initial deviation		Costs: Maintenance deviation		Costs: Maintenance growth		Savings: Fuel Price deviation		Savings: Fuel Price growth		Savings: Steam Flow deviation		Savings: Recovery deviation	
%Δ	NPV	%Δ	NPV	%Δ	NPV	%Δ	NPV	%	NPV	%Δ	NPV	%	NPV	%Δ	NPV	%Δ	NPV
+50	28,872	+50	71,485	+50	36,595	+50	55,205			+25	87,744			+50	116,091	+50	116,091
+25	44,135	+20	65,574	+25	47,996	+25	57,301	5	58,109	+12.5	73,571	5	76,824	+25	87,744	+25	87,744
0	59,397	0	59,397	0	59,397	0	59,397	10	56,820	0	59,397	10	94,250	0	59,397	0	59,397
-25	83,337	-30	44,686	-25	70,799	-25	61,494	15	55,532	-12.5	45,224	15	111,677	-25	31,051	-25	31,051
-50	113,935	-50	29,307	-50	82,200	-50	63,590	20	54,243	-25	31,051	20	129,103	-50	2,704	-50	2,704

Kiln Size <u>DT 104</u>; Fuel Type <u>Wood</u>

Interest Rate deviation		Economic Life deviation		Costs: Initial deviation		Costs: Maintenance deviation		Costs: Maintenance growth		Savings: Fuel Price deviation		Savings: Fuel Price growth		Savings: Steam Flow deviation		Savings: Recovery deviation	
%Δ	NPV	%Δ	NPV	%Δ	NPV	%Δ	NPV	%	NPV	%Δ	NPV	%	NPV	%Δ	NPV	%Δ	NPV
+50	-47,772	+50	-44,119	+50	-67,075	+50	-48,464			+50	-39,413			+50	-39,413	+50	-39,413
+25	-46,022	+20	-44,193	+25	-55,673	+25	-46,369	5	-45,561	+25	-41,843	5	-42,779	+25	-41,843	+25	-41,843
0	-44,272	0	-44,272	0	-44,272	0	-44,272	10	-46,849	0	-44,272	10	-41,285	0	-44,272	0	-44,272
-25	-41,527	-30	-38,083	-25	-32,871	-25	-42,176	15	-48,138	-25	-46,701	15	-39,791	-25	-46,701	-25	-46,701
-50	-38,018	-50	-34,670	-50	-21,470	-50	-40,080	20	-49,426	-50	-49,131	20	-38,298	-50	-49,131	-50	-49,131

TABLE 13. SENSITIVITY INDEXES FOR THE INDUSTRIAL KILN.

Fuel Type	Sensitivity Index (dNPV/d%Δ)
Bunker C oil	
Fuel price growth	2,396
Fuel price deviation	779
Steam flow deviation	779
Recovery deviation	779
Interest rate deviation	593
Initial cost deviation	456
Maintenance cost growth	258
Economic life deviation	256
Maintenance cost deviation	84
Natural gas	
Fuel price growth	3,785
Fuel price deviation	1,134
Steam flow deviation	1,134
Recovery deviation	1,134
Interest rate deviation	851
Initial cost deviation	456
Economic life deviation	422
Maintenance cost growth	258
Maintenance cost deviation	84
Residue	
Initial cost deviation	456
Maintenance cost growth	258
Fuel price deviation	97
Steam flow deviation	97
Recovery deviation	97
Interest rate deviation	97
Economic life deviation	94
Maintenance cost deviation	84
Fuel price growth	60

CONCLUSIONS

1. Steam-jet recovery resulted in 20 percent energy recovery. This reduces the steam requirement from the boiler.
2. The project would be economically feasible for a situation where Bunker C oil or natural gas is used to generate steam, but not feasible for a situation where wood residue is used to generate steam.
3. For a hypothetical investment in a 104', double track kiln, the NPV was sensitive to steam costs factors which include the fuel cost to produce steam, steam recovery, and the steam flow requirement of the kiln.

SUGGESTIONS FOR FURTHER STUDY

Suggested areas for further study include an industrial scale technical and economic analysis of a steam-jet heat recovery system, and the effect of extractive compounds on the heat recovery system. An industrial scale study would have to include an engineering analysis of kiln construction and heat recovery design factors necessary for system implementation, and the system could be analyzed for operational problems. Extractive compounds evaporate from the lumber with the moisture. The effect of these compounds condensing in the steam coils or being reheated in boiler tubes is not known but should be analyzed.

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APPENDICES

APPENDIX 1. THEORETICAL HEAT REQUIREMENTS*

The theoretical heat requirements were calculated to dry a full charge of Douglas-fir in the Oregon State University experimental dry kiln using a conventional schedule and a superheated steam schedule. The theoretical recovery was calculated for a steam-jet heat recovery system used in conjunction with the superheated steam schedule, and the net heat used by the system was calculated.

Calculation #1: Total heat requirement for a conventional schedule

TABLE 14. CONVENTIONAL DRYING SCHEDULE FOR DOUGLAS-FIR.

Time (hrs)	T_d (°F)	T_w (°F)	MC at start of step (%)	MC at end of step (%)
0-24	180	170	50	32
24-42	180	165	32	24
42-60	180	160	24	18
60-84	180	150	18	15

Initial moisture content ∿ 50%

Final moisture content ∿ 15%

$$\text{Mass (oven dry)} = 23 \text{ layers} \times 4' \times 8' \times \frac{1.75''}{12} \times 28.1 \frac{\text{lbs o.d.}}{\text{ft}^3} =$$

3016.07 lbs

Mass green = 3016 x 1.50 = 4524.1 lbs

Mass final = 3016 x 1.15 = 3468.5 lbs

Moisture removed = 1055.6 lbs

Moisture remaining 452.4 lbs

*All data not referenced was taken from Shottafer and Shuler (1974)

Specific heat

c_w = water - 1 BTU/lb°F

c_{wd} = wood - 0.266 + 0.000644 (T_{ave} - 32) BTU/lb°F

c_a = air - .24 BTU/lb°F

c_{wv} = water vapor - .45 BTU/lb°F

c_s = steam ∿ depends on temperature

Temperature of ambient air - 70°F

Relative humidity of ambient air - 70%

H_1 - heat the wood substance to kiln temperature

$$H_1 = c_{wd} M_{od} \Delta T$$

c_{wd} = specific heat of wood (BTU/lb_m°F)

$$c_{wd} = .266 + 0.000644 \left(\frac{T_f + T_i}{2} - 32\right)$$

T_f = kiln temperature - final

T_i = initial temperature - ambient

M_{od} = mass oven dry of wood

ΔT = temperature difference = $T_f - T_i$

$$H_1 = [.266 + 0.000644 \left(\frac{180 + 70}{2}\right) - 32]\ (3016.07)(110)$$

$$H_1 = 108{,}120.4 \text{ BTU}$$

H_2 - heat required to overcome hygroscopic forces

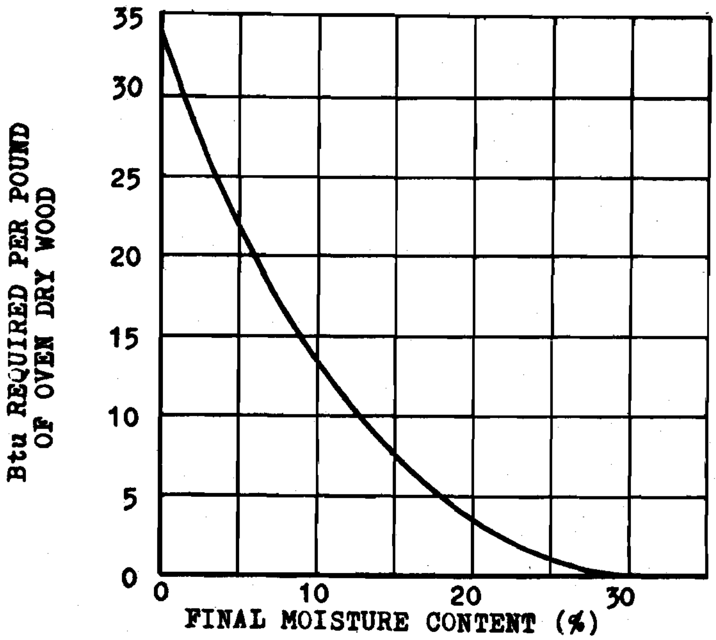
$$H_2 = M_{od} \cdot H_{des}$$

H_{des} = heat of desorption (BTU/lb_{wd})

$$H_2 = (3016.07)(7.5)$$

$$H_2 = 22{,}620.6 \text{ BTU}$$

Figure 12. Heat required to overcome hygroscopic forces as related to final moisture content



H_3 = heat required to raise the temperature of remaining water to kiln operating temperature

$H_3 = M_{rw} \cdot c_w \cdot \Delta T$

M_{rw} = mass of remaining water lb_m

ΔT = temperature difference between ambient air and final kiln temperature

$H_3 = (452.4)(1)(110)$

$H_3 = 49{,}764$

H_4 = heat required to raise to temperature and evaporate moisture from the kiln

$$H_4 = M_{ew} \cdot c_w \, \Delta T + M_{ew} \cdot h_{fg}$$

M_{ew} = mass of evaporated water

h_{fg} = heat of vaporization at 180°F

$$H_4 = (1055.6)(1)(110) + (1055.6)(990)$$

$$H_4 = 1{,}161{,}160 \text{ BTU}$$

H_5 = heat required to raise the temperature and humidify the vent air

$$H_5 = K \left[\frac{\Delta MC_1 \; \Delta t_1}{d_1} + \frac{\Delta MC_2 + \Delta t_2}{d_2} + \ldots \text{etc}\right] +$$

$$A \left[\Delta MC_1 \left(\Delta S_1 \, c_w + h_{fg1}\right) + \Delta MC_2 \left(\Delta S_2 \, c_w + h_{fg2} + \ldots \text{etc}\right)\right]$$

K = convenience factor = $M_{od} \, (1 + E)[c_a + (b) \, c_{wr}]$

E = percent excess air (%)

b = lbs of water vapor/lb incoming vent air (lb/lb)

A = convenience factor = $M_{od} \cdot E$

ΔMC_1 = moisture content loss in stage 1 of drying (percent)

Δt_1 = temperature difference between kiln temperature in stage 1 of drying (°F) and ambient air

d_1 = amount of water vapor that can be absorbed by the incoming vent air (lb/lb)

$d = j - b$

j = lbs of water vapor that can be held by a pound of heated air in the kiln (lb/lb)

ΔMC_2, Δt_2, d_2 = conditions in stage two of drying

ΔS_1 = change in temperature of the humidifying air (°F)

$\Delta S = DBT - S_o$

DBT = dry bulb temperature (°F)

S_o = temperature of water going to the boiler (°F)

h_{fg1} = latent heat of vaporization of water at the dry bulb temperature (BTU/lb_m)

$K = (3016.07)(1.10)[.24 + (.01)(.45)]$

$K = 811.2$

$A = (3016)(.10)$

$A = 301.6$

$$H_5 = 811.2\ [110\ (\frac{.18}{.42} + \frac{.08}{.34} + \frac{.06}{.27} + \frac{.03}{.19})] + 301.6\ [1110\ (.35)]$$

$$= (811.2)(110)(1.044) + (301.6)(110)(.35)$$

$$= 93{,}158.21 + 117{,}171.6$$

$$H_5 = 210{,}329.8 \text{ BTU}$$

Heat lost to the outside of the kiln - H_6

The heat lost to the outside, q, is approximated by the following formula

$$q = \upsilon A \Delta T$$

where υ = overall heat transfer coefficient $(\frac{BTU}{hr\ ft^2\ °F})$

A = surface area through which the heat is transferred

ΔT = temperature difference between the inside of the kiln and the ambient air

The overall heat transfer coefficient, U, can be approximated from kiln construction information. One method of solving the problem is to use the electrical resistance analogy where $R = \frac{x}{kA}$, $R_s = \sum_{i=1}^{n} Ri$, and $\frac{1}{Rp} = \sum_{i=1}^{n} \frac{1}{Ri}$. For this study, the wall area will be the same for each k, conductivity coefficient, and each x, thickness through which the heat must travel. Therefore, $R_s = (\sum_{i=1}^{n} \frac{x_i}{R_i}) \frac{1}{A}$, or $U = \sum_{i=1}^{n} \frac{k_i}{x_i}$, or $UA = \frac{1}{R}$. Then $q = UA\Delta T$ or $\frac{1}{R} \Delta T$.

Area:

Ceiling, floor	-	11.66'	x	8.58'	= 100.04 ft^2
Side (left, right)	-	11.66'	x	10.42'	= 121.50 ft^2
Front, back	-	10.42'	x	8.58'	= 89.40 ft^2
a) Door	-	7'	x	5.21'	= 36.47 ft^2

Thermal conductivity coefficients, k

Plywood	k = 0.08 BTU/hr ft °F
Fiberglass	k = 0.023 BTU/hr ft °F
Foamglass	k = 0.033 BTU/hr ft °F
Aluminum	k = 118 BTU/hr ft °F

Boundary layer coefficients

Inside	h_1 = 3.5 BTU/hr ft^2 °F	(2 mph wind)
Outside	h_2 = 1.65 BTU/hr ft^2 °F	(closed room)

Resistance/heat loss

<u>Ceiling</u>

$$R = \frac{1}{A} (\frac{1}{h_1} + \frac{x}{k_{Al}} + \frac{x}{k_{fg}} + \frac{x}{k_{pw}} + \frac{1}{h_2})$$

$$= \frac{1}{100.04\ ft^2}\left(\frac{1}{3.5} + \frac{1/96}{118} + \frac{9/12}{.023} + \frac{1/24}{.08} + \frac{1}{1.65}\right)\frac{hr\ ft^2\ °F}{BTU}$$

$$= \frac{1}{100.04}(.286 + 8.82 \times 10^{-5} + 32.609 + .521 + .606)$$

$$R = .34$$

$$\frac{1}{R} = 2.940$$

$$T_{outside} \sim 80°F$$

$$T_{inside} \sim 180°F$$

$$q_c = \frac{1}{R}\Delta T$$

$$q_c = 294\ BTU/hr$$

<u>Floor</u>

$$R = \frac{1}{A}\left(\frac{1}{h_1} + \frac{x}{k_{Al}} + \frac{x}{k_{fg}}\right)$$

$$= \frac{1}{100.04}\left(\frac{1}{3.5} + \frac{1/48}{118} + \frac{5/12}{.033}\right)$$

$$= \frac{1}{100.04}(.286 + 1.77 \times 10^{-4} + 12.501)$$

$$R = .128$$

$$\frac{1}{R} = 7.823\ \frac{BTU}{hr\ °F}$$

$$T_{outside} = 60°F$$

$$T_{inside} = 180°$$

$$q_f = \frac{1}{R}\Delta T$$

$$q_f = 937.5\ BTU/hr$$

<u>Side wall</u>

$$R = \frac{1}{A}\left(\frac{1}{h_1} + \frac{x}{k_{Al}} + \frac{x}{k_{fg}} + \frac{x}{k_{pw}} + \frac{1}{h_2}\right)$$

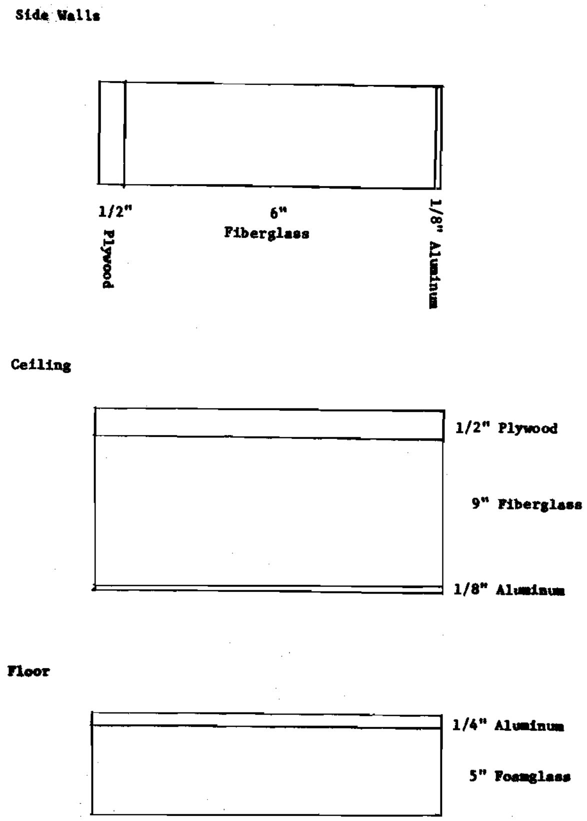
$$= \frac{1}{121.50}\left(\frac{1}{3.5} + \frac{1/96}{118} + \frac{6/12}{.023} + \frac{1/24}{.08} + \frac{1}{1.65}\right)$$

$$= \frac{1}{121.50}(.286 + 8.82 \times 10^{-5} + 21.739 + .521 + .606)$$

$$R = .1906$$

$$\frac{1}{R} = 5.248\ \frac{BTU}{hr\ °F}$$

Figure 13. Wall construction for the OSU experimental kiln.



$T_{outside} \cong 70°F$

$T_{inside} \cong 180°F$

$q_{sw} = 577.3$

Two side walls, $\therefore q_{sw} = 1,154.5$

Back wall

$$R = \frac{1}{A}\left(\frac{1}{h_1} + \frac{x}{k_{Al}} + \frac{x}{k_{fg}} + \frac{x}{k_{pw}} + \frac{1}{h_2}\right)$$

$$= \frac{1}{89.40}\left(\frac{1}{3.5} + \frac{1/96}{118} + \frac{6/12}{.023} + \frac{1/24}{.08} + \frac{1}{1.65}\right)$$

$R = .259$

$\frac{1}{R} = 3.860$

$q = \frac{1}{R}\Delta T$

$\Delta T = 110°F$

$q_{bw} = 424.65$ BTU/hr

Front

1) Area excluding door

Total $\sim$ 89.40

- door $\sim$ 36.47

52.93

$$R_1 = \frac{1}{A}\left(\frac{1}{h_1} + \frac{x}{k_{Al}} + \frac{x}{k_{fg}} + \frac{x}{k_{pw}} + \frac{1}{h_2}\right)$$

$$= \frac{1}{52.93}(23.1546)$$

$R_1 = .437$

$\frac{1}{R_1} = 2.286$

Assume 10% more heat is lost around the door.

$$R_2 = \frac{1}{36.47}\left[\frac{23.1546}{1.10}\right]$$

$$R_2 = .577$$

$$\frac{1}{R_2} = 1.733$$

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= 2.286 + 1.733$$

$$\frac{1}{R_p} = 4.019$$

$$q = \frac{1}{R_p} \Delta T$$

$$q_{fw} = 442.0 \text{ BTU/hr}$$

Total heat loss

$$q_T = \Sigma q_i$$

$$= 294 + 937.5 + 1{,}154.5 + 424.6 + 442.0$$

$$q_T = 3252.6 \text{ BTU/hr}$$

Add 5% to account for plywood studs, Al channels, and leaks that are not accounted for previously.

$$q_T = 3252.6\ (1.05)$$

$$q_T = 3415.23 \text{ BTU/hr}$$

$$\underline{\quad \text{X } 84 \text{ hrs} \quad}$$
$$286{,}879.3 \text{ BTU} \sim \text{total}$$

Calculation #2: DETERMINATION OF H_T FOR A SUPERHEATED STEAM SCHEDULE

TABLE 15. SUPERHEATED STEAM SCHEDULE FOR DOUGLAS-FIR.

Hour	Dry bulb	Wet bulb	EMC	Moisture removed
0-42	225	212	9.0	1055.6 lbs

$H_1 = c_{wd} M_{od} \Delta T$

$c_{wd} = 0.266 + .000644 \left(\frac{225 + 70}{2} - 32\right) = .340$

$H_1 = 159{,}125.5$ BTU

$H_2 = (3016.07)(7.5)$

$H_3 = M_{rw} \cdot c_w \cdot \Delta T_1{}^*$

$H_3 = (452.4)(1)(142)$

$H_3 = 64{,}240.8$

$H_4 = M_{ew} \cdot c_w \cdot \Delta T_1 + M_{ew} h_{fg} + M_{ew} \cdot c_s \cdot \Delta T_2$

ΔT_1 = temperature difference between initial and evaporation conditions

ΔT_2 = temperature difference between evaporation and final conditions

$H_4 = (1055.6)[(1)(142) + 970.3 + (.4896)(.3)]$

$H_4 = 1{,}180{,}545.8$

$H_5 = \phi$ There is no vent air--all drying is done in a superheated steam environment

$H_6 = \frac{1}{R} \Delta T$

Ceiling:

$$R = \frac{1}{100.04} \left(\frac{1}{2049} + \frac{1/96}{118} + \frac{9/12}{.023} + \frac{1/24}{.08} + \frac{1}{1.65}\right)$$

$R = .337$

$\frac{1}{R} = 2.96$

$q_c = 296.0$ BTU/hr

---

*The kiln operating temperature is 225°F. However, the temperature at which the water vaporizes is 212°F. Since the water remaining does not vaporize, its final temperature is 212°F.

Floor:

$$R = \frac{1}{100.04}(12.502)$$

$$R = .125$$

$$\frac{1}{R} = 8.002$$

$$q_f = 960.3$$

Side wall:

$$R = \frac{1}{A}\left(\frac{1}{2049} + \frac{1/96}{118} + \frac{6/12}{.023} + \frac{1/24}{.08} + \frac{1}{1.65}\right)$$

$$R = .188$$

$$\frac{1}{R} = 5.313$$

$$q = 584.5$$

$$q_{sw} = 1{,}168.96$$

Back wall:

$$R = .256$$

$$\frac{1}{R} = 3.9096$$

$$q_{bw} = 430.1$$

Front wall:

$$\frac{1}{R_{wall\text{-}door}} = 2.3144$$

$$\frac{1}{R_{door}} = 1.7542$$

$$\frac{1}{R_{total}} = 4.0686$$

$$q_{fw} = 447.5$$

$$q_{total} = 3302.9$$

Allow for 5% excess leakage

q_T = 3468 BTU/hr

$H_6 = q_T \cdot T$

H_6 = 3468 x 42

H_6 = 145,653

Calculation #3: DETERMINATION OF ENERGY RECOVERY WITH STEAM JET THERMOCOMPRESSOR

Expected recovery ranges between 38 and 55 percent (Results, Phase One). Therefore, expected energy savings will range between (.38)(1,572,185.7) = 597,431 BTU and (.55)(1,572,185.7) = 864,702 BTU. The actual recovery is probably between the two. Assume the actual recovery is (38 + 55)/2 = 46.5% or 731,066 BTU.

APPENDIX 2. STEAM COIL CALCULATIONS

Heat transfer across heating coils is described by Fourier's law of heat transfer by conduction, Equation 5.

$$dQ/dt = -kA\ dT/dX \qquad \text{Equation 5}$$

Q = heat transferred (BTU)

t = time to transfer heat (hour)

k = heat transfer coefficient (BTU/hr-ft^2-°F)

A = heat transfer area (ft^2)

X = distance heat moves (ft)

T = temperature (°F)

Equation 4 can be approximated by Equation 6.

$$Q = Ul\ \Delta T \qquad \text{Equation 6}$$

U = coefficient (BTU/hr-ft-°F)

l = lineal feet of coil (ft)

ΔT = temperature difference (°F)

Try (1978) reported that the heat transfer coefficient for the extruded fin copper coil was 23 BTU/hr-ft-°F (air velocity is 600 fpm). Since there is 128 lineal feet of heating coil in the kiln, the heat transfer is (23)(128) = 2,944 BTU/hr-°F. Since 55 lb-steam/hr passed through the coils, the heat transfer, Q, was 55,000 BTU/hr (55 lb/hr · 1000 BTU/lb). At 2,944 BTU/hr-°F, the temperature difference, ΔT, was 17°F (55,000/2,944). To maintain 230°F in the kiln, it would be necessary to use 13 psig (248°F).

The kiln was examined for feasibility of installing additional coil. The plenum chamber could hold an additional 128 lineal feet of coil. The new coil was one-inch, nominal, schedule 40 steel pipe with 3/4-inch fins. The heat transfer for the new coil was 19.5 BTU/hr-°F-ft (Schutte, 1978).

Using all of the coils, the average heat transfer coefficient was 21 BTU/hr-°F-ft, (23 + 19.5)/2. The total heat transfer capacity was 5,376 BTU/hr-°F (21 · 256), and the temperature difference was 10°F (55,000/5,376). To maintain 230°F in the kiln, it would be necessary to use ten psig (240°F) steam.

This analysis assumes ideal conditions for heat transfer. Since the maximum steam pressure is ten psig, there is no margin for error. To account for any deviations from ideal, it was decided to supply 16 lineal feet of coil on each of the kiln with high pressure, boiler steam as an auxiliary heat source.

APPENDIX 3. RAW DATA FOR CHARGE 3 AND 4

Figure 14. Drying schedule for charge 3

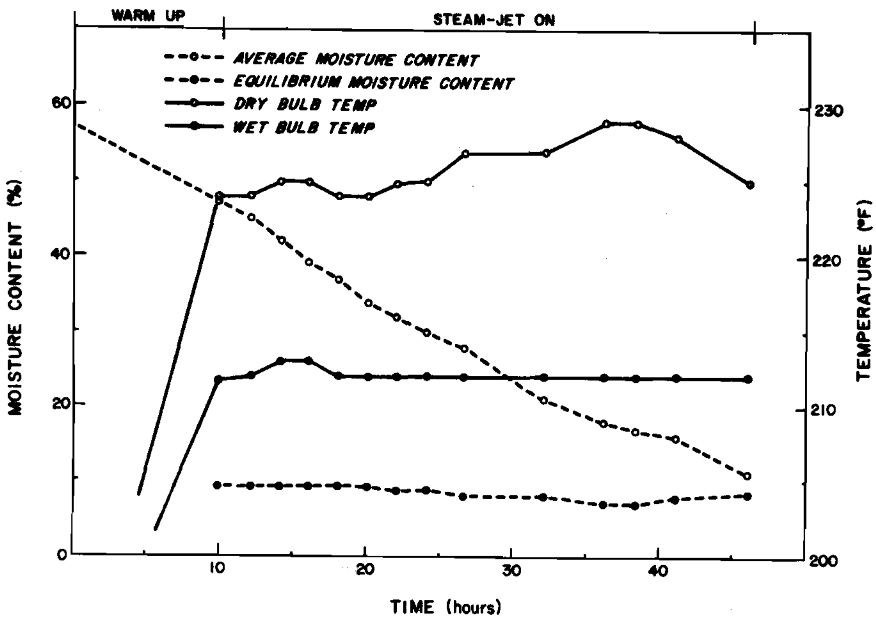


TABLE 16. RAW DATA FOR CHARGE 3

I. MASS DATA			
A. MEASURED			
M_4	Mass of condensate collected in bucket "4"	(lbm)	281
M_5	Mass of condensate collected in barrel "5"	(lbm)	1004
$M_{6'}$	Mass of condensate collected in barrel "6"	(lbm)	858
M_7	Mass loss from charge "7"	(lbm)	667
M_w	Mass of condensate collected during "warm up"	(lbm)	649
B. DETERMINED			
M_1	Motive steam used by steam-jet $= M_5 - M_2$	(lbm)	618
M_2	Vapor entrained by steam-jet $= M_7 - M_4$	(lbm)	386
M_3	Total flow through steam-jet $= M_5$	(lbm)	1004
M_6	Steam used for auxiliary heat $= M_{6'}$	(lbm)	858
II. TEMPERATURE AND PRESSURE DATA			
T_1, T_6	Temperature of steam from boiler	(°F)	296
T_2	Temperature of entrained vapor	(°F)	210-213
T_3	Temperature of steam entering coils	(°F)	234-238
T_4	Temperature at kiln dry bulb	(°F)	225-228
T_5	Temperature of condensate exiting coil	(°F)	200
$T_{6'}$	Temperature of condensate exiting coil	(°F)	200
P_1, P_6	Pressure of steam from boiler	(psig)	57
P_2	Pressure of entrained vapor	(in.H_2O)	+0.5-+1.5
P_3	Pressure of steam entering coils	(psig)	8.2-9.5
P_4	Pressure in kiln	(in.H_2O)	+0.5-+1.5

TABLE 16, continued:

III. HEAT USE

A. WARM UP: $H_w = M_w \cdot h_{fg}$

M_w = 649 lbm

T ≅ 296°F

P ≅ 57 psig

h_{fg} ≅ 908 BTU/lb

HEAT USE, H_w - 589,292 BTU

B. DRYING RUN: $H_D = (M_5 \cdot h_{fgs}) + (M_6 \cdot h_{fg6})$

1. Regular Heat, H_5

M_5 = 1004

T_3 ≅ 236°F

P_3 ≅ 9.0 psig

h_{fg} ≅ 956 BTU/lb

HEAT USE - - - - - - - - - - - - - - - - 959,824 BTU

2. Auxiliary heat, H_6

M_6 = 858 lb

T_6 ≅ 296°F

P_6 ≅ 57 psig

h_{fg} ≅ 908 BTU/lb_m

HEAT USE - - - - - - - - - - - - - - - - 779,064 BTU

DRYING, H_D - 1,738,888 BTU

C. TOTAL HEAT USE, $H_T = H_w + H_D$ 2,328,180 BTU

D. RECOVERED HEAT: $H_R = M_2 \cdot h_{fg3}$ 369,016 BTU

E. NET HEAT USED: $H_N = H_T - H_R$ 1,959,164 BTU

TABLE 16, continued:

IV. RECOVERY		
A.	Recovery of steam during steam-jet operation $M_2/(M_5+M_{6'})$	21%
B.	Recovery of steam during kiln operation $M_2/(M_5+M_{6'}+M_w)$	16%
C.	Recovery of heat during steam-jet operation H_R/H_D	21%
D.	Recovery of heat during kiln operation H_R/H_T	16%

Figure 15. Drying schedule for charge 4

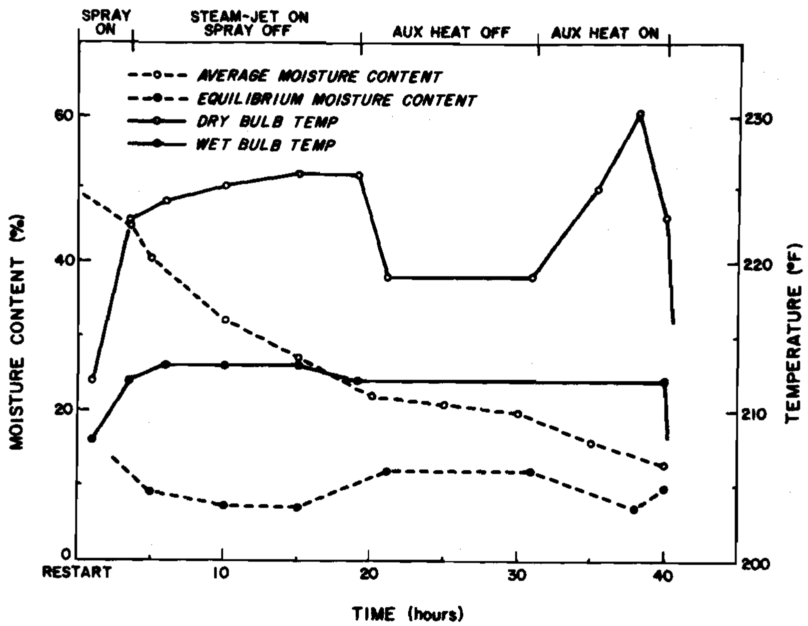


TABLE 17. RAW DATA FOR CHARGE 4

I. MASS DATA			
A. MEASURED			
M_4	Mass of condensate collected in bucket "4"	(lbm)	197
M_5	Mass of condensate collected in barrel "5"	(lbm)	1253
M_6	Mass of condensate collected in barrel "6"	(lbm)	749
M_7	Mass loss from charge "7"	(lbm)	704
M_w	Mass of condensate collected during "warm up"	(lbm)	218
B. DETERMINED			
M_1	Motive steam used by steam-jet $= M_3 - M_2$	(lbm)	746
M_2	Vapor entrained by steam-jet $= M_7 - M_4$	(lbm)	507
M_3	Total flow through steam-jet $= M_5$	(lbm)	1253
M_6	Steam used for auxiliary heat $= M_6$	(lbm)	749
II. TEMPERATURE AND PRESSURE DATA			
T_1, T_6	Temperature of steam from boiler	(°F)	297
T_2	Temperature of entrained vapor	(°F)	210-212
T_3	Temperature of steam entering coils	(°F)	235-237
T_4	Temperature at kiln dry bulb	(°F)	220-226
T_5	Temperature of condensate exiting coil	(°F)	200
T_6	Temperature of condensate exiting coil	(°F)	200
P_1, P_6	Pressure of steam from boiler	(psig)	59
P_2	Pressure of entrained vapor	(in.H_2O)	+0.4-+1.0
P_3	Pressure of steam entering coils	(psig)	7.8-8.9
P_4	Pressure in kiln	(in.H_2O)	+0.4-+1.0

TABLE 17, continued:

III. HEAT USE

A. WARM UP: $H_w = M_w \cdot h_{fg}$

M_w = 218 lbm

T ≅ 297°F

P ≅ 59 psig

h_{fg} ≅ 908 BTU/lbm

HEAT USE, H_w - - - - - - - - - - - - - - - - - - - 197,944 BTU

B. DRYING RUN: $H_D = (M_5 \cdot h_{fgs}) + (M_6 \cdot h_{fg6})$

1. Regular heat, H

M_5 = 1253 lbm

T_3 ≅ 235°F

P_3 ≅ 8.0 psig

h_{fg} ≅ 954 BTU/lb

HEAT USE - - - - - - - - - - - - - - 1,195,362 BTU

2. Auxiliary heat, H_6

M_6 = 749 lbm

T_6 ≅ 297°F

P_6 ≅ 59 psig

h_{fg} ≅ 908 BTU/lb

HEAT USE - - - - - - - - - - - - - - - 680,092 BTU

DRYING, H_D - - - - - - - - - - - - - - - - - - 1,875,454 BTU

C. TOTAL HEAT USE, $H_T = H_w + H_D$ 2,073,398 BTU

D. RECOVERED HEAT: $H_R = M_2 \cdot h_{fg3}$ 483,678 BTU

E. NET HEAT USED: $H_N = H_T - H_R$ 1,589,720 BTU

TABLE 17, continued:

IV. RECOVERY		
A.	Recovery of steam during steam-jet operation $M_2/(M_5+M_6)$	25%
B.	Recovery of steam during kiln operation $M_2/(M_5+M_6+M_w)$	23%
C.	Recovery of heat during steam-jet operation H_R/H_D	26%
D.	Recovery of heat during kiln operation H_R/H_T	23%

APPENDIX 4. CALCULATION OF ANNUAL SAVINGS

Wood Residue

$$C_w \frac{(\text{cost}}{\text{unit})} \cdot \frac{\text{unit}^1}{16 \cdot 10^6 \text{ BTU}} \cdot \frac{1 \text{ BTU (fuel)}^2}{0.65 \text{ BTU (steam)}} \cdot \frac{1181 \text{ BTU (steam)}^3}{\text{pound (steam)}} \cdot$$

$$R(\text{lb steam}) \cdot \frac{F(\text{lb})}{(\text{hour})} \cdot \frac{20 \cdot 360 \text{ (hr)}^4}{(\text{year})}$$

C_w = cost of wood - obtained from local suppliers = \$4.50/unit ± \$2.50/unit

R = recovery (%) = 20%

F = steam flow - average - obtained from experimental data or kiln manufacturer

Annual Savings = $[C_w + G(A/G,i,n)] \cdot F \cdot R \cdot F_w$

$$F_w = \frac{(1181)(20)(360)}{(16 \cdot 10^6)(0.65)} = 0.8176$$

G = growth in fuel price

$A/G,i,n$ = factor to equate growth to equivalent annual cash flow - Riggs, 1974

Bunker C Oil

$$C_o \frac{(\text{cost}}{\text{gal})} \cdot \frac{\text{gallon}^1}{152{,}000 \text{ BTU}} \cdot \frac{\text{BTU (fuel)}^2}{0.80 \text{ BTU (steam)}} \cdot 1181 \cdot R \cdot F \cdot 20 \cdot 360$$

[1] Brubaker, 1976

[2] Corder, 1972

[3] Combustion Engineering, 1967

[4] 35 hours - warm up and dry
 6 hours - cool, unload, load kiln
41 hours - total

35/41 · 24 = 20 hrs/day = average kiln operation

C_g = cost of natural gas - obtained from local suppliers = 0.3837 \$/therm

Annual Savings = $[C_g + G(A/G,i,n)] \cdot F \cdot R \cdot F_g$

$$F_g = \frac{(1181)(20)(360)}{(100{,}000)(0.76)} = 111.8842$$

APPENDIX 5. NET PRESENT VALUE AND PAYBACK FOR BASE DATA*

	Before Tax	After Tax	Year	Interest Factor	Present Value
Experimental Kiln					
Cash Outflows					
Initial Cost	3,574	3,574	0	1	3,574
Maintenance	800	800	1-10	4.1924	3,354
Cash Inflows					
Steam Savings	278	278	1-10	4.1924	1,165
Depreciation	ϕ	ϕ	ϕ	ϕ	ϕ
Net Present Value (Inflows - Outflows)					-5,762
104', Double Track Experimental Kiln					
1. Bunker C oil					
Cash Outflows					
Initial Cost	57,700	57,700	0	1	57,000
Maintenance	4,000	2,000	1-10	4.1924	8,835
Total Outflows					66,085
Cash Inflows					
Steam Savings	37,181	18,591	1-10	4.1924	77,941
Depreciation	5,770	2,885	1-10	4.1924	12,695
Total Inflows					90,036
NPV					23,951
2. Natural gas					
Total Outflows					66,085
Cash Inflows					
Steam Savings	54,092	27,046	1-10	4.1924	113,387
Depreciation					12,695
Total Inflows					125,482
NPV					59,397
3. Wood residue					
Total Outflows					66,085
Cash Inflows					
Steam Savings	4,636	2,318	1-10	4.1924	9,718
Depreciation					12,695
Total Inflows					21,813
NPV					-44,272

*Method adopted from Weston and Brigham (1974).