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# Forest and Wildlife Research Center
# Mississippi Forest Products Laboratory

FINAL REPORT

## DEVELOP APPARATUS AND PROCESS FOR SECOND-STAGE DRYING

ASSISTANCE INSTRUMENT NO. DE-FG01-94CE1555R

MISSISSIPPI STATE UNIVERSITY
SERVICE LEARNING RESEARCH
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# DISCLAIMER

FINAL TECHNICAL REPORT

FOR

SEPTEMBER 26, 1994 - SEPTEMBER 27, 1996

FOR PROJECT ENTITLED

# DEVELOP APPARATUS AND PROCESS FOR SECOND-STAGE DRYING

## ASSISTANCE INSTRUMENT NO. DE-FG01-94CE1555R


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## I. INTRODUCTION

This is the final technical report for this project. The effort on this project has been continuous and productive in gaining a better understanding of the processes involved in the drying of softwoods such as southern yellow pine.

### A. INTRODUCTION TO SECOND-STAGE DRYING

The United States' annual wood fiber consumption is estimated to be between 311 and 368 million cubic meters. The majority of this wood goes into paper and paper based products. The remaining portion goes into sawn lumber and composites. The United States softwood lumber consumption typically ranges between 80 and 100 million cubic meters (33.9 - 42.4 billion board-feet) (Haygreen and Bowyer 1989, Schniewind 1989). In

order to meet the high demand for softwood construction lumber, a rapid timber conversion rate is necessary. This rapid conversion rate means wood must be converted from round wood form to finished products in as little time as possible. To facilitate rapid and efficient drying, high-temperature drying is practiced. Lumber drying is classified as high-temperature when drying temperatures are elevated above the boiling point of water. High-temperature drying of softwoods is practiced around the world. It is a proven technology for drying dimension lumber quickly and economically.

In a 12-month survey conducted in 1992-1993 by the United States Department of Agriculture, Forest Products Laboratory (Rice et al. 1994), it was reported that 56 million cubic meters (24 billion board feet) of softwood lumber was kiln dried in that period. This volume represented between 56 percent and 70 percent of the total softwood lumber production. Most of that lumber was dried using high-temperature kiln schedules.

The accelerated rate at which high-temperature kiln schedules dry lumber is directly related to the increased temperature. As the drying rate is increased, productivity is also increased because more lumber can be dried during a given period of time. An increased drying rate also decreases the residence time of each unit of lumber in the kiln. Decreased residence time imparts a savings in cost per unit of lumber.

This savings has been demonstrated (Koch 1972). While the energy required to remove water from wood may be fixed, decreasing the residence time in any kiln reduces the net loss of heat through the kiln structure. These two variables, residence time and kiln temperature, must be monitored closely to reach maximum efficiency.

In addition to these factors there are other ways in which the cost of kiln drying may be reduced. Greater amounts of insulation and "tighter" kiln structures both help decrease energy loss. Improved inventory management has been promoted as a means of reducing the cost. Ventilation has also been studied with the goal of energy conservation.

Currently, venting is a necessary process in both conventional and high-temperature drying. As excess water vapor builds up in the kiln, the vents are opened and the water vapor is removed. While this process does effectively control the amount of water vapor in the kiln, it is not energy efficient. A large amount of energy is required to heat the lumber and to remove its water. Each time the vents are opened and the steam from the kiln is released, it carries it's latent heat of vaporization with it.

Superheated drying is a process that eliminates the need for ventilation air in the primary kiln. Second-stage drying could then utilize condensing heat exchangers located adjacent to the kiln to recover sensible and latent energy from the exhausted gases from the primary kiln.

The fluid used in the second-stage kiln includes ventilation air because of the lower operating temperatures in the second-stage kiln.

Using the second-stage drying process, more lumber can be dried for a given amount of heat energy supplied to the first-stage kiln than can be dried under traditional high-temperature processes.

Preliminary calculations indicated that the amount of heat energy recovered by condensing the water vapor would be greater than the amount of sensible heat that would be recovered by the heat exchanger. Therefore, condensing the steam from the primary kiln and using it in a second-stage kiln would provide a net heat gain and energy savings over current practices.

Second-stage drying has several advantages over other forms of "vent free" technology such as vapor recompression. First, the initial cost may be lower. The heat exchangers are of simple design. It may be possible to retrofit existing kilns for supplying exhaust to the second-stage kiln. The second major advantage is low operating costs. The only power requirement for second-stage drying is the cost of air circulation. A fan system is required for circulating air across lumber in the secondary kiln. The third advantage is ease of maintenance. The surfaces of the heat exchangers are exposed directly to the kiln chamber and are readily accessible for inspection and maintenance. Regular kiln inspection will reveal if extractives or particulates have built up on their surfaces. When it is found that build up of extractives or particulates occurs, the stainless steel surfaces may be easily cleaned. These factors may make second-stage drying an attractive and industrially feasible method of saving energy in high-temperature kiln drying.

The secondary dry kiln has electrical power requirements similar to that of the primary kiln. Power is required for the air circulation system, the vent action, and the recorder controller. The circulating air passes across the heat exchanger and picks up heat. The hot air is then passed through lumber in the second-stage chamber. As the moisture laden air exits the lumber, it is exhausted out the air vent system. Cool air is admitted and heated as it crosses the heat exchanger. This circulation promotes efficient heat exchanger operation.

The relationship between sensible heat and latent heat of vaporization at the heat exchanger was studied in this experiment. This relationship may be used to determine how much lumber may be dried, relative to conventional high-temperature drying, by utilizing second-stage drying. This relationship may also be helpful in developing time based drying schedules for second-stage drying if more research is conducted and industrial feasibility is achieved.

## B. LITERATURE REVIEW

### 1. Description of high-temperature drying

The process of high-temperature drying dates back to the late nineteenth century. During high-temperature drying, the dry-bulb temperature is raised above the boiling point of water, often in the range of 110 to 138 degrees Celsius (C) (230 to 280 degrees Fahrenheit [F]) (Simpson 1991). These elevated temperatures facilitate rapid moisture movement from the wood to the atmosphere in the kiln. High-temperature drying rates may be several times faster than drying rates observed under conventional conditions.

High-temperature drying was not fully implemented on a commercial scale in the United States until the middle of the 1960's (Koch 1972). Since that time, it has proven to be a rapid and economical method for drying softwood lumber on a commercial scale. High-temperature drying is a fast and efficient way to dry permeable softwoods without appreciable degrade. High-temperature drying is easily automated, requires less drying time per charge, increases throughput, lowers water sorption characteristics, reduces shrinkage and swelling potential, and decreases occurrence of some defects (Kollmann 1961).

High-temperature drying also has some notable disadvantages. These disadvantages include darkening of the lumber surfaces, increased tool wear, increased loose knot fall out, higher lumber moisture gradients, and increased risk of kiln fire (Kollmann 1961).

High-temperature dry kilns are similar to conventional kilns with respect to venting. In both types of kilns, the wet bulb temperature is increased by the addition of live steam and by the moisture vapor supplied by the drying lumber. The wet bulb temperature is decreased by opening the vents, as the wet bulb temperature is highly responsive to the action of the vents opening and closing. A large amount of energy in the form of heat is simultaneously lost when steam is vented from the kiln.

### 2. Energy savings in high-temperature drying

High-temperature kilns provide an energy savings on the order of 50% compared to conventional drying (Koch 1972). It is true that for a given piece of wood, with a given moisture content, the same amount of energy is required to remove the moisture whether at high or low temperatures. The energy savings in high-temperature comes from four principle sources: increased kiln insulation, decreased residence time, faster drying mechanism, and less vented make-up air.

The first major source of energy savings is improved kiln insulation. Efficient insulation reduces the loss of sensible heat conducted through the building (Edison 1990, Olin 1990). Despite the extra effort to equip high-temperature kilns with more efficient insulation, kiln structures still lose some energy to their surroundings whenever the kiln is running.

The second major source of energy savings comes from the decreased residence time of the lumber in the kiln. Residence time is directly proportional to energy consumption. There are perhaps no kilns which are perfectly closed systems. Energy is required to maintain the physical structure of a kiln at temperatures above that of ambient air. Energy is also required to circulate the air in the kiln. Clearly, as residence time is reduced, the operational cost of running the kiln per unit of wood is reduced.

The third energy savings is caused by a change in the drying mechanism at high temperatures. As stated previously, the energy required to dry wood is fixed. At high temperatures, however, the mechanism of drying changes as liquid water in the wood builds up pressure when above the boiling point. The pressure effectively "boils" the water off of the surface of the wood (Koch 1972). As drying continues, this action proceeds toward the core of the wood. This process occurs more rapidly than simple diffusion which is the primary mechanism of conventional drying.

The final source of energy savings in high-temperature drying comes from the decreased amount of ventilation time. The high temperature air has the capacity to hold more water than air at conventional kiln temperatures. This difference means that a larger quantity of water vapor will be held in the air at any given relative humidity. Since the warm air can contain more water vapor (relative to conventional temperature drying), each time the vents are opened a greater amount of water vapor will be exhausted. This increased capacity means that the vents will be closed longer, and less "cool" make-up air will be brought into the kiln.

In summary, there are several factors which contribute to the efficiency of high-temperature drying. Greater attention to insulation, reduced residence time, a relatively faster mechanism of drying, and less vented make-up air all reduce the cost of drying.

### 3. Types of high-temperature drying

High-temperature drying takes place using one of two methods. In the most common method, the dry-bulb temperature is elevated above the boiling point of water and the wet bulb temperature is maintained below the boiling point of water. In this situation the atmosphere in the kiln is a mixture of air and steam.

The second method of high-temperature drying is called superheated drying. In this case the dry kiln operates with only steam in the kiln atmosphere (Kauman 1956). The wet bulb temperature is maintained at the boiling point of water and the dry-bulb temperature is raised above the boiling point of water. The wet bulb temperature in the dry kiln may not exceed the boiling point of water because this would require a kiln chamber pressure greater than atmospheric. Dry kiln pressures greater than atmospheric are not feasible, partly because of safety issues (kiln explosion) but mostly because even the tightest of kiln envelopes will leak some steam.

The equilibrium moisture content of wood corresponding to a given kiln atmosphere may be read directly from a superheated steam - equilibrium moisture content table or predicted theoretically from the dry-bulb and wet bulb temperatures of the environment. High-temperature drying conditions provide a fast and efficient route for drying softwoods and highly permeable hardwoods (Kauman 1956).

## 4. Considerations for Improving High-Temperature Drying

There are many ways in which high-temperature drying may be improved. One way is eliminating losses that occur during venting. Each time the vents are opened and steam escapes, all of the latent heat of vaporization contained in the steam escapes. In order to improve energy efficiency, it is necessary to minimize or eliminate venting. Eliminating venting will eliminate the loss of this energy (latent heat of vaporization) if the vapor can be condensed and the heat recovered.

Another benefit of eliminating venting is the elimination of gaseous emissions. This reduction is an important consideration of all wood drying operations including new and existing dry kilns. Gaseous volatile organic compound emission reduction is an increasing concern of the United States Environmental Protection Agency (McCredie 1991). A full discussion of this issue is beyond the scope of this study, but it is a noteworthy benefit.

If venting is eliminated, excess water vapor will accumulate in the kiln. Water vapor must be continuously removed from the kiln atmosphere if drying is to continue and if the pressure within the kiln is to remain near atmospheric. A mechanism must be in place to remove steam from the drying atmosphere other than simple ventilation.

One such proposed mechanism for removal of steam from the kiln atmosphere is vapor recompression (Miller 1977). Vapor recompression uses a mechanical compressor to compress excess steam in the kiln. Steam in the kiln is drawn into the compressor through an intake port. The compression effectively raises the temperature of the steam. The compressed steam is then recirculated to the steam heat coils in the kiln. Miller claims that the compressor provides a substantial savings in heat energy. The only theoretical limitation to the drying rate is the compressor volume. The faster the compressor can remove vapor, the faster moisture can be evaporated from the surface of the lumber. One practical drawback of this process is the effect of extractives and particulate matter on the compressor. In commercial softwood lumber drying, especially with resinous species such as southern yellow pine, extractives tend to accumulate on every surface within the kiln. There also may be particulate matter such as sawdust, small chips, and dirt in the kiln atmosphere during drying. Therefore, a filtration system must be used in conjunction with this method. If a filtration system is not used, these materials would obviously be detrimental to the compressor's efficiency and ultimate life-span.

Second-stage kilns with heat exchangers provide a surface for both sensible and latent thermal energy recovery from the exhaust gases of the first-stage kiln. It is proposed that a second-stage dry kiln could be located adjacent to a new kiln or retro-fit beside an existing kiln. The heat exchanger would be on the interior surface of the second-stage kiln (Bouchillon and Taylor 1994).

Each kilogram of steam that is condensed provides $2.255 \times 10^{6}$ Joules of heat energy (Sternheim and Kane 1991). This heat energy would otherwise be vented out the roof.

The gross energy requirement for drying softwood is between $1.117 \times 10^{9}$ to $1.563 \times 10^{9}$ Joules per cubic meter (2500--3500 BTU/board foot) (Bridges 1996). This reauirement means that each kilogram of water vapor which condenses on the heat exchanger has the potential for drying $1.443 \times 10^{-3}$ to $2.019 \times 10^{-3}$ cubic meters (0.63 to 0.88 board feet) of wood.

In addition to recovering the latent heat of condensation, some sensible heat will also be recovered by the heat exchangers.

Significant experimental findings have been obtained for the pilot-scale system which was fabricated and tested during this project. A visit was made with representatives at the headquarters of the Irvington-Moore Corporation, a major manufacturer of dry kilns, Jacksonville, Florida. Technical details of the results of analytical and experimental efforts on the various tasks planned for this project are presented below.

## II. RESULTS OF TASKS UNDERTAKEN IN THE PROJECT

Technical results of the various tasks undertaken in this project are presented below. The tasks are listed in the order presented in the proposal for this project.

## A. TASK 1. COMPUTER SIMULATION REFINEMENT AND EXTENSION OF THE THEORY TO COMMERCIAL-SIZED KILNS

### 1. Task 1A. Verification of Computer Model Simulation of the Drying Process for Lumber in a Superheated Steam Kiln.

A preliminary literature search was conducted and several pertinent articles were obtained. Complete bibliographical information are presented in this report, both in the Literature Cited Section as well as the Other References Section.

The existing pole drying computer model was modified for prediction of the drying rates and energy requirements for dimensioned southern pine lumber. The correlation equations for drying (Milota and Tschernitz, 1990) were particularly useful in providing empirical formulation of the constant drying rate as well as for the transition to the asymptotic approach to completely dry wood. Also, the theory for equilibrium moisture in wood (Simpson and Rosen, 1981) was useful in modeling the equilibrium moisture content in pine at various temperatures and humidities.

#### a. PRELIMINARY CALCULATIONS WITH THE FIRST MODEL

An example of the predictive capability of the computer model in relation to the experimental cases on which it was based is presented as Figure 1. This presents a comparison of the predicted values with a curve approximating experimental values (Milota and Tschernitz, 1990).

Further work on the model was undertaken to approximate the drying of southern pine lumber in a superheated steam condition. An empirical adjustment of the dry-bulb temperature to account for the increased heat transfer and evaporative rate with superheated steam was postulated. The function used was:

$$T_{DB} = 212 + (T_{DB} - 212) \times ((T_{DB} - 212)/33)^{0.66}$$

This adjustment gave good approximate drying times in relation to experimental values (Taylor 1995). Comparison of these predictions are shown as Figures 2-4 below.

During a visit with Irvington-Moore, actual steam consumption rates for a specific designed kiln were requested with a positive response that these could be made available. Continuing cooperation with them is expected to yield actual experimental operating data for comparison with predictions of energy losses which will be predicted by an appropriate model to be developed.

As a beginning step, a typical dry-bulb/wet-bulb schedule for the Irvington-Moore Kiln Boss dry kiln has been programmed with the drying model described above. This preliminary result does not reflect the temperature losses through the lumber stacks, consequently, the predictions are for a drying rate that is slightly too fast. An example of the temperature schedules and the lumber moisture prediction is presented as Figure 5.

### b. DETAILED DESCRIPTION OF THE COMPUTER MODEL

#### 1). CALCULATION OF TEMPERATURE-PRESSURE RELATIONSHIPS

The well known equations for the pressure-temperature relationships amongst the dry-bulb temperature, the wet-bulb temperature, the relative humidity, and the specific humidity were taken from the literature for properties of steam (Keenan and Keyes, 19xx).

The equilibrium pressure for steam based on the dry-bulb temperature is calculated from:

$$PDB = 10^{(.4343*LOG(PC)-(X/TDB)*(A+B*X+C*X^3)/(1+D*X))} \qquad (1)$$

where:

PDB is the equilibrium pressure of steam at the dry-bulb temperature
TC = 647.27 and is the critical temperature in deg. K
TDBK is the dry-bulb temperature in deg. K
PC = 218.167 and is the critical pressure in MPa
A = 3.2437814
B = 5.86826E-03
C = 0.0000000111702379
D = 2.187462E-03
and
X = (TC-TDB)

The equilibrium pressure for steam based on the wet-bulb temperature (PWB) is then calculated from the same formula using the wet-bulb temperature (TWBK) in deg. Kelvin.

The partial pressure of the vapor is then calculated from:

FPV = PWB - (TDB - TWB)/2700

If the velocity (VEL) is less than 1329 ft/min, then:

$$FV = ( VEL / 1329)^{0.3}$$

or if the velocity (VEL) is greater than 1329 ft/min, then:

$$FV = ( VEL / 1329)^{0.5}$$

Then a correction (FCR) is calculated according to:

$$FCR = (0.01208+0.006797*(TDB-TWB)-2.482E-05*(TDB-TWB)^{2}*FV$$

Then the steady evaporation rate (ST) is predicted as:

$$ST = STCOEFF * EXP( - STRATE / TDBR)$$

where:

STCOEFF = 150.4
STRATE = 7156.5
TDBR is the dry-bulb temperature in degrees Rankine

Then another adjustment factor is calculated for wet-bulb temperature depression, i.e. (TDB - TWB).

FN = 5, or

if (TDBF-TWBF) is less than 46, then:

$$FN = 0.75 + (0.093 * (TDBF-TWBF))$$

Then the moisture evaporated per unit surface area is calculated from:

$$FM = ((ST *(FMC - EMC))^{(-FN)} + FCR^{(-FN)})^{(-1.0/FN)}$$

where:

FMC is the moisture content of the board at the time.
EMC is the predicted equilibrium moisture content of the boards.
FCR is calculated above to account for velocity variations.

During this investigation, it was found that the prediction was based on experiments with one board with four sides exposed. It was a 2 x 6-inch board, so it had a perimeter of 16 inches, 12 of which were on the wide board sides. An adjustment of 0.75 times the predicted moisture evaporation rate was used in the model and produced good prediction for full dry kiln situations. Consequently, FM was adjusted by 0.75 *FM.

### 5). PREDICTION OF AVERAGE MOISTURE CONTENT OF WOOD IN THE KILN

The final moisture content (FMC) for the time step was calculated by:

FMC = FMC - 200 / (THK*RHO) * FM * DT

where:

FMC is the average moisture content of the boards at the time considered
THK is the board thickness in inches
RHO is the board dry density in $lbm/ft^3$
FM is calculated above and
DT is the time step interval

### 6). VENTILATION AIR REQUIREMENTS

The next step in the calculations is the prediction of the ventilation air required for the dry kiln being evaluated.

The total moisture generated may be determined from multiplying the evaporation rate per unit area per unit time (FM) by the board feet in the kiln. The surface area of the 2 x 6 boards which is exposed for moisture evaporation is 1 square foot per board foot, thus the total moisture evaporation rate is:

FFM = FM * ABF

The amount of dry air required for absorbing the moisture for maintenance of the wet-bulb temperature condition in the dry kiln can be calculated from:

FFMDDAIN = FFM/(GAM-GAMA)

where:

FFMDDAIN is the mass rate of flow of dry air
FFM is the moisture to be exhausted
GAM is the specific humidity of the dry kiln
and
GAMMA is the specific humidity of the outside air

The preceding equations for relative and specific humidity predictions are then used to calculate the specific humidity of both the dry kiln condition and the outside air condition.

If the wet-bulb temperature is 212°F, then only steam is exhausted and no ventilation air is required.

**7). CALCULATION OF THE ENERGY REQUIRED TO HEAT THE VENT AIR**

The energy rate required to heat the vent air can be calculated from:

QVENT = FFMDDAIN*(0.24*(TDB-TDBA)+GAMA*(0.44*(TDB-TDBA)))

where:

QVENT is the energy rate to heat the vent air in BTU/HR
FFMDDAIN is the dry air vent rate in lbm/min
0.24 is the specific heat of dry air
TDB is the dry-bulb temperature in the kiln
TDBA is the outside dry-bulb temperature
GAMA is the specific humidity of the outside air
0.44 is the specific heat of steam

## 8). CALCULATION OF THE HEAT RATE REQUIREMENT FOR EVAPORATION OF MOISTURE FROM THE WOOD IN THE KILN

The required heat rate for the drying of the lumber can be calculated from:

$$QR = (FM * (1062 + (0.45 * ( TDB - 212 ))) * ABF)$$

where:

QR is the required heat rate in BTU/HR
FM is the evaporation rate per unit area per unit time
1062 is the latent heat of vaporization of water
TDB is the dry-bulb temperature in the kiln
ABF is the board feet or square feet of surface area

## 9). OTHER HEAT LOSSES

Other heat losses in the operation of a dry kiln include losses through the walls, ceiling, floor periphery, infiltration through the doors, and heating up the wood in the kiln on start-up.

The walls and ceiling losses can be approximated by assuming that the walls and ceiling have a thermal resistance rating of 10. This is used in the general equation of heat transfer as:

$$Q = A * DT/R \quad \text{(Btu/hr)}$$

where:

A is the area in square feet
DT is the temperature difference in deg. F
Q is the heat transfer rate in Btu/hr and
R is the thermal resistance

The units for the thermal resistance are hr/(deg F-Btu-ft$^2$).

The perimeter loss around the floor may be approximated by assuming that the thermal resistance can be taken as 5 hr/(deg. F-Btu-ft) in the relationship:

$$Q_P = L_P * DT / R_P$$

where:

$L_P$ is the length of the perimeter
DT is the temperature difference
$R_P$ is the thermal resistance of the perimeter and
$Q_P$ is the heat loss around the perimeter in Btu/hr

The energy rate required for heating the water in the lumber in the kiln on the initial start-up may be approximated by:

QHTW = (BFT/12)*RHO*(FMC)/100*(TWB-TWB1)

where:

QHTW is the heat required to heat the water in the lumber from the previous wet-bulb temperature
(TWB1) to the current wet-bulb temperature
(TWB) in the time stepped fashion of the kiln predictions.

Also, the energy rate required for heating the lumber in the kiln on initial startup may be approximated by:

QHTL = (BFT/12)*RHO*(TWB-TWB1)*0.5

where:

QHTL is the heat required to heat the dry lumber in the kiln from the previous wet-bulb temperature (TWB1) to the current wet-bulb temperature (TWB) in the time stepped fashion of the kiln predictions.

The 0.5 is the specific heat of the dry lumber.

### 10). TOTAL HEAT RATE REQUIREMENTS FOR THE DRY KILN

The total heat rate requirements for the dry kiln may then be assembled from the above calculations as:

QT = QT + QR * dt + QVENT * dt + QLOSS * dt + QHTW + QHTL

where:

QT is the total energy required in BTU from the start of the kiln to the current time condition in the time stepping process of numerical predictions
QR is the energy rate required for evaporation
QVENT is the energy required to heat the vent air
QLOSS is the loss through the walls and perimeter
QHTW and QHTL are the energy requirements for heating wet lumber and
dt is the time interval of the calculation.

### 11). PREDICTION OF ENERGY AVAILABLE FOR Second-Stage KILN

The energy available for use in the second-stage kiln may be determined by specifying the wet-bulb and dry-bulb temperature to which the heat exchanger will take the vented gases from the first-stage kiln.

First, the specific humidity of the resultant gas mixture is determined. Then the thermal energy which can be recovered by sensible and latent heat during reduction to that state is determined by considering the difference in the energy level at the reduced state and the original state leaving the first-stage kiln.

The equation used for sensible heat recovery is:

```
QSREC2 = FFMDDAIN*(0.24*(TDB-TDB2)+GAM*(0.44*(TDB-TDB2)))
```

where:

- QSREC2 is the sensible heat recovery in BTU
- FFMDDAIN is the dry air ventilation rate in lbm/min
- TDB is the dry-bulb temperature in the kiln
- TDB2 is the dry-bulb temperature in the heat exchanger
- GAM is the specific humidity of the gas mixture in the kiln
- 0.24 is the specific heat for the dry air
- 0.44 is the specific heat for the steam

The equation for the latent heat recovery is:

```
QLREC2 = (QMFS - FFMDDAIN*(GAM2))*1062
```

where:

- QLREC2 is the latent heat recovery from the gas admitted to the heat exchanger for the second-stage kiln
- QMFS is the mass rate of moisture evaporation from the lumber, i.e., FM*ABF
- FFMDDAIN is the mass rate of flow of dry vent air
- GAM2 is the specific humidity at the conditions in the heat exchanger
- 1062 is the latent heat of fusion of water in Btu/lbm

Note that if superheat drying conditions are used in the first-stage kiln, then the mass rate of flow of dry air in the vent is zero, and theoretically, all of the steam generated is available to be condensed on the surface of the heat exchanger, provided the temperature in the second-stage kiln is less than 212°F.

## 12). PREDICTIONS OF OPERATION WITH THE COMPUTER MODEL

Appication of the computer model to four various dry kiln situations was made. Three different drying schedules were recommended by Dr. Taylor for the first-stage kiln operation, along with a schedule for the second-stage kiln.

A typical commercial double track kiln design for 100,000 board feet of 2 x 6 lumber was used. The dimensions were 32 feet wide, 68 feet long, 20 feet high at the sides and 22 feet high in the center.

Both tabular and graphical interpretation of the results of these predictions are presented below.

## 13). DRYING SCHEDULE 1 - IRVINGTON-MOORE KILN-BOSS

Table 1 presents the computer model predictions for a typical commercial kiln (Kiln-Boss) drying schedule of dry-bulb and wet-bulb temperatures as a function of time. This data is then presented in graphical form in Figures 6 thorugh 10. Figure 6 shows the temperture-time history for the drying schedule in the kiln. Figure 7 depicts the moisture level in the wood in the kiln as a function of time. Figure 8 represents the energy rate and the total accumulated energy required for heating the vent air for this schedule. Figure 9 represents the energy rate for drying and the total energy requirement, including losses, for the operation of the dry kiln.

**14). DRYING SCHEDULE 2 - SUPERHEAT DRYING CONDITIONS**

Figure 10 shows the energy which would be available for use in a second-stage kiln calculated based on the observation that the dew point temperature in the heat exchanger would be 170°F for the second-stage kiln to achieve a 150°F dry-bulb temperature. Notice that because the wet-bulb temperature is maintained at 170°F, there would be no latent heat energy available from the first-stage exhaust product stream.

Table 2 presents the computer model predictions for a typical commercial kiln (Schedule 2 proposed by Dr. Taylor) drying schedule of dry-bulb and wet-bulb temperatures as a function of time. This data is then presented in graphical form in Figures 11 thorugh 15. Figure 11 shows the temperture-time history for the drying schedule in the kiln. Figure 12 depicts the moisture level in the wood in the kiln as a function of time. Figure 13 represents the energy rate and the total accumulated energy required for heating the vent air for this schedule. Figure 14 represents the energy rate for drying and the total energy requirement, including losses, for the operation of the dry kiln.

Figure 15 shows the energy which would be available for use in a second-stage kiln. Calculation is based on the fact that the dew point temperature in the heat exchanger would be 170°F for the second-stage kiln to achieve a 150°F dry-bulb temperature. Notice that because the wet-bulb temperature is maintained at 212°F in the latter stages of the schedule, there would more latent heat energy available from the first-stage exhaust product stream than could be used by the second-stage kiln. Details of this comparison will be discussed below.

### 15). DRYING SCHEDULE 3 - HIGH TEMPERATURE DRYING

Table 3 presents the computer model predictions for a typical commercial kiln (Schedule 3 proposed by Dr. Taylor) drying schedule of dry-bulb and wet-bulb temperatures as a function of time. This data is then presented in graphical form in Figures 16 thorugh 20. Figure 16 shows the temperture-time history for the drying schedule in the kiln. Figure 17 depicts the moisture level in the wood in the kiln as a function of time. Figure 18 represents the energy rate and the total accumulated energy required for heating the vent air for this schedule. Figure 19 represents the energy rate for drying and the total energy requirement, including losses, for the operation of the dry kiln.

Figure 20 shows that the energy which would be available for use in a second-stage kiln is calculated on the assumption that the dew point temperature in the heat exchanger would be 170°F for the second-stage kiln to achieve a 150°F dry-bulb temperature. Notice that because the wet-bulb temperature is maintained at 180°F in the latter stages of the schedule, there would some latent heat energy available from the first-stage exhaust product stream which could be used by the second-stage kiln. Details of this comparison will be discussed below.

### 16). Second-Stage KILN PREDICTIONS

Using the same model for predictions of the operation of the second-stage kiln, the results are presented in both tabular and graphical form.

Table 4 presents the computer model predictions for a typical second-stage kiln (Schedule proposed by Dr. Taylor) drying schedule of dry-bulb and wet-bulb temperatures as a function of time. This data is then presented in graphical form in Figures 21 though 25. Figure 21 shows the temperature-time history for the drying schedule in the kiln. Figure 22 depicts the moisture level in the wood in the kiln as a function of time. Figure 23 represents the energy rate and the total accumulated energy required for heating the vent air for this schedule. Figure 24 represents the energy rate for drying.

Figure 25 shows the energy rate for drying and the total energy which would be required, including losses, in a second-stage kiln.

**2. Task 1B. Establish Energy Loss Predictions for Specific Kiln Designs for the First-Stage Kiln**

Energy loss predictions for typical commercial kiln design were discussed in detail above.

An energy consumption schedule was obtained from a kiln company for a conventional kiln design. This is essentially the energy requirements for the first-stage kiln. Preliminary results have been obtained; however, additional effort is required to explain the higher energy consumption rates at the initial stages of drying. Part of this energy is required to heat up the lumber in the kiln, the kiln, and the heat exchangers in the case of steam operated dry kilns. A plot is shown in Figure 26 of the design energy requirements as supplied by the kiln company, compared with the theoretically predicted energy requirement as a function of drying time before the energy losses in the walls of the kiln and heating of the kiln and lumber was considered in the model.

**3. Task 1C. Establish Energy Loss Predictions for Specific Kiln Designs for the Second-Stage Kiln**

Energy loss predictions for typical commercial kiln design were discussed in detail above.

A copy of the computer program in FORTRAN is included as APPENDIX A.

## B. TASK 2. DETAILED HEAT EXCHANGER EQUIPMENT DESIGN

### 1. DETAILS OF HEAT EXCHANGER DESIGN

The heat exchanger panels must provide surface area which is greater than the face area of the walls and ceiling of the second-stage kiln.

In order to produce commercially viable panels, a sheet rolling technique for production must be employed. The "V" grooved and the deep grooved sheets prepared for the experimental pilot-scale equipment were made on an ordinary sheet metal braking apparatus.

A simple combination of straight sections combined with circular sections will provide for a design which may be readily made with appropriate rollers in a typical cold rolling operation such as is used in the metal building industry for panel stiffening techniques.

Geometric relationships have been established for such an arrangement. Figure 29 provides reference information relative to the analysis for the layout of the panels.

First, a relative dimension is selected for the straight sections of the panel. With reference to the figure, values for X1 and Y1 are selected. Then the value of X2 is selected. Then the radius may be determined as follows.

First, the angle THETA1 (TH1) is determined from the geometric relationship that:

TH1 = ARCTAN (X1/Y1)

Then the radius (R) is determined from:

R = (X2-X1)/ COS(TH1)

Then for the circular section to have tangency with the straight section, the value of Y2 is determined from:

Y2 = Y1 - R SIN(TH1)

When this has been established, then the circular section may be determined by selecting a value of X and calculating the value of Y by successively taking:

TH = ARCOS((X2-X)/R)
and
Y = Y2 + R SIN(TH)

Once the initial profile is established up to the center of the circular section, then mirror imaging may be used to generate the remainder of the profiles.

For example, if the following values are used:

X1 = 6, Y1 = 10, and X2 = 10,

then the resultant surface area is 1.63 times the frontal area.

Using X1 = 6, Y1 = 16, and X2 = 10, then the resultant surface area is 2.21 times the frontal area.

A total depth of surface shouldn't exceed about 3 inches for appropriate heat transfer characteristics. Therefore, the recommended design for the 2.21 dimension combination would be:

$X1 = 0.5$ inches, $Y1 = 1.333$ inches, and $X2 = 0.8333$ inches. The total depth would then be 3.13 inches.

This should be a suitable configuration for use as a heat exchanger panel in second-stage kiln designs.

A sketch of the detailed heat exchanger equipment is presented as Figure 27.

## C. TASK 3. PILOT-SCALE DESIGN AND FABRICATION

### 1. Task 3A. Establish Three Different Designs for Heat Exchanger Geometries to be Tested in the Pilot-Scale System.

Configurations of commercially available rolled metal sheeting typically used in metal building construction, right angle deep grooved metal sheeting, and a deep "V" groove heat exchanger panel were fabricated for use in the pilot-scale test apparatus.

Detailed designs were made for insertion into three chambers which are inserted into the steam coil dry kiln of the Forest Products Laboratory (FPL). The designs incorporate a catch basin for the condensate on the surface of the heat exchanger surfaces. Two of the designs used galvanized steel material and one used an aluminum coated steel panel. The galvanized steel material oxidized rather quickly during the tests. The aluminum coated steel sheet only corroded where the surface was scratched.

Two stainless steel heat exchanger surfaces were ordered for further testing of these designs.

Perspective drawings of the three test panel designs are presented as Figures 28 through 30.

### 2. Task 3B. Fabrication of the Pilot-Scale Equipment

Drawings of the detailed design of the pilot-scale experimental apparatus were made and the general apparatus was fabricated.

The existing dry kiln at the FPL has been used to simulate the first-stage kiln. Three compartments, each with its own circulating blower, inlet damper, and outlet damper, are being used for testing the three different heat exchanger configurations. Collection of the condensate from the heat exchanger surfaces allows approximate determination of the energy recovery from each of the three heat exchanger designs.

A perspective drawing of the test cells is presented as Figure 31.

### 3. Task 3C. Assembly of the Pilot-Scale System

The pilot-scale system was fabricated and testing was conducted on the system.

## D. TASK 4. EXPERIMENTAL EVALUATION OF THE PILOT-SCALE SYSTEM

Experimental evaluation of the pilot-scale system consisted of first establishing approximate velocity distributions in the test cells. Then a series of experiments were conducted with various operating temperatures in the test cells and with different thermal conditions in the FPL steam tube heated dry kiln.

### 1. Determination of Velocities in the Three Test Chambers.

The three test chambers are mounted on the movable platform which is used to load the lumber charge into the dry kiln of the FPL. Consequently, the three test chambers can be moved away from the door for access to the front panel. The velocities at the vertical center of the test panel were measured at 5 different locations for each inch of clearance in the 5, 6, and 7 inch distances from the front edge of the test section to the movable interior baffle. Additional baffling was added to achieve better velocity distributions across the panel. A table of velocity measurements is presented below as Tables 5A, 5B, and 5C. Also, a velocity measurement was made at the top center of the baffle for the three cells. A table of those velocity measurements is presented as Table 6.

### 2. Determination of Heat Transfer Characteristics

The three heat exchanger test panels were installed in the three test chambers and 10 test runs were made to determine the operational characteristics of the experimental laboratory-scale apparatus. Two thermocouples were installed in each test cell. The temperature was recorded every minute during a two hour test run. The condensate from the heat exchanger surfaces was collected and weighed. Then the recovered latent heat of condensation was determined and reported in the results. A table of the summary of the results of these experiments is presented as Table 7.

As was expected, the convoluted heat exchanger surfaces did yield a higher heat transfer rate than did the surface of classical metal building sheeting.

### 3. Additional Testing of the Heat Transfer in the Test Cells

Thirty additional tests were then conducted. A summary of these results, including the 10 previous runs, are included as Tables 8, 9, and 10 for each of the heat transfer panel designs.

A preliminary evaluation of the heat transfer rate for the heat transfer panels as a function of the temperature difference between the dry-bulb temperature in the primary kiln and the air temperature of the circulation in the test cells are presented as Figures 32, 33, and 34.

The stainless steel test panels for the pilot-scale experimental apparatus were installed in the general apparatus for the performance of the tests at different first-stage kiln conditions.

Only the deep grooved and the accordion folded panels were fabricated in stainless steel. The flat panel aluminized panel had only slight degradation of the surface on a small scratched area, so it was not necessary to replicate that panel.

### 4. Additional Testing of the Heat Transfer in the Test Cells

Additional data has been collected for the deep grooved and accordion folded stainless panels as well as for the flat aluminized steel panel. Those results are presented below as Tables 11, 12, and 13.

A preliminary evaluation of the heat transfer rate for the heat transfer panels as a function of the temperature difference between the dry-bulb temperature in the primary kiln and the air temperature of the circulation in the test cells are presented as Figures 35, 36, and 37 for the deep grooved stainless and the accordion folded stainless and the flat aluminized steel panels.

As was expected, the convoluted heat exchanger surfaces did yield a higher heat transfer rate than did the surface of classical metal building sheeting.

### 5. Testing with Water Spray

This task was extended with the heat exchanger panels being used as test panels with liquid water spray onto the exterior surface. This allowed additional information on the heat exchange process to be obtained. A summary of the results are presented in Figures 38, 39, and 40. This yielded condensation at rates approximately 10 times that for the air circulation on the exterior of the test panels as was expected for the combination of condensation/boiling heat transfers across a metal barrier.

Again, as expected, the convoluted heat exchanger surfaces did yield a higher heat transfer rate than did the surface of classical metal building sheeting.

## E. TASK 5. PRELIMINARY DESIGN OF A PROTOTYPE SYSTEM

Preliminary design of a prototype system has reached only rudimentary level in which the concepts for a possible configuration is presented.

### A. ESTIMATION OF CONDUCTION COEFFICIENT FOR FLAT PANEL HEAT EXCHANGER

Heat transfer potential for forced air in full sized second-stage chamber:

$V$ = air velocity ~ 3 m/s
$L$ = length ~ 7 m
$T$ = temperature ~ 65 C
$n$ = kinematic viscosity ~ $18 \times 10^{-6}$ $m^2/s$

$k_{ss}$ = conductivity of air ~ $28 \times 10^{-3}$ J/s m C
S = surface roughness factor ~ 3
Pr = Prandtl number ~ 0.698
Re = Reynold's number = V x L / n = $1.167 \times 10^{6}$
Nu = Nusselt number ~ 0.037 x $Re^{0.8}$ x $Pr^{0.33}$ = 2345
$h_{ss}$ = heat transfer coefficient ~ Nu x S x $k_{ss}$ / L = 28.14 J/s $m^2$ C = 4.96 Btu/(hr-$ft^2$-F)

Thickness and thermal conductivity of the aluminized metal:

$w_{am}$ = thickness = $500 \times 10^{-6}$ m
$k_{am}$ = thermal conductivity = 60 J/s m C (carbon steel)

Thermal conductance of the aluminized metal is:

$k_m/w_m$ = 60 J/s m C/$500 \times 10^{-6}$ m = $120 \times 10^{3}$ J/s $m^2$ C.

Thickness and thermal conductivity of the stainless steel:

$w_s$ = thickness = $500 \times 10^{-6}$ m
$k_s$ = thermal conductivity = 15 J/s m C (stainless steel)

Thermal conductance of the stainless steel is:

$k_s/w_s$ = 15 J/s m C/$500 \times 10^{-6}$ m = $30 \times 10^{3}$ J/s $m^2$ C.

With both types of metal, the aluminized steel and the stainless steel, the metallic conductance is considered infinitely larger than the conductance of the air. Therefore, the air is the limiting factor of the sensible heat transfer and only its conduction coefficient will be considered.

### B. SURFACE AREA REQUIREMENTS FOR SECOND-STAGE KILN

The surface area requirements for the second-stage kiln for a typical 100,000 board foot kiln are about 5 million Btu/hr. With a temperature difference of 212 - 150 = 62°F; the difference between the steam condensing temperature and the dry-bulb temperature in the second-stage kiln, the area required for heat transfer can be calculated from:

$$Q = h_{ss} \times A \times DT \quad \text{or } A = q/(h_{ss} \times DT)$$

then

$$A = 5 \times 10^6 / (4.96 \times 62) = 16{,}259 \text{ sq. ft.}$$

The frontal surface area of the side-walls and ceiling would be only 5,304 square feet. If the surface area was 2 x the frontal surface area, there would not be sufficient surface area for the drying cycle in the second-stage kiln.

Thus, a double track second-stage kiln could not be used in connection with a first-stage double track kiln using a superheated steam drying schedule.

Checking on the requirements for a single track kiln, the heat transfer requirements would be approximately 1/2 of those required for the double-track kiln. There would be approximately enough surface area with a 2:1 surface area to frontal area; however, it would require about 5 drying cycles of the first-stage kiln for one cycle of the second-stage kiln. This would not be economically viable.

**CONCLUSIONS**

Although there is sufficient available energy in the exhaust gases from first-stage kiln operations to provide operational energy for a second-stage dry kiln operating at lower temperatures, the required surface area for the energy recovery heat exchangers is prohibitive for its re-capture. Also, scheduling problems associated with the first and second-stage kilns would not be acceptable to the industry. This is because of the high capital costs involved in the kilns, with the resultant requirement of as continuous use as possible.

From the experiments using water on the exterior of a heat exchanger panel exposed to the first-stage superheated kiln, it may be feasible to utilize a closed kiln concept with wall condensation vapor removal. This would have the advantage of restricting Volitle Organic Compounds from being exhausted from the kiln. Further investigations are recommended on this concept of closed kiln operations.

A perspective drawing of a possible configuration which would could be used if the scheduling of charges and drying cycles could be appropriately orchestrated is presented as Figure 41.

## F. TASK 6. TECHNICAL REPORT OF RESULTS

This report is the conclusion of this effort.

# III. REPORT OF VISIT WITH IRVINGTON-MOORE, INC.

A visit to the Irvington-Moore, Inc. manufacturing facility in Jacksonville, FL was made by Dr. Fred Taylor and Dr. C. W. Bouchillon for the purpose of discussing possible commercialization of the concepts being developed in this project.

Personnel at the meeting included Mr. Tom Goodwin, Mr. Todd Ross, and Mr. Mike Patterson. We reviewed the general concept, discussed our plans for both theoretical and experimental development of the preliminary designs, and explored possible interactions with them during the course of our developmental activities.

Mr. Mike Patterson, Sales Engineer, was to cooperate with us especially in that he had an assignment to investigate condensing surfaces for another project.

Subsequent to our visit, Mr. Mike Patterson and Mr. E. Alan Robbins, Equipment Applications Specialist, visited the FPL for an orientation on this project and other projects of mutual interest.

They also responded affirmatively to our request for some actual energy consumption data from a specific kiln. This data will come from some operating company and would take a few months to obtain; however, we never received any data from them.

Unfortunately, their interest in this project has not continued at the initial level.

**REFERENCES CITED**


Boston, E., et al. 1990. Energy Crafted Home. West River Communications, Inc. Brattleboro, Vermont. 527 p.

Bouchillon, C. W., Mechanical Engineer. July 1996. Private consultation.

Bouchillon, C. W., and F. W. Taylor. 1994. Apparatus and Process for Second-stage Drying. Draft Technical Proposal. Mississippi State University, Starkville, Mississippi.

Bridges, G. 1996. Wellons Company, Kiln Representative. Personal communication, interview & letter.

Haygreen, J. G., and J. L. Bowyer. 1989. Forest Products and Wood Science: An Introduction 2nd ed., Iowa State University Press. Ames, Iowa. 500 p.

Kauman, W. G. 1956. Equilibrium moisture content relations and drying control in superheated steam drying. Forest Products Journal. 6(9):322-328.

Keenan and Keyes. 1936, Thermodynamic Properties of Steam. J. Wiley & Sons, Inc., New York, Chapman & Hall, London. 89 p.

Koch, P. 1972. Utilization of Southern Pines, Vols. I & II. USDA Forest Service, Agricultural Handbook No. 420. Supt. of Gov. Docs., Washington DC. 1663 p.

Kollmann, F. F. P. 1961. High-temperature drying research, application, and experience in Germany. Forest Products Journal. 11(11):508-515.

McCredie, W. H. 1991. Impact of the 1990 Clean Air Act Amendments on the Lumber and Wood Products Industry. Paper presented at the 25th International Particleboard/Composite Materials Symposium. Washington State University, Pullman, Washington.

Miller, W. 1977. Energy conservation in timber-drying kilns by vapor recompression. Forest Products Journal. 27(9):54-58.

Milota, Michael R., and John L. Tschernitz. 1990. Correlation of Loblolly Pine Drying Rates at High Temperature. Wood and Fiber Science. 22(3):298,313.

Olin, H. B. 1990. Construction Principles, Materials, and Methods. Van Nostrand Reinhold, New York, New York. pp. 105.1-105.3

Rice, R. W., J. L. Howe, R. S. Boone, and J. L. Tschernitz. 1994. Kiln Drying Lumber in the United States. A Survey of Volume, Species, Kiln Capacity, Equipment, and Procedures, 1992-1993. USDA Forest Service. General Technical Report FPL-GTR-81. 24 p.

Schniewind, A. P. 1989. Concise Encyclopedia of Wood & Wood-Based Materials. MIT Press, Cambridge, Massachusetts. 354 p.

Simpson, W. T. (ed.). 1991. Dry Kiln Operators Manual. USDA Forest Service, Agricultural Handbook No. 188. Supt. of Gov. Docs., Washington DC. 273 p.

Simpson, W. T., and Howard N. Rosen. 1981. Equilibrium Moisture Content of Wood at High Temperatures. Wood and Fiber Science. 13(3):150-158.

Sternheim, M. M., and J. W. Kane. 1991. General Physics. John Wiley & Sons. New York, New York. 891 p.

Taylor, Fred 1995, Private Communication.

**SELECTED REFERENCES**

Biggerstaff, T. 1965. Drying diffusion coefficients in wood. Forest Products Journal. 15(3):127-133.

Bouchillon, C. W., and F. W. Taylor. 1994. Apparatus and Process for Second-stage Drying. Draft Technical Proposal. Mississippi State University, Starkville, Mississippi.

Burghardt, M. D. 1986. Engineering Thermodynamics with Applications. Harper & Row. New York, NY. 608 p.

Calvert, W. W. 1958. High-temperature kiln drying of lumber - a summary of Canadian progress. Forest Product Journal. 8(7):200-204.

Cook, F. W. 1968. Steam sprays-the third factor in relative humidity or equilibrium moisture content control. Forest Products Research Society News Digest (Drying Division). Synopsis of talk presented at 10/1968 meeting of West Coast Dry Kiln Club. 2 p.

Glover, T. J. 1993. Pocket Ref. Sequoia Publishing, Inc. Littleton, Colorado. 490 p.

Haygreen, J. G., and J. L. Bowyer. 1989. Forest Products and Wood Science: An Introduction 2nd ed., Iowa State University Press. Ames, Iowa. 500 p.

Incropera, F. P., and D. P. DeWitt. 1981. Fundamentals of Heat Transfer. John Wiley & Sons. New York, NY. 819 p.

Irvington-Moore. Kiln Operator's Handbook For Drying Systems. Jacksonville, FL. Part No. 35358.000

Ladell, J. L. 1956. High-temperature drying of yellow birch. Forest Products Journal. 6(11):469-475.

Ladell, J. L. 1954. The outlook for high-temperature seasoning in Canada. Forest Products Journal. 4(5):260-263.

Lide, D. R. (ed.). 1994. Handbook of Chemistry and Physics. CRC Press, Inc. Boca Raton, FL. 2413 p.

Little, R. L., and W. M. Moschler. 1995. Controlling corrosion in lumber dry kiln buildings. Forest Products Journal. 45(5):55-58.

Mathewson, J. S. 1954. High-temperature drying: Its application to the drying of lumber. Journal of Forest Products Research Society. 4(5):276-279.

McMillan, J. M. 1985. Drying Eastern Hardwood Lumber. USDA Forest Service Handbook No. 528. Supt. of Gov. Docs. Washington DC. 104 p.

Pratt, W. E. 1956. Estimating the moisture content of lumber during the drying process. Forest Products Journal. 6(9):333-337.

Rosen, H. N. 1977. Humidity control can be important when high-temperature drying hardwoods. Forest Products Research Society News Digest. File No. G-2.10. Forest Products Society, Madison, WI. 3 p.

Shafer, J. Jr. 1975. Some ways to minimize needless heat loss from existing dry kilns. Forest Products Research Society News Digest (Drying Division). File No. F-1.21. Forest Products Society, Madison, WI. 2 p.

Strickler, M. D. 1968. High temperature moisture relations of grand fir. Forest Products Journal. 18(4):69-75.

Weast, R. C. (ed.). 1965. Handbook of Chemistry and Physics. Chemical Rubber Company, Cleveland, Ohio. p E-9.

Williams, C. W. 1959. Highlights leading up to modern kiln drying. Forest Products Journal. 9(1):11A-15A.

TABLE 1. OUTPUT OF THE COMPUTER PROGRAM FOR DRY KILN OPERATIONAL SIMULATION - KILN-BOSS SCHEDULE.

WITH 170 F TDP IN PRIMARY KILN

TDB2 = 150.0 TWB2 = 110.0 MCI = 100.000000
BFT = 100000.000000 THK = 2.000000 RHO = 32.000000

| T | FMC | QVENT | QVT | QR | QT | QAVL | QAVLT | TDB | TWB |
|---|---|---|---|---|---|---|---|---|---|
| .1 | 100.0 | .5109E+07 | .5109E+06 | .6959E+07 | .1095E+08 | .0000E+00 | .0000E+00 | 135.0 | 85.0 |
| 1.0 | 96.7 | .2239E+07 | .3413E+07 | .1153E+08 | .3978E+08 | .0000E+00 | .0000E+00 | 166.5 | 130.0 |
| 2.0 | 91.3 | .2595E+07 | .5773E+07 | .1898E+08 | .6564E+08 | .0000E+00 | .0000E+00 | 201.5 | 151.2 |
| 3.0 | 83.3 | .1706E+07 | .8388E+07 | .2096E+08 | .9756E+08 | .0000E+00 | .0000E+00 | 220.0 | 169.2 |
| 4.0 | 76.7 | .9354E+06 | .9487E+07 | .1783E+08 | .1210E+09 | .5821E+07 | .4506E+07 | 220.0 | 179.4 |
| 5.0 | 70.4 | .9985E+06 | .1046E+08 | .1774E+08 | .1397E+09 | .4896E+07 | .9828E+07 | 220.0 | 177.8 |
| 6.0 | 64.3 | .1044E+07 | .1148E+08 | .1731E+08 | .1582E+09 | .3867E+07 | .1417E+08 | 220.0 | 176.3 |
| 7.0 | 56.9 | .1932E+07 | .1296E+08 | .2453E+08 | .1806E+09 | .3810E+07 | .1804E+08 | 247.0 | 174.8 |
| 8.0 | 48.5 | .1973E+07 | .1497E+08 | .2297E+08 | .2068E+09 | .2180E+07 | .2100E+08 | 250.0 | 173.2 |
| 9.0 | 41.1 | .1832E+07 | .1687E+08 | .1999E+08 | .2300E+09 | .6611E+06 | .2232E+08 | 250.0 | 171.7 |
| 10.0 | 34.7 | .1665E+07 | .1861E+08 | .1704E+08 | .2500E+09 | .0000E+00 | .2245E+08 | 250.0 | 170.2 |
| 11.0 | 29.3 | .1411E+07 | .2014E+08 | .1435E+08 | .2672E+09 | .0000E+00 | .2245E+08 | 250.0 | 170.0 |
| 12.0 | 24.8 | .1184E+07 | .2142E+08 | .1203E+08 | .2817E+09 | .0000E+00 | .2245E+08 | 250.0 | 170.0 |
| 13.0 | 21.0 | .9909E+06 | .2250E+08 | .1008E+08 | .2939E+09 | .0000E+00 | .2245E+08 | 250.0 | 170.0 |
| 14.0 | 17.8 | .8290E+06 | .2340E+08 | .8429E+07 | .3041E+09 | .0000E+00 | .2245E+08 | 250.0 | 170.0 |
| 15.0 | 15.2 | .6933E+06 | .2415E+08 | .7049E+07 | .3126E+09 | .0000E+00 | .2245E+08 | 250.0 | 170.0 |
| 15.1 | 14.9 | .6810E+06 | .2422E+08 | .6924E+07 | .3134E+09 | .0000E+00 | .2245E+08 | 250.0 | 170.0 |

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TABLE 2. OUTPUT OF THE COMPUTER PROGRAM FOR DRY KILN OPERATIONAL SIMULATION - SCHEDULE 2.

FOR SCHEDULE 3 - WITH 170 TDP IN PRIMARY KILN

TDB2 = 150.0 TWB2 = 110.0 MCI = 100.000000
BFT = 100000.000000 THK = 2.000000 RHO = 32.000000

| T | FMC | QVENT | QVT | QR | QT | QAVL | QAVLT | TDB | TWB |
|---|---|---|---|---|---|---|---|---|---|
| .1 | 100.0 | .6771E+05 | .6771E+04 | .1306E+07 | .5986E+07 | .0000E+00 | .0000E+00 | 80.0 | 75.0 |
| 1.0 | 98.5 | .5289E+06 | .4642E+06 | .7616E+07 | .4474E+08 | .0000E+00 | .0000E+00 | 179.0 | 163.2 |
| 2.0 | 92.7 | .0000E+00 | .5783E+06 | .3030E+08 | .8048E+08 | .3079E+08 | .1517E+08 | 289.0 | 212.0 |
| 3.0 | 81.6 | .0000E+00 | .5783E+06 | .3275E+08 | .1134E+09 | .3328E+08 | .4847E+08 | 300.0 | 212.0 |
| 4.0 | 70.5 | .0000E+00 | .5783E+06 | .3269E+08 | .1464E+09 | .3321E+08 | .8171E+08 | 300.0 | 212.0 |
| 5.0 | 59.4 | .0000E+00 | .5783E+06 | .3251E+08 | .1792E+09 | .3303E+08 | .1148E+09 | 300.0 | 212.0 |
| 6.0 | 48.4 | .0000E+00 | .5783E+06 | .3201E+08 | .2116E+09 | .3252E+08 | .1476E+09 | 300.0 | 212.0 |
| 7.0 | 37.7 | .0000E+00 | .5783E+06 | .3043E+08 | .2431E+09 | .3092E+08 | .1794E+09 | 300.0 | 212.0 |
| 8.0 | 28.0 | .0000E+00 | .5783E+06 | .2627E+08 | .2717E+09 | .2668E+08 | .2083E+09 | 300.0 | 212.0 |
| 9.0 | 20.3 | .0000E+00 | .5783E+06 | .2000E+08 | .2948E+09 | .2032E+08 | .2315E+09 | 300.0 | 212.0 |
| 10.0 | 14.6 | .0000E+00 | .5783E+06 | .1434E+08 | .3118E+09 | .1457E+08 | .2485E+09 | 300.0 | 212.0 |
| 10.0 | 14.6 | .0000E+00 | .5783E+06 | .1434E+08 | .3118E+09 | .1457E+08 | .2485E+09 | 300.0 | 212.0 |

\DRYVA\DRYVA8.DAT

TABLE 3. OUTPUT OF THE COMPUTER PROGRAM FOR DRY KILN OPERATIONAL SIMULATION - SCHEDULE 3.

WITH 170 F TDP IN PRIMARY KILN

TDB2 = 150.0 TWB = 110.0 MCI = 100.000000
BFT = 100000.000000 THK = 2.000000 RHO = 32.000000

| T | FMC | QVENT | QVT | QR | QT | QAVL | QAVLT | TDB | TWB |
|---|---|---|---|---|---|---|---|---|---|
| .1 | 100.0 | .0000E+00 | .0000E+00 | .1207E+07 | .4020E+07 | .0000E+00 | .0000E+00 | 75.0 | 70.0 |
| 1.0 | 98.7 | .2002E+07 | .9046E+06 | .6683E+07 | .2168E+08 | .0000E+00 | .0000E+00 | 135.6 | 104.0 |
| 2.0 | 94.2 | .3770E+07 | .4064E+07 | .1833E+08 | .5057E+08 | .0000E+00 | .0000E+00 | 193.8 | 137.7 |
| 3.0 | 85.9 | .3066E+07 | .7588E+07 | .2674E+08 | .8716E+08 | .0000E+00 | .0000E+00 | 233.9 | 163.3 |
| 4.0 | 76.2 | .1984E+07 | .1002E+08 | .2799E+08 | .1225E+09 | .7145E+07 | .2727E+07 | 249.9 | 177.6 |
| 5.0 | 66.7 | .1691E+07 | .1177E+08 | .2664E+08 | .1524E+09 | .8920E+07 | .1149E+08 | 250.0 | 180.0 |
| 6.0 | 57.7 | .1593E+07 | .1341E+08 | .2509E+08 | .1800E+09 | .8404E+07 | .2015E+08 | 250.0 | 180.0 |
| 7.0 | 49.4 | .1449E+07 | .1493E+08 | .2283E+08 | .2056E+09 | .7644E+07 | .2815E+08 | 250.0 | 180.0 |
| 8.0 | 42.0 | .1273E+07 | .1628E+08 | .2006E+08 | .2284E+09 | .6717E+07 | .3530E+08 | 250.0 | 180.0 |
| 9.0 | 35.6 | .1091E+07 | .1746E+08 | .1719E+08 | .2482E+09 | .5757E+07 | .4148E+08 | 250.0 | 180.0 |
| 10.0 | 30.2 | .9228E+06 | .1845E+08 | .1454E+08 | .2651E+09 | .4868E+07 | .4674E+08 | 250.0 | 180.0 |
| 11.0 | 25.6 | .7753E+06 | .1929E+08 | .1221E+08 | .2793E+09 | .4090E+07 | .5117E+08 | 250.0 | 180.0 |
| 12.0 | 21.7 | .6496E+06 | .2000E+08 | .1023E+08 | .2913E+09 | .3427E+07 | .5489E+08 | 250.0 | 180.0 |
| 13.0 | 18.5 | .5436E+06 | .2059E+08 | .8563E+07 | .3013E+09 | .2868E+07 | .5800E+08 | 250.0 | 180.0 |
| 14.0 | 15.8 | .4547E+06 | .2108E+08 | .7162E+07 | .3097E+09 | .2399E+07 | .6060E+08 | 250.0 | 180.0 |
| 14.4 | 14.8 | .4233E+06 | .2125E+08 | .6668E+07 | .3127E+09 | .2233E+07 | .6152E+08 | 250.0 | 180.0 |

\DRYVA\DRYVA91.WP

TABLE 4. OUTPUT OF THE COMPUTER PROGRAM FOR DRY KILN OPERATIONAL SIMULATION - SECOND-STAGE KILN.

```
FOR SECOND STAGE KILN                                              \DRYVA\DRYVA4.WP
TDB =       150.000000  TWB =        110.000000  MCI =        100.000000
BFT =    100000.000000  THK =          2.000000  RHO =         32.000000
```

| T, | FMC, | QVENT, | QVT, | QR, | QT, | TDB, | TWB |
|---|---|---|---|---|---|---|---|
| .10 | 100.00 | .0000E+00 | .0000E+00 | .4417E+06 | .5894E+07 | 75.00 | 75.00 |
| 1.00 | 99.37 | .6245E+06 | .2558E+06 | .2959E+07 | .1211E+08 | 100.96 | 85.82 |
| 2.00 | 97.85 | .1745E+07 | .1490E+07 | .5430E+07 | .2183E+08 | 125.91 | 96.55 |
| 3.00 | 95.48 | .2611E+07 | .3758E+07 | .7632E+07 | .3397E+08 | 143.11 | 104.68 |
| 4.00 | 92.57 | .2747E+07 | .6511E+07 | .8481E+07 | .4673E+08 | 149.94 | 109.23 |
| 5.00 | 89.64 | .2579E+07 | .9142E+07 | .8181E+07 | .5802E+08 | 150.00 | 110.00 |
| 6.00 | 86.80 | .2495E+07 | .1168E+08 | .7914E+07 | .6865E+08 | 150.00 | 110.00 |
| 7.00 | 84.06 | .2414E+07 | .1413E+08 | .7655E+07 | .7894E+08 | 150.00 | 110.00 |
| 8.00 | 81.40 | .2334E+07 | .1649E+08 | .7404E+07 | .8889E+08 | 150.00 | 110.00 |
| 9.00 | 78.84 | .2258E+07 | .1879E+08 | .7161E+07 | .9852E+08 | 150.00 | 110.00 |
| 10.00 | 76.35 | .2183E+07 | .2100E+08 | .6925E+07 | .1078E+09 | 150.00 | 110.00 |
| 11.00 | 73.95 | .2111E+07 | .2315E+08 | .6696E+07 | .1168E+09 | 150.00 | 110.00 |
| 12.00 | 71.63 | .2041E+07 | .2522E+08 | .6474E+07 | .1256E+09 | 150.00 | 110.00 |
| 13.00 | 69.39 | .1973E+07 | .2722E+08 | .6260E+07 | .1340E+09 | 150.00 | 110.00 |
| 14.00 | 67.22 | .1908E+07 | .2916E+08 | .6052E+07 | .1421E+09 | 150.00 | 110.00 |
| 15.00 | 65.12 | .1845E+07 | .3103E+08 | .5851E+07 | .1500E+09 | 150.00 | 110.00 |
| 16.00 | 63.09 | .1783E+07 | .3284E+08 | .5656E+07 | .1576E+09 | 150.00 | 110.00 |
| 17.00 | 61.13 | .1724E+07 | .3459E+08 | .5468E+07 | .1650E+09 | 150.00 | 110.00 |
| 18.00 | 59.24 | .1666E+07 | .3629E+08 | .5286E+07 | .1721E+09 | 150.00 | 110.00 |
| 19.00 | 57.41 | .1611E+07 | .3792E+08 | .5109E+07 | .1790E+09 | 150.00 | 110.00 |
| 20.00 | 55.63 | .1557E+07 | .3950E+08 | .4939E+07 | .1857E+09 | 150.00 | 110.00 |
| 21.00 | 53.92 | .1505E+07 | .4103E+08 | .4774E+07 | .1921E+09 | 150.00 | 110.00 |
| 22.00 | 52.27 | .1455E+07 | .4251E+08 | .4615E+07 | .1984E+09 | 150.00 | 110.00 |
| 23.00 | 50.67 | .1406E+07 | .4394E+08 | .4461E+07 | .2044E+09 | 150.00 | 110.00 |
| 24.00 | 49.12 | .1359E+07 | .4532E+08 | .4312E+07 | .2102E+09 | 150.00 | 110.00 |
| 25.00 | 47.63 | .1314E+07 | .4665E+08 | .4168E+07 | .2158E+09 | 150.00 | 110.00 |
| 26.00 | 46.18 | .1270E+07 | .4794E+08 | .4028E+07 | .2213E+09 | 150.00 | 110.00 |
| 27.00 | 44.79 | .1228E+07 | .4919E+08 | .3894E+07 | .2266E+09 | 150.00 | 110.00 |
| 28.00 | 43.44 | .1187E+07 | .5039E+08 | .3764E+07 | .2317E+09 | 150.00 | 110.00 |
| 29.00 | 42.13 | .1147E+07 | .5156E+08 | .3638E+07 | .2366E+09 | 150.00 | 110.00 |
| 30.00 | 40.87 | .1109E+07 | .5268E+08 | .3516E+07 | .2413E+09 | 150.00 | 110.00 |
| 31.00 | 39.65 | .1071E+07 | .5377E+08 | .3398E+07 | .2459E+09 | 150.00 | 110.00 |
| 32.00 | 38.48 | .1036E+07 | .5482E+08 | .3285E+07 | .2504E+09 | 150.00 | 110.00 |
| 33.00 | 37.34 | .1001E+07 | .5584E+08 | .3175E+07 | .2547E+09 | 150.00 | 110.00 |
| 34.00 | 36.24 | .9675E+06 | .5682E+08 | .3069E+07 | .2589E+09 | 150.00 | 110.00 |
| 35.00 | 35.17 | .9351E+06 | .5777E+08 | .2966E+07 | .2629E+09 | 150.00 | 110.00 |
| 36.00 | 34.15 | .9038E+06 | .5869E+08 | .2867E+07 | .2668E+09 | 150.00 | 110.00 |
| 37.00 | 33.15 | .8736E+06 | .5958E+08 | .2771E+07 | .2706E+09 | 150.00 | 110.00 |
| 38.00 | 32.19 | .8444E+06 | .6043E+08 | .2678E+07 | .2742E+09 | 150.00 | 110.00 |
| 39.00 | 31.26 | .8161E+06 | .6126E+08 | .2589E+07 | .2777E+09 | 150.00 | 110.00 |
| 40.00 | 30.37 | .7888E+06 | .6206E+08 | .2502E+07 | .2811E+09 | 150.00 | 110.00 |
| 41.00 | 29.50 | .7624E+06 | .6284E+08 | .2418E+07 | .2844E+09 | 150.00 | 110.00 |
| 42.00 | 28.66 | .7369E+06 | .6359E+08 | .2337E+07 | .2876E+09 | 150.00 | 110.00 |
| 43.00 | 27.85 | .7122E+06 | .6431E+08 | .2259E+07 | .2907E+09 | 150.00 | 110.00 |
| 44.00 | 27.07 | .6884E+06 | .6501E+08 | .2184E+07 | .2937E+09 | 150.00 | 110.00 |
| 45.00 | 26.31 | .6654E+06 | .6568E+08 | .2110E+07 | .2966E+09 | 150.00 | 110.00 |
| 46.00 | 25.58 | .6431E+06 | .6634E+08 | .2040E+07 | .2994E+09 | 150.00 | 110.00 |
| 47.00 | 24.87 | .6216E+06 | .6697E+08 | .1972E+07 | .3021E+09 | 150.00 | 110.00 |
| 48.00 | 24.19 | .6008E+06 | .6758E+08 | .1906E+07 | .3047E+09 | 150.00 | 110.00 |
| 49.00 | 23.53 | .5807E+06 | .6817E+08 | .1842E+07 | .3072E+09 | 150.00 | 110.00 |
| 50.00 | 22.89 | .5613E+06 | .6874E+08 | .1780E+07 | .3097E+09 | 150.00 | 110.00 |
| 51.00 | 22.27 | .5425E+06 | .6929E+08 | .1721E+07 | .3120E+09 | 150.00 | 110.00 |
| 52.00 | 21.68 | .5243E+06 | .6982E+08 | .1663E+07 | .3143E+09 | 150.00 | 110.00 |
| 53.00 | 21.10 | .5068E+06 | .7034E+08 | .1607E+07 | .3165E+09 | 150.00 | 110.00 |
| 54.00 | 20.54 | .4898E+06 | .7083E+08 | .1554E+07 | .3187E+09 | 150.00 | 110.00 |
| 55.00 | 20.01 | .4734E+06 | .7131E+08 | .1502E+07 | .3207E+09 | 150.00 | 110.00 |
| 56.00 | 19.49 | .4576E+06 | .7178E+08 | .1451E+07 | .3227E+09 | 150.00 | 110.00 |
| 57.00 | 18.98 | .4423E+06 | .7223E+08 | .1403E+07 | .3247E+09 | 150.00 | 110.00 |
| 58.00 | 18.50 | .4275E+06 | .7266E+08 | .1356E+07 | .3266E+09 | 150.00 | 110.00 |
| 59.00 | 18.03 | .4132E+06 | .7308E+08 | .1311E+07 | .3284E+09 | 150.00 | 110.00 |
| 60.00 | 17.57 | .3993E+06 | .7349E+08 | .1267E+07 | .3301E+09 | 150.00 | 110.00 |
| 61.00 | 17.13 | .3860E+06 | .7388E+08 | .1224E+07 | .3318E+09 | 150.00 | 110.00 |
| 62.00 | 16.71 | .3731E+06 | .7426E+08 | .1183E+07 | .3335E+09 | 150.00 | 110.00 |
| 63.00 | 16.30 | .3606E+06 | .7462E+08 | .1144E+07 | .3351E+09 | 150.00 | 110.00 |
| 64.00 | 15.90 | .3485E+06 | .7498E+08 | .1105E+07 | .3366E+09 | 150.00 | 110.00 |
| 65.00 | 15.52 | .3368E+06 | .7532E+08 | .1068E+07 | .3381E+09 | 150.00 | 110.00 |
| 66.00 | 15.15 | .3256E+06 | .7565E+08 | .1033E+07 | .3396E+09 | 150.00 | 110.00 |
| **66.50** | **14.97** | **.3201E+06** | **.7581E+08** | **.1015E+07** | **.3403E+09** | **150.00** | **110.00** |

TABLE 5A. AIR VELOCITIES MEASURED AFTER ADJUSTING AIR DIFFUSER FOR BETTER BALANCED AIR FLOW PROFILE - CELL 1.

| BAFFLE POSITION (INCHES) | ANEMOMETER DEPTH (INCHES) | TEST PORT A | B | C | D | E |
|---|---|---|---|---|---|---|
| 5 | 1 | 1000 | 1150 | 1200 | 1150 | 1000 |
| | 2 | 900 | 110 | 1150 | 1050 | 1000 |
| | 3 | 800 | 1050 | 1150 | 1000 | 850 |
| | 4 | 750 | 950 | 1100 | 950 | 800 |
| | 5 | 750 | 950 | 1050 | 900 | 700 |
| 6 | 1 | 900 | 1100 | 1100 | 1050 | 950 |
| | 2 | 850 | 1050 | 1050 | 1000 | 800 |
| | 3 | 700 | 950 | 1000 | 950 | 750 |
| | 4 | 650 | 800 | 950 | 800 | 650 |
| | 5 | 600 | 800 | 850 | 750 | 550 |
| | 6 | 600 | 750 | 800 | 750 | 500 |
| 7 | 1 | 900 | 1000 | 1000 | 1000 | 900 |
| | 2 | 850 | 1000 | 1000 | 1000 | 700 |
| | 3 | 700 | 900 | 950 | 950 | 600 |
| | 4 | 600 | 700 | 850 | 850 | 350 |
| | 5 | 500 | 650 | 750 | 750 | 300 |
| | 6 | 500 | 500 | 650 | 700 | 300 |
| | 7 | 550 | 450 | 600 | 700 | 300 |

TABLE 5B. AIR VELOCITIES MEASURED AFTER ADJUSTING AIR DIFFUSER FOR BETTER BALANCED AIR FLOW PROFILE - CELL 2.

| BAFFLE POSITION (INCHES) | ANEMOMETER DEPTH (INCHES) | TEST PORT A | B | C | D | E |
|---|---|---|---|---|---|---|
| 5 | 1 | 1000 | 1100 | 1050 | 950 | 1000 |
| | 2 | 900 | 1050 | 1000 | 900 | 1000 |
| | 3 | 850 | 1000 | 950 | 900 | 900 |
| | 4 | 800 | 900 | 900 | 850 | 750 |
| | 5 | 750 | 850 | 850 | 800 | 700 |
| 6 | 1 | 950 | 1000 | 1000 | 950 | 900 |
| | 2 | 900 | 1000 | 950 | 850 | 850 |
| | 3 | 800 | 900 | 850 | 800 | 750 |
| | 4 | 750 | 800 | 850 | 800 | 700 |
| | 5 | 700 | 650 | 750 | 700 | 550 |
| | 6 | 600 | 600 | 750 | 650 | 550 |
| 7 | 1 | 900 | 950 | 1000 | 950 | 850 |
| | 2 | 850 | 900 | 950 | 900 | 800 |
| | 3 | 800 | 750 | 850 | 850 | 700 |
| | 4 | 750 | 700 | 750 | 800 | 550 |
| | 5 | 700 | 500 | 600 | 750 | 400 |
| | 6 | 650 | 400 | 550 | 600 | 450 |
| | 7 | 500 | 350 | 500 | 500 | 300 |

TABLE 5C. AIR VELOCITIES MEASURED AFTER ADJUSTING AIR DIFFUSER FOR BETTER BALANCED AIR FLOW PROFILE - CELL 3.

| BAFFLE POSITION (INCHES) | ANEMOMETER DEPTH (INCHES) | TEST PORT A | B | C | D | E |
|---|---|---|---|---|---|---|
| 5 | 1 | 1050 | 1100 | 1200 | 1200 | 1150 |
| | 2 | 1000 | 1100 | 1200 | 1100 | 1050 |
| | 3 | 850 | 1050 | 1150 | 950 | 950 |
| | 4 | 900 | 1050 | 1050 | 900 | 800 |
| | 5 | 850 | 950 | 1000 | 800 | 800 |
| 6 | 1 | 900 | 1000 | 1100 | 1150 | 950 |
| | 2 | 850 | 1000 | 1000 | 1100 | 800 |
| | 3 | 800 | 1000 | 1000 | 900 | 700 |
| | 4 | 750 | 900 | 900 | 800 | 650 |
| | 5 | 750 | 800 | 800 | 700 | 650 |
| | 6 | 700 | 750 | 750 | 650 | 500 |
| 7 | 1 | 900 | 950 | 1000 | 1100 | 900 |
| | 2 | 900 | 950 | 1000 | 1000 | 750 |
| | 3 | 850 | 900 | 900 | 950 | 650 |
| | 4 | 750 | 850 | 850 | 750 | 400 |
| | 5 | 700 | 700 | 700 | 700 | 400 |
| | 6 | 650 | 700 | 700 | 600 | 250 |
| | 7 | 650 | 550 | 600 | 500 | 200 |

TABLE 6. AIR VELOCITY MEASURED AT THE TOP CENTER OF THE BAFFLE FOR EACH CELL.

| | BAFFLE POSITION (INCHES) | ANEMOMETER DEPTH (INCHES) | FPM |
|---|---|---|---|
| CELL #1 | 5 | 3 | 600 |
| | 6 | 3 | 650 |
| | 7 | 3 | 700 |
| CELL #2 | 5 | 3 | 600 |
| | 6 | 3 | 650 |
| | 7 | 3 | 750 |
| CELL #3 | 5 | 3 | 650 |
| | 6 | 3 | 650 |
| | 7 | 3 | 750 |

TABLE 7. SUMMARY OF HEAT EXCHANGE TEST RESULTS FOR RUNS 1-10.

| TEST # 1 | | AVERAGE TEMP F. | NET CONDENSATE (GRAMS) | NET BTUs |
|---|---|---|---|---|
| DB/WB 200/180 | CELL 1 | 133.1 | 1560 | 3334.2 |
| VENTS: CLOSED | CELL 2 | 146.6 | 2040 | 4360.1 |
| BAFFLES 5 | CELL 3 | 141.4 | 2110 | 4509.7 |

| TEST # 2 | | AVERAGE TEMP F. | NET CONDENSATE (GRAMS) | NET BTUs |
|---|---|---|---|---|
| DB/WB 200/180 | CELL 1 | 137.2 | 1536 | 3282.9 |
| VENTS: CLOSED | CELL 2 | 147.2 | 1957 | 4182.7 |
| BAFFLES 6 | CELL 3 | 142.9 | 1948 | 4163.4 |

| TEST # 3 | | AVERAGE TEMP F. | NET CONDENSATE (GRAMS) | NET BTUs |
|---|---|---|---|---|
| DB/WB 200/180 | CELL 1 | 137.5 | 1227 | 2622.5 |
| VENTS: CLOSED | CELL 2 | 147.9 | 1675 | 3580.0 |
| BAFFLES 7 | CELL 3 | 144.2 | 1680 | 3590.6 |

| TEST # 4 | | AVERAGE TEMP F. | NET CONDENSATE (GRAMS) | NET BTUs |
|---|---|---|---|---|
| DB/WB 220/180 | CELL 1 | 144.9 | 593 | 1267.4 |
| VENTS: CLOSED | CELL 2 | 154.5 | 540 | 1154.1 |
| BAFFLES 5 | CELL 3 | 149.8 | 713 | 1523.9 |

| TEST # 5 | | AVERAGE TEMP F. | NET CONDENSATE (GRAMS) | NET BTUs |
|---|---|---|---|---|
| DB/WB 220/180 | CELL 1 | 136.6 | 993 | 2122.3 |
| VENTS: CLOSED | CELL 2 | 148.3 | 1032 | 2205.7 |
| BAFFLES 6 | CELL 3 | 144.2 | 1141 | 2438.6 |

| TEST # 6 | | AVERAGE TEMP F. | NET CONDENSATE (GRAMS) | NET BTUs |
|---|---|---|---|---|
| DB/WB 220/180 | CELL 1 | 141.8 | 561 | 1199.0 |
| VENTS: CLOSED | CELL 2 | 151.8 | 557 | 1190.5 |
| BAFFLES 7 | CELL 3 | 149.8 | 591 | 1263.1 |

| TEST # 7 | | AVERAGE TEMP F. | NET CONDENSATE (GRAMS) | NET BTUs |
|---|---|---|---|---|
| DB/WB 240/180 | CELL 1 | 144.8 | 125 | 267.2 |
| VENTS: CLOSED | CELL 2 | 154.2 | 65 | 138.9 |
| BAFFLES 5 | CELL 3 | 149.3 | 143 | 305.6 |

TABLE 7. SUMMARY OF HEAT EXCHANGE TEST RESULTS FOR RUNS 1-10. (Continued)

| TEST # 8 | | | AVERAGE TEMP F. | NET CONDENSATE (GRAMS) | NET BTUs |
|---|---|---|---|---|---|
| DB/WB | 240/180 | CELL 1 | 145.1 | 0 | 0.0 |
| VENTS: | CLOSED | CELL 2 | 153.7 | 0 | 0.0 |
| BAFFLES | 6 | CELL 3 | 149.4 | 112 | 239.4 |

| TEST # 9 | | | AVERAGE TEMP F. | NET CONDENSATE (GRAMS) | NET BTUs |
|---|---|---|---|---|---|
| DB/WB | 240/180 | CELL 1 | 102 | 102 | 218.0 |
| VENTS: | CLOSED | CELL 2 | 149.4 | 121 | 258.6 |
| BAFFLES | 7 | CELL 3 | 147.6 | 130 | 277.8 |

| TEST # 10 | | | AVERAGE TEMP F. | NET CONDENSATE (GRAMS) | NET BTUs |
|---|---|---|---|---|---|
| DB/WB | 190/190 | CELL 1 | 138.4 | 2762 | 5903.2 |
| VENTS: | CLOSED | CELL 2 | 150.2 | 3839 | 8205.1 |
| BAFFLES | 5 | CELL 3 | 148.5 | 3577 | 7645.1 |

TABLE 8. SUMMARY OF BASIC DATA FOR THE EXPERIMENTAL MEASUREMENTS FOR CELL 1 - RUNS 1-40.

CELL 1

| RUN NO | TDB-KILN | TWB-KILN | AVG TEM | BAF POS. | BTUs COL |
|---|---|---|---|---|---|
| 1 | 200 | 180 | 133.1 | 5 | 3334.2 |
| 2 | 200 | 180 | 137.2 | 6 | 3282.9 |
| 3 | 200 | 180 | 137.5 | 7 | 2622.5 |
| 4 | 220 | 180 | 144.9 | 5 | 1267.4 |
| 5 | 220 | 180 | 136.6 | 6 | 2122.3 |
| 6 | 220 | 180 | 141.8 | 7 | 1199.0 |
| 7 | 240 | 180 | 144.8 | 5 | 267.2 |
| 8 | 240 | 180 | 145.1 | 6 | 0.0 |
| 9 | 240 | 180 | 139.8 | 7 | 218.0 |
| 10 | 190 | 190 | 138.4 | 5 | 5903.2 |
| 11 | 240 | 212 | 150.3 | 5 | 4849.5 |
| 12 | 240 | 212 | 134.0 | 5 | 4616.5 |
| 13 | 240 | 212 | 141.7 | 6 | 2133.0 |
| 14 | 240 | 212 | 142.4 | 6 | 2280.5 |
| 15 | 240 | 212 | 140.3 | 7 | 4808.9 |
| 16 | 250 | 212 | 141.6 | 5 | 4148.5 |
| 17 | 250 | 212 | 143.2 | 6 | 3464.5 |
| 18 | 250 | 212 | 129.4 | 6 | 4586.6 |
| 19 | 250 | 212 | 137.6 | 7 | 4041.6 |
| 20 | 260 | 212 | 139.7 | 5 | 3522.3 |
| 21 | 260 | 212 | 142.5 | 6 | 2496.4 |
| 22 | 260 | 212 | 132.7 | 6 | 3569.3 |
| 23 | 260 | 212 | 140.0 | 7 | 2051.8 |
| 24 | 212 | 212 | 132.3 | 5 | 9017.2 |
| 25 | 212 | 212 | 140.0 | 5 | 7933.6 |
| 26 | 212 | 212 | 164.1 | 5 | 5091.0 |
| 27 | 212 | 212 | 165.9 | 5 | 4813.3 |
| 28 | 212 | 212 | 126.3 | 5 | 10628.7 |
| 29 | 212 | 212 | 119.8 | 5 | 9609.3 |
| 30 | 212 | 212 | 149.1 | 5 | 4531.1 |
| 31 | 250 | 212 | 164.4 | 5 | 1305.9 |
| 32 | 250 | 212 | 165.5 | 5 | 949.0 |
| 33 | 250 | 212 | 136.3 | 5 | 5377.4 |
| 34 | 250 | 212 | 149.2 | 5 | 4355.8 |
| 35 | 250 | 212 | 150.0 | 5 | 4084.4 |
| 36 | 250 | 212 | 127.0 | 5 | 6454.6 |
| 37 | 250 | 212 | 134.2 | 5 | 5078.2 |
| 38 | 250 | 212 | 135.8 | 5 | 4605.9 |
| 39 | 250 | 212 | 114.1 | 5 | 7927.7 |
| 40 | 250 | 212 | 122.4 | 5 | 7226.2 |

TABLE 9. SUMMARY OF BASIC DATA FOR THE EXPERIMENTAL MEASUREMENTS FOR CELL 2 - RUNS 1-40.

**Cell 2**

| RUN NO | TDB-KILN | TWB-KILN | AVG TEM | BAF POS. | BTUs COL |
|---|---|---|---|---|---|
| 1 | 200 | 180 | 146.6 | 5 | 4360.1 |
| 2 | 200 | 180 | 147.2 | 6 | 4182.7 |
| 3 | 200 | 180 | 147.9 | 7 | 3580.0 |
| 4 | 220 | 180 | 154.5 | 5 | 1154.1 |
| 5 | 220 | 180 | 148.3 | 6 | 2205.7 |
| 6 | 220 | 180 | 151.8 | 7 | 1190.5 |
| 7 | 240 | 180 | 154.2 | 5 | 138.9 |
| 8 | 240 | 180 | 153.7 | 6 | 0.0 |
| 9 | 240 | 180 | 149.4 | 7 | 258.6 |
| 10 | 190 | 190 | 150.2 | 5 | 8205.1 |
| 11 | 240 | 212 | 164.5 | 5 | 6719.6 |
| 12 | 240 | 212 | 149.5 | 5 | 9459.6 |
| 13 | 240 | 212 | 149.8 | 6 | 7493.3 |
| 14 | 240 | 212 | 152.8 | 6 | 7546.8 |
| 15 | 240 | 212 | 149.7 | 7 | 7715.6 |
| 16 | 250 | 212 | 150.0 | 5 | 7130.0 |
| 17 | 250 | 212 | 154.4 | 6 | 8222.2 |
| 18 | 250 | 212 | 141.7 | 6 | 8348.3 |
| 19 | 250 | 212 | 149.4 | 7 | 6198.1 |
| 20 | 260 | 212 | 145.5 | 5 | 7097.9 |
| 21 | 260 | 212 | 147.4 | 6 | 5721.5 |
| 22 | 260 | 212 | 139.2 | 6 | 6950.5 |
| 23 | 260 | 212 | 144.3 | 7 | 5627.5 |
| 24 | 212 | 212 | 138.7 | 5 | 15386.3 |
| 25 | 212 | 212 | 142.7 | 5 | 14841.3 |
| 26 | 212 | 212 | 175.1 | 5 | 7454.9 |
| 27 | 212 | 212 | 177.0 | 5 | 7149.2 |
| 28 | 212 | 212 | 138.6 | 5 | 16309.7 |
| 29 | 212 | 212 | 133.3 | 5 | 15168.3 |
| 30 | 212 | 212 | 168.5 | 5 | 9380.6 |
| 31 | 250 | 212 | 177.5 | 5 | 3607.7 |
| 32 | 250 | 212 | 178.1 | 5 | 3069.1 |
| 33 | 250 | 212 | 151.8 | 5 | 8786.4 |
| 34 | 250 | 212 | 161.4 | 5 | 6882.1 |
| 35 | 250 | 212 | 161.4 | 5 | 6166.1 |
| 36 | 250 | 212 | 142.0 | 5 | 10699.3 |
| 37 | 250 | 212 | 148.3 | 5 | 8673.1 |
| 38 | 250 | 212 | 149.3 | 5 | 7935.8 |
| 39 | 250 | 212 | 128.2 | 5 | 13351.6 |
| 40 | 250 | 212 | 136.0 | 5 | 11718.8 |

TABLE 10. SUMMARY OF BASIC DATA FOR THE EXPERIMENTAL MEASUREMENTS FOR CELL 3 - RUNS 1-40.

Cell 3

| RUN NO | TDB-KILN | TWB-KILN | AVG TEM | BAF POS. | BTUs COL |
|---|---|---|---|---|---|
| 1 | 200 | 180 | 141.4 | 5 | 4509.7 |
| 2 | 200 | 180 | 142.9 | 6 | 4163.4 |
| 3 | 200 | 180 | 144.2 | 7 | 3590.6 |
| 4 | 220 | 180 | 149.8 | 5 | 1523.9 |
| 5 | 220 | 180 | 144.2 | 6 | 2438.6 |
| 6 | 220 | 180 | 149.8 | 7 | 1263.1 |
| 7 | 240 | 180 | 149.3 | 5 | 305.6 |
| 8 | 240 | 180 | 149.4 | 6 | 239.4 |
| 9 | 240 | 180 | 147.6 | 7 | 277.8 |
| 10 | 190 | 190 | 148.5 | 5 | 7645.1 |
| 11 | 240 | 212 | 165.0 | 5 | 5886.1 |
| 12 | 240 | 212 | 147.1 | 5 | 9008.7 |
| 13 | 240 | 212 | 152.0 | 6 | 7732.7 |
| 14 | 240 | 212 | 155.0 | 6 | 6879.9 |
| 15 | 240 | 212 | 153.4 | 7 | 6640.6 |
| 16 | 250 | 212 | 148.6 | 5 | 6702.5 |
| 17 | 250 | 212 | 154.8 | 6 | 7452.7 |
| 18 | 250 | 212 | 143.1 | 6 | 6694.0 |
| 19 | 250 | 212 | 151.5 | 7 | 4385.7 |
| 20 | 260 | 212 | 141.6 | 5 | 5939.5 |
| 21 | 260 | 212 | 146.5 | 6 | 4289.5 |
| 22 | 260 | 212 | 140.9 | 6 | 4445.6 |
| 23 | 260 | 212 | 147.9 | 7 | 3362.0 |
| 24 | 212 | 212 | 141.6 | 5 | 12956.2 |
| 25 | 212 | 212 | 146.3 | 5 | 12665.6 |
| 26 | 212 | 212 | 173.0 | 5 | 6488.8 |
| 27 | 212 | 212 | 175.8 | 5 | 6409.7 |
| 28 | 212 | 212 | 136.1 | 5 | 15298.1 |
| 29 | 212 | 212 | 131.3 | 5 | 14869.1 |
| 30 | 212 | 212 | 161.9 | 5 | 9177.5 |
| 31 | 250 | 212 | 172.9 | 5 | 3270.1 |
| 32 | 250 | 212 | 173.3 | 5 | 2714.4 |
| 33 | 250 | 212 | 148.3 | 5 | 8128.5 |
| 34 | 250 | 212 | 157.1 | 5 | 6484.5 |
| 35 | 250 | 212 | 156.4 | 5 | 6159.7 |
| 36 | 250 | 212 | 141.8 | 5 | 10263.3 |
| 37 | 250 | 212 | 148.3 | 5 | 7997.7 |
| 38 | 250 | 212 | 148.7 | 5 | 8128.1 |
| 39 | 250 | 212 | 125.5 | 5 | 13088.8 |
| 40 | 250 | 212 | 132.7 | 5 | 11567.0 |

TABLE 11. SUMMARY OF BASIC DATA FOR THE EXPERIMENTAL MEASUREMENTS FOR THE DEEP GROOVED STAINLESS STEEL PANEL.

Deep grooved (SS)

| Test # | TDB | TWB | Ave Cell Temp (Y) | gm H2O coll. | BTUs coll. (X) |
|---|---|---|---|---|---|
| 1 | 250 | 212 | 118.2 | 6793 | 14519 |
| 2 | 250 | 212 | 123.8 | 7190 | 15367 |
| 3 | 250 | 212 | 129.0 | 6163 | 13172 |
| 4 | 250 | 212 | 130.0 | 6445 | 13775 |
| 5 | 250 | 212 | 127.6 | 5779 | 12351 |
| 6 | 250 | 212 | 120.8 | 7273 | 15545 |
| 7 | 250 | 212 | 120.5 | 6862 | 14666 |
| 8 | 250 | 212 | 126.7 | 6679 | 14275 |
| 9 | 250 | 212 | 130.4 | 6565 | 14031 |
| 10 | 250 | 212 | 132.8 | 5890 | 12589 |
| 11 | 250 | 212 | 129.1 | 6767 | 14463 |
| 12 | 250 | 212 | 164.7 | 2139 | 4572 |
| 13 | 250 | 212 | 166.7 | 2474 | 5288 |
| 14 | 250 | 212 | 169.5 | 1972 | 4215 |
| 15 | 250 | 212 | 170.3 | 2100 | 4488 |
| 16 | 250 | 212 | 145.6 | 4126 | 8818 |
| 17 | 250 | 212 | 145.4 | 4769 | 10193 |
| 18 | 250 | 212 | 152.4 | 3361 | 7183 |
| 19 | 250 | 212 | 150.2 | 3592 | 7677 |
| 20 | 250 | 212 | 167.6 | 3426 | 7322 |
| | | Sum Y | 2821.3 | Sum X | 214510 |
| | | Ave Y | 141.1 | Ave X | 10726 |

Y^=b0+b1x

b0=-0.004376
b1=187.99
r2=0.971

When X = 0, Y = 187.99 Degrees F
When Y = 0, X = 42959.0 BTUs

Total surface area = 4582.9
Avg BTUs/hour*degree= 114.3 (X@Y=0/Y
Avg BTUs/hour*degree*sq in 0.0249 (X@Y=0/Y
Avg BTUs/hour*degree*sq ft
kiln wall area 9.873

TABLE 12. SUMMARY OF BASIC DATA FOR THE EXPERIMENTAL MEASUREMENTS FOR THE ACCORDION GROOVED STAINLESS STEEL PANEL.

Accordian Folded (stainless)

| Test # | TDB | TWB | Ave Cell Temp | gm H2O coll. | BTUs coll. |
|---|---|---|---|---|---|
| 1 | 250 | 212 | 115.8 | 6389 | 13655 |
| 2 | 250 | 212 | 124.4 | 5624 | 12020 |
| 3 | 250 | 212 | 126.1 | 5601 | 11971 |
| 4 | 250 | 212 | 129.3 | 5031 | 10753 |
| 5 | 250 | 212 | 125.2 | 5443 | 11633 |
| 6 | 250 | 212 | 119.9 | 5866 | 12537 |
| 7 | 250 | 212 | 116.1 | 6537 | 13972 |
| 8 | 250 | 212 | 127.1 | 5727 | 12240 |
| 9 | 250 | 212 | 130.5 | 5347 | 11428 |
| 10 | 250 | 212 | 129.7 | 5585 | 11937 |
| 11 | 250 | 212 | 128.7 | 5518 | 11794 |
| 12 | 250 | 212 | 157.1 | 2761 | 5901 |
| 13 | 250 | 212 | 164.5 | 1926 | 4116 |
| 14 | 250 | 212 | 166.3 | 1874 | 4005 |
| 15 | 250 | 212 | 169.9 | 1357 | 2900 |
| 16 | 250 | 212 | 150.8 | 3404 | 7275 |
| 17 | 250 | 212 | 152.8 | 2818 | 6023 |
| 18 | 250 | 212 | 166.3 | 1756 | 3753 |
| 19 | 250 | 212 | 147.9 | 3426 | 7322 |
| 20 | 250 | 212 | 167.2 | 1561 | 3336 |
| | | Sum Y | 2815.6 | Sum X | 178574 |
| | | Ave Y | 140.8 | Ave X | 8929 |

Y^=b0+b1x

b0=184.67
b1=-0.004915
r2=0.989

When X = 0, Y = 184.67 Degrees F
When Y = 0, X = 37573.0 BTUs

Total surface area = 3686.5
Avg BTUs/hour*degree= 101.7
Avg BTUs/hour*degree*sq in 0.0276
Avg BTUs/hour*degree*sq ft
kiln wall area 8.788

TABLE 13. SUMMARY OF BASIC DATA FOR THE EXPERIMENTAL MEASUREMENTS FOR THE FLAT ALUMINIZED STEEL PANEL.

Flat (aluminized)

| Test # | TDB | TWB | Ave Cell Temp | gm H20 coll. | BTUs coll. |
|---|---|---|---|---|---|
| 1 | 250 | 212 | 97.6 | 4051 | 8658 |
| 2 | 250 | 212 | 107.0 | 3627 | 7752 |
| 3 | 250 | 212 | 111.1 | 3389 | 7243 |
| 4 | 250 | 212 | 113.5 | 3240 | 6925 |
| 5 | 250 | 212 | 110.0 | 3389 | 7243 |
| 6 | 250 | 212 | 102.3 | 3783 | 8085 |
| 7 | 250 | 212 | 99.2 | 4070 | 8699 |
| 8 | 250 | 212 | 106.6 | 3823 | 8171 |
| 9 | 250 | 212 | 110.0 | 3623 | 7743 |
| 10 | 250 | 212 | 110.7 | 3547 | 7581 |
| 11 | 250 | 212 | 108.1 | 3640 | 7780 |
| 12 | 250 | 212 | 145.6 | 1643 | 3512 |
| 13 | 250 | 212 | 148.4 | 1503 | 3212 |
| 14 | 250 | 212 | 149.9 | 1425 | 3046 |
| 15 | 250 | 212 | 153.3 | 1198 | 2560 |
| 16 | 250 | 212 | 127.2 | 2712 | 5796 |
| 17 | 250 | 212 | 128.1 | 2667 | 5700 |
| 18 | 250 | 212 | 144.3 | 1774 | 3792 |
| 19 | 250 | 212 | 129.4 | 2546 | 5442 |
| 20 | 250 | 212 | 152.5 | 1223 | 2614 |
| | | Sum Y | 2454.8 | Sum X | 121555 |
| | | Ave Y | 122.7 | Ave X | 6078 |

Y^=b0+b1x

b0=177.25
b1=-0.00897
r2=0.994

When X = 0, Y = 177.25 Degrees F
When Y = 0, X = 19760.0 BTUs

Total surface area = 1818
Avg BTUs/hour*degree= 55.7
Avg BTUs/hour*degree*sq in 0.0307
Avg BTUs/hour*degree*sq ft
kiln wall area 4.816

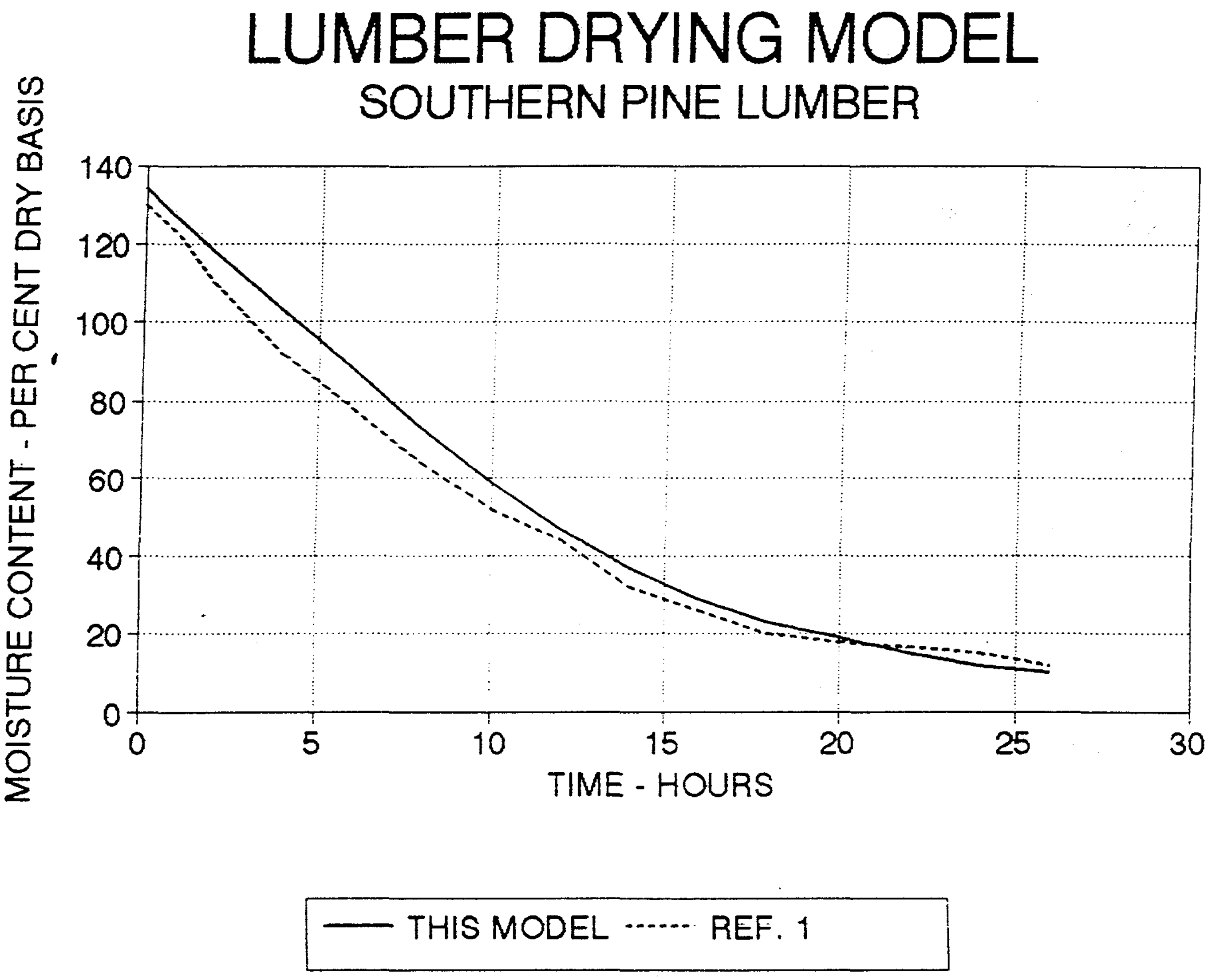



FIGURE 1. COMPARISON OF PREDICTIVE DRYING RATES OF COMPUTER MODEL WITH EXPERIMENT RESULTS FROM REF. 1.

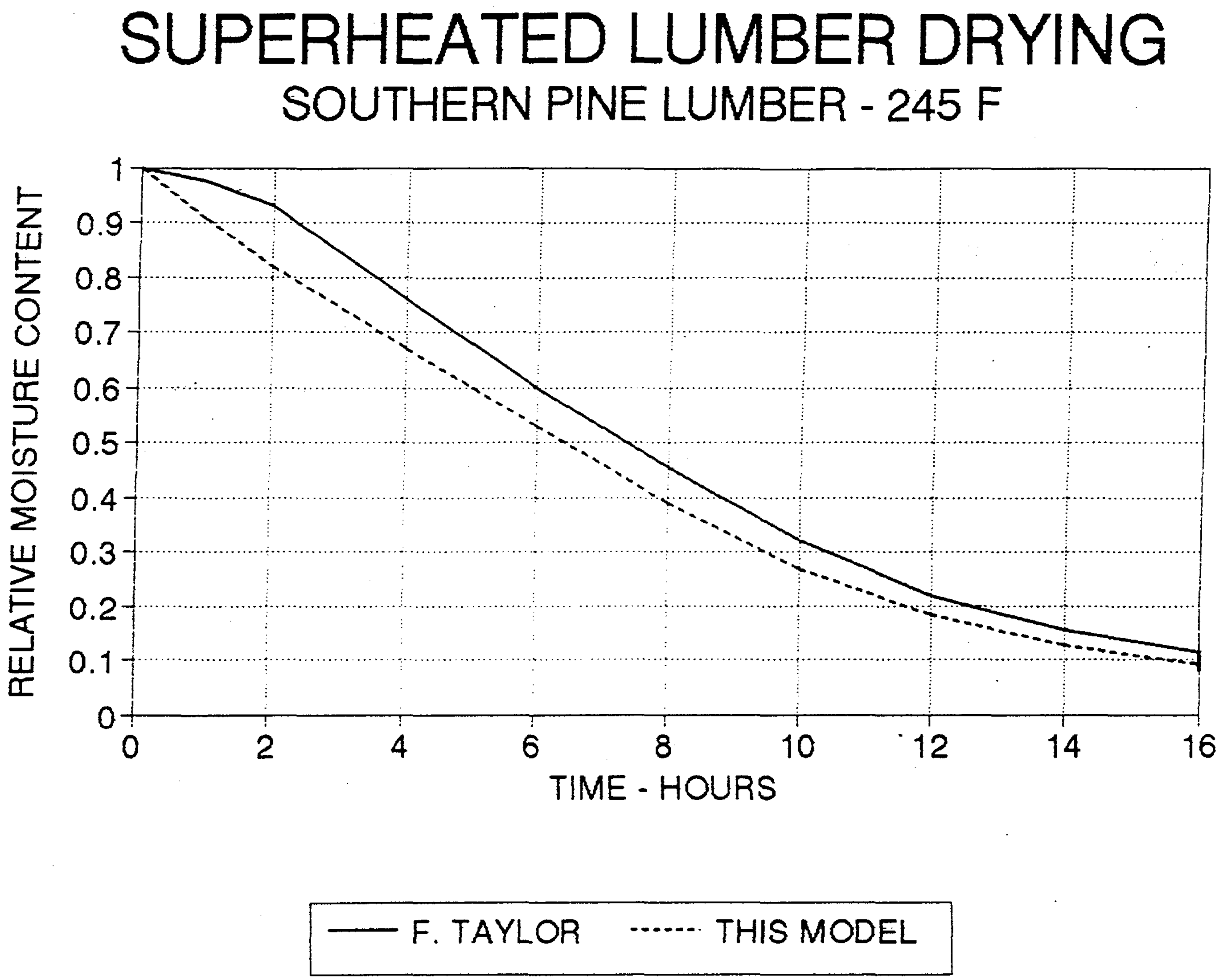



FIGURE 2. COMPARISON OF PREDICTED DRYING RATES OF COMPUTER MODEL WITH REPORTED RESULTS OF TAYLOR FOR SUPERHEATED STEAM DRYING AT 245°F.

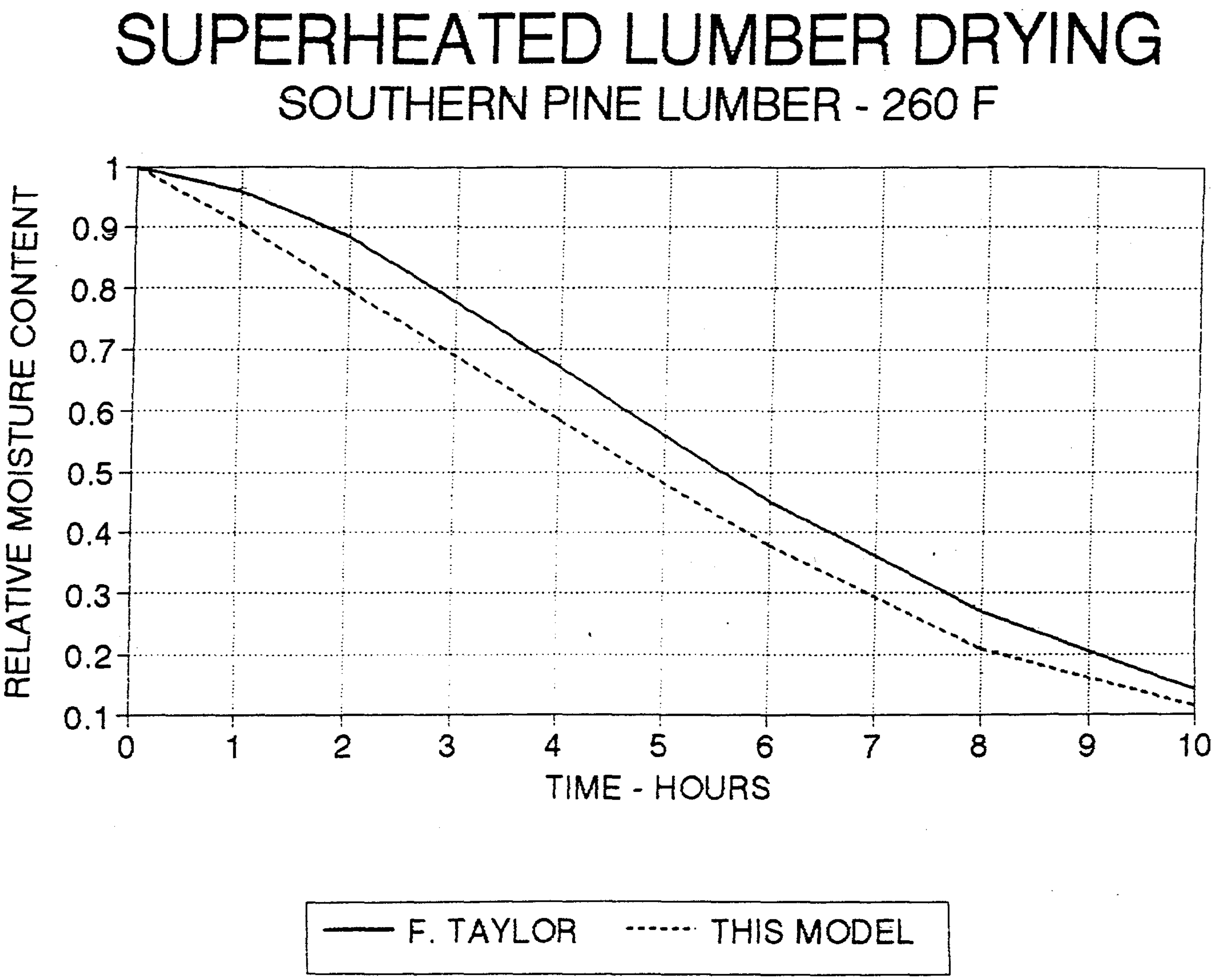



FIGURE 3. COMPARISON OF PREDICTED DRYING RATES OF COMPUTER MODEL WITH REPORTED RESULTS OF TAYLOR FOR SUPERHEATED STEAM DRYING AT 260°F.

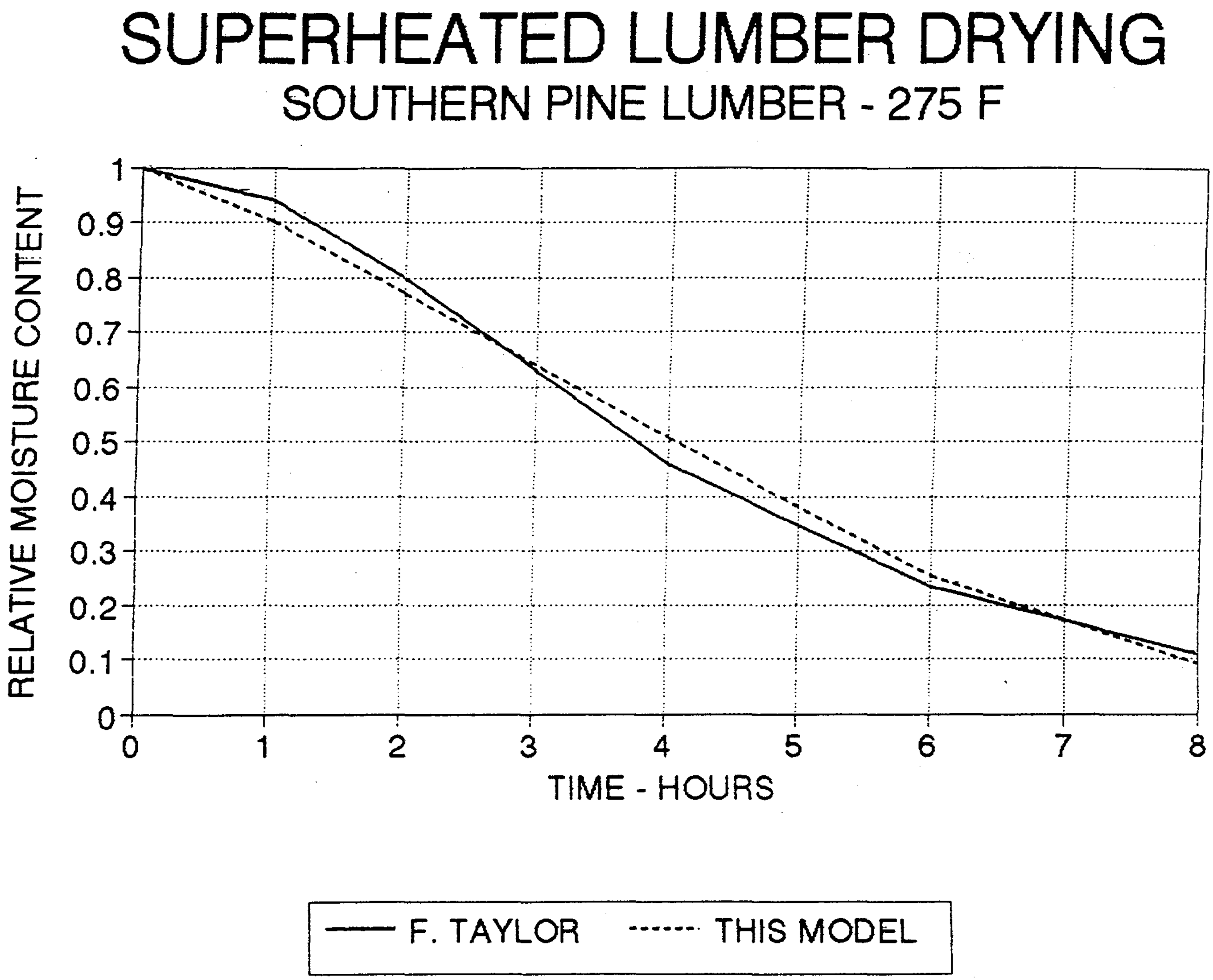



FIGURE 4. COMPARISON OF PREDICTED DRYING RATES OF COMPUTER MODEL WITH REPORTED RESULTS OF TAYLOR FOR SUPERHEATED STEAM DRYING AT 275°F.

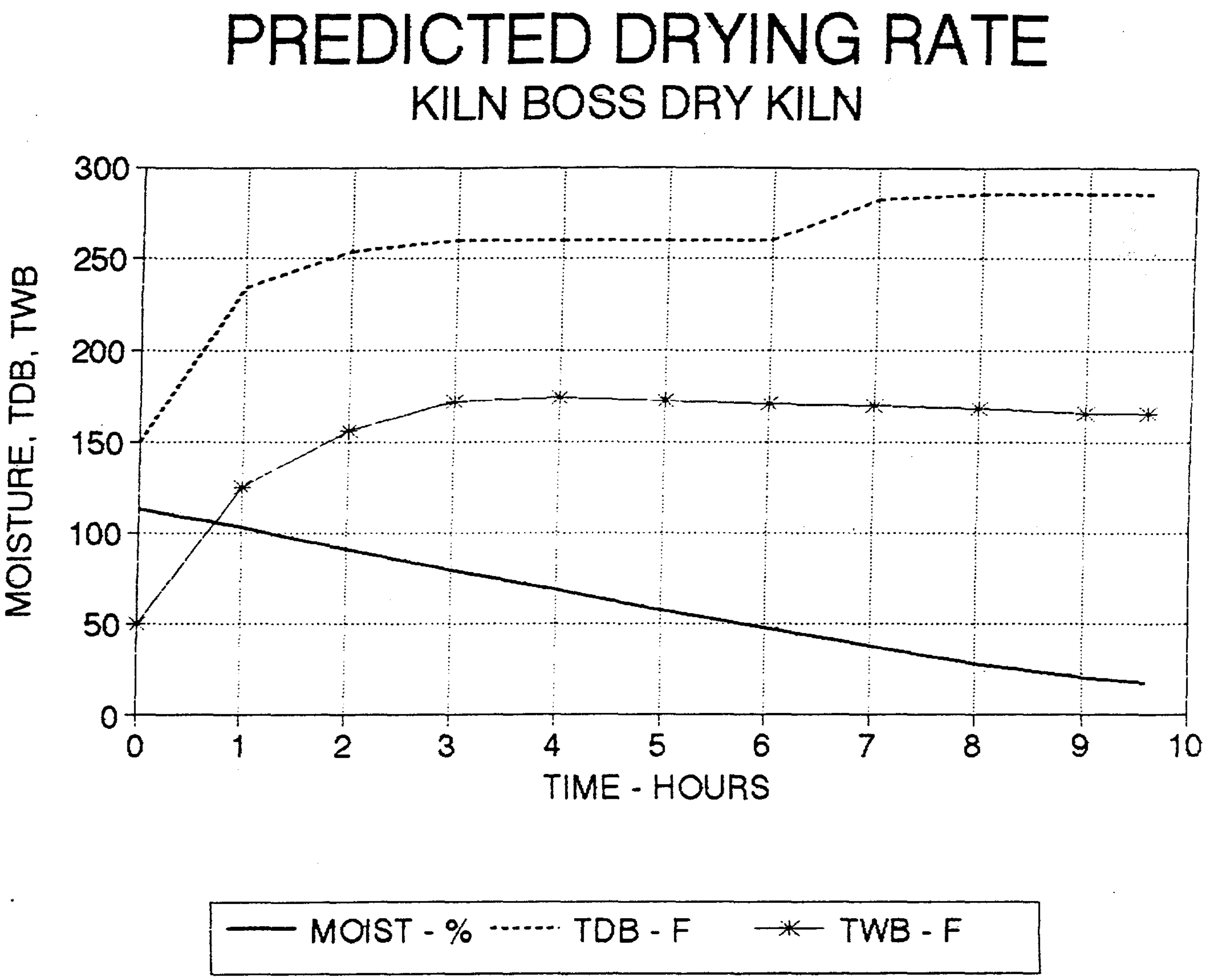



FIGURE 5. PRELIMINARY LUMBER DRYING PREDICTIONS FOR AN IRVINGTON-MOORE KILN-BOSS DRYING SCHEDULE.

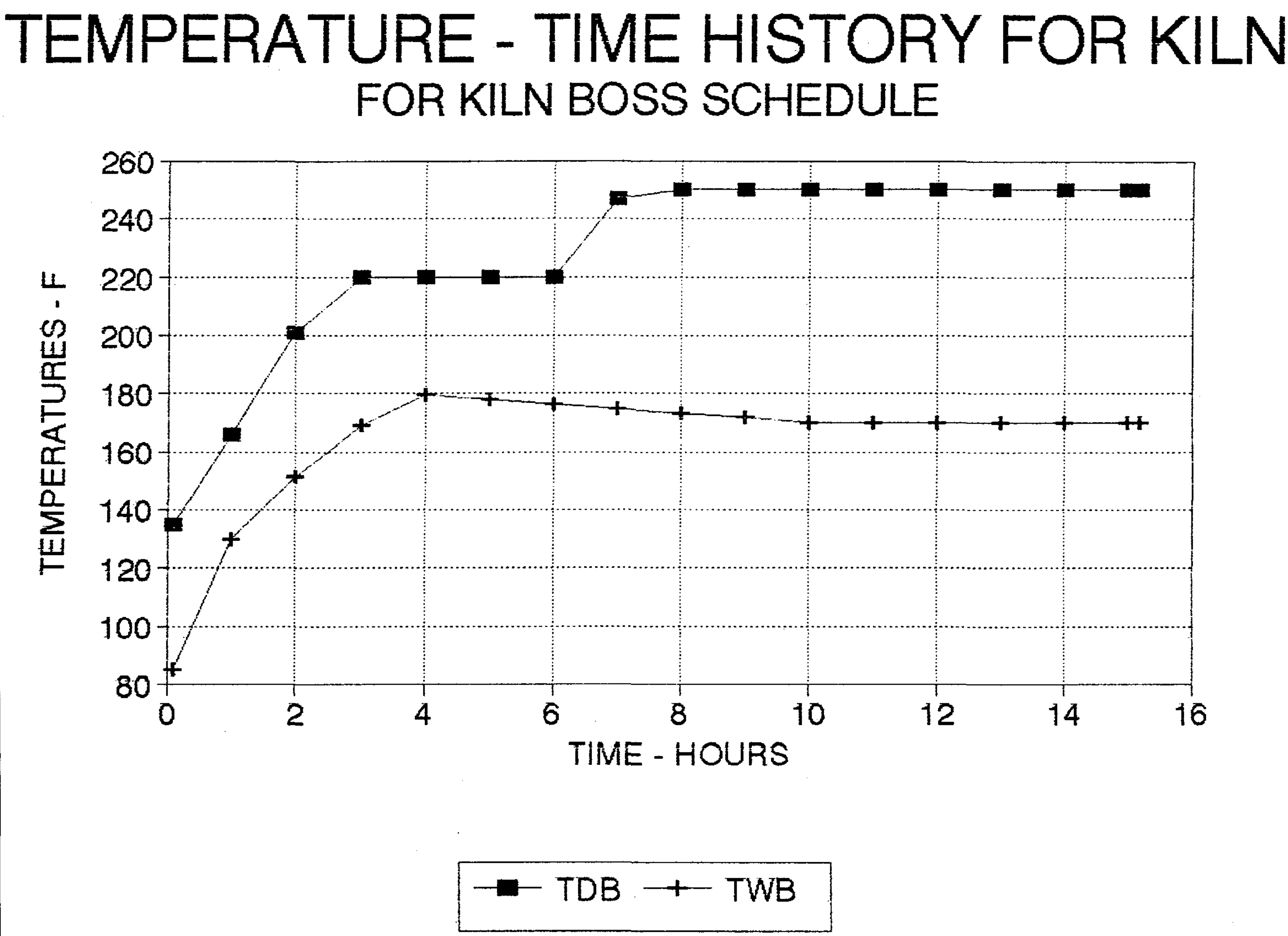



FIGURE 6. TEMPERATURE-TIME HISTORY FOR KILN-BOSS DRYING SCHEDULE.

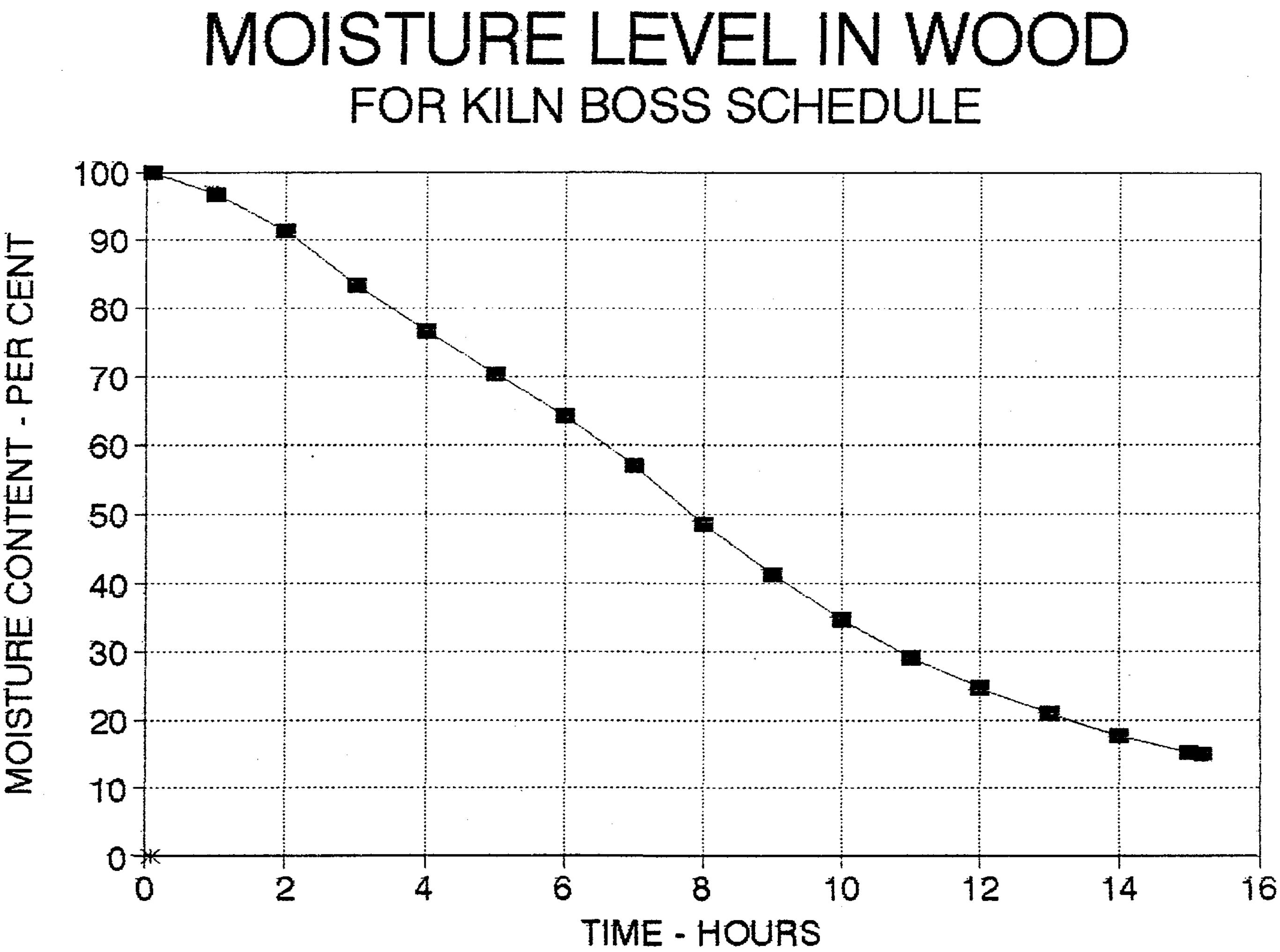



FIGURE 7. PREDICTED AVERAGE MOISTURE IN LUMBER IN DRY KILN KILN-BOSS DRYING SCHEDULE.

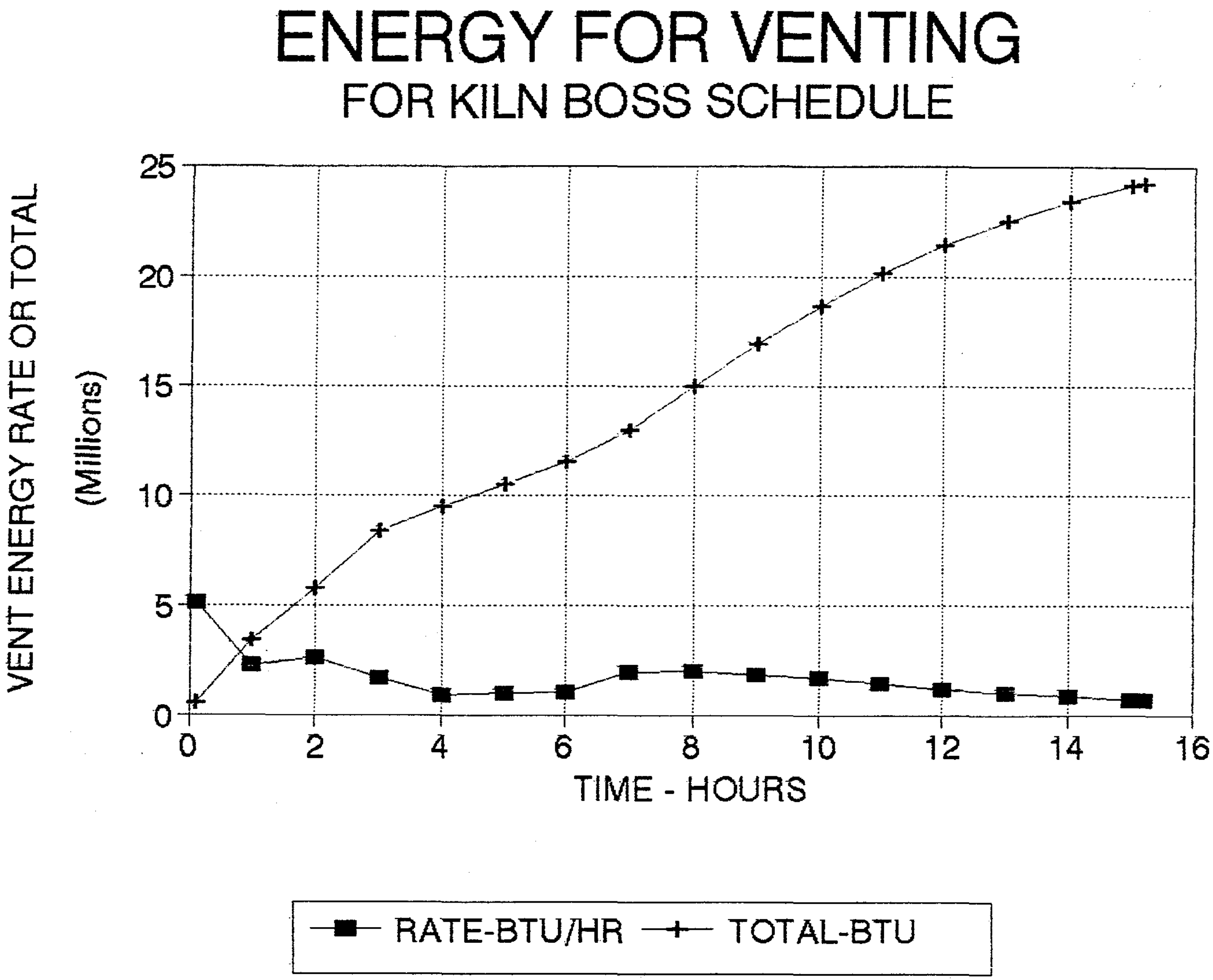



FIGURE 8. PREDICTED ENERGY RATE AND TOTAL ACCUMULATED FOR HEATING THE VENT AIR FOR KILN-BOSS DRYING SCHEDULE.

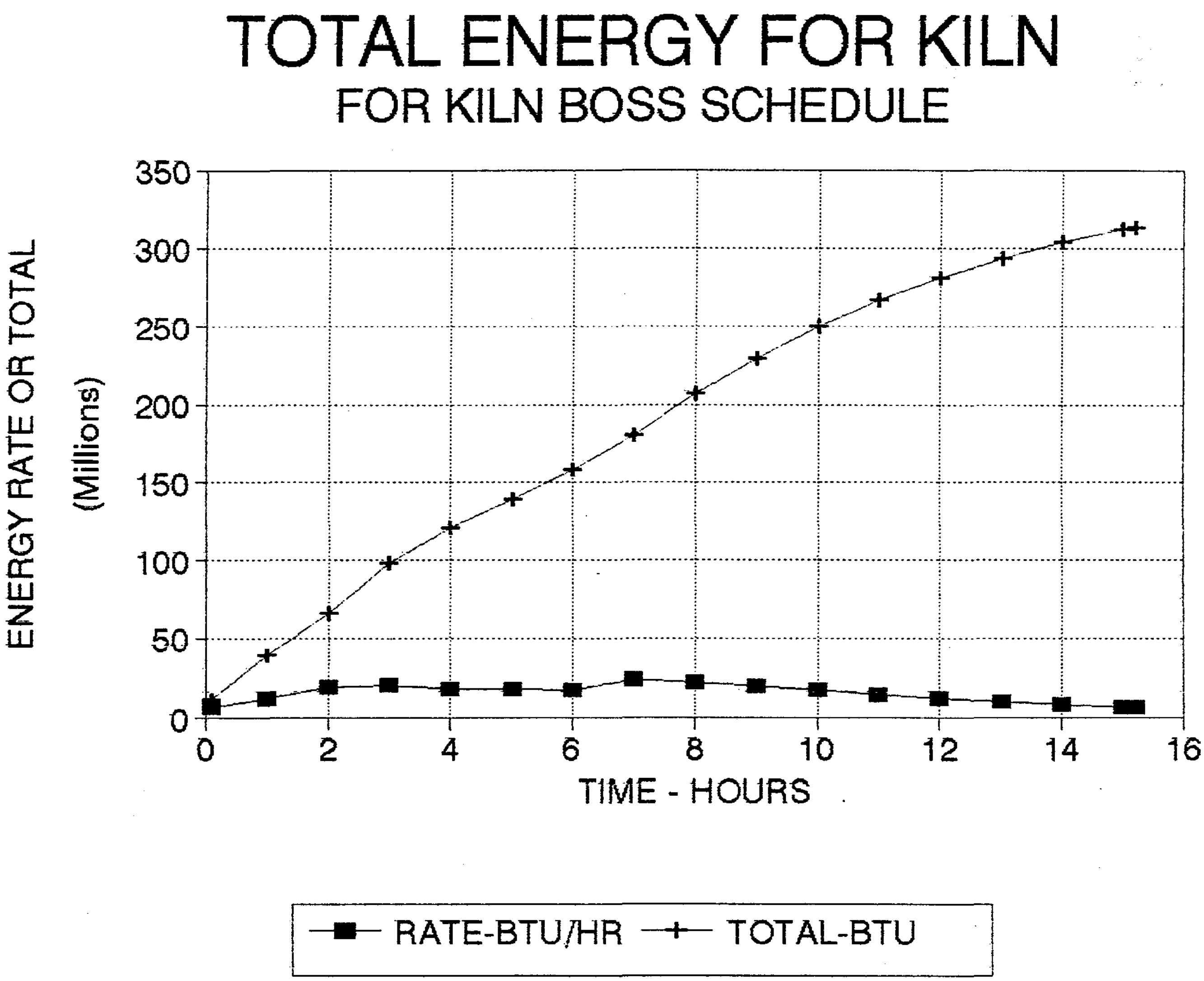



FIGURE 9. PREDICTED HEAT RATE FOR EVAPORATION AND TOTAL ACCUMULATED ENERGY FOR KILN-BOSS SCHEDULE.

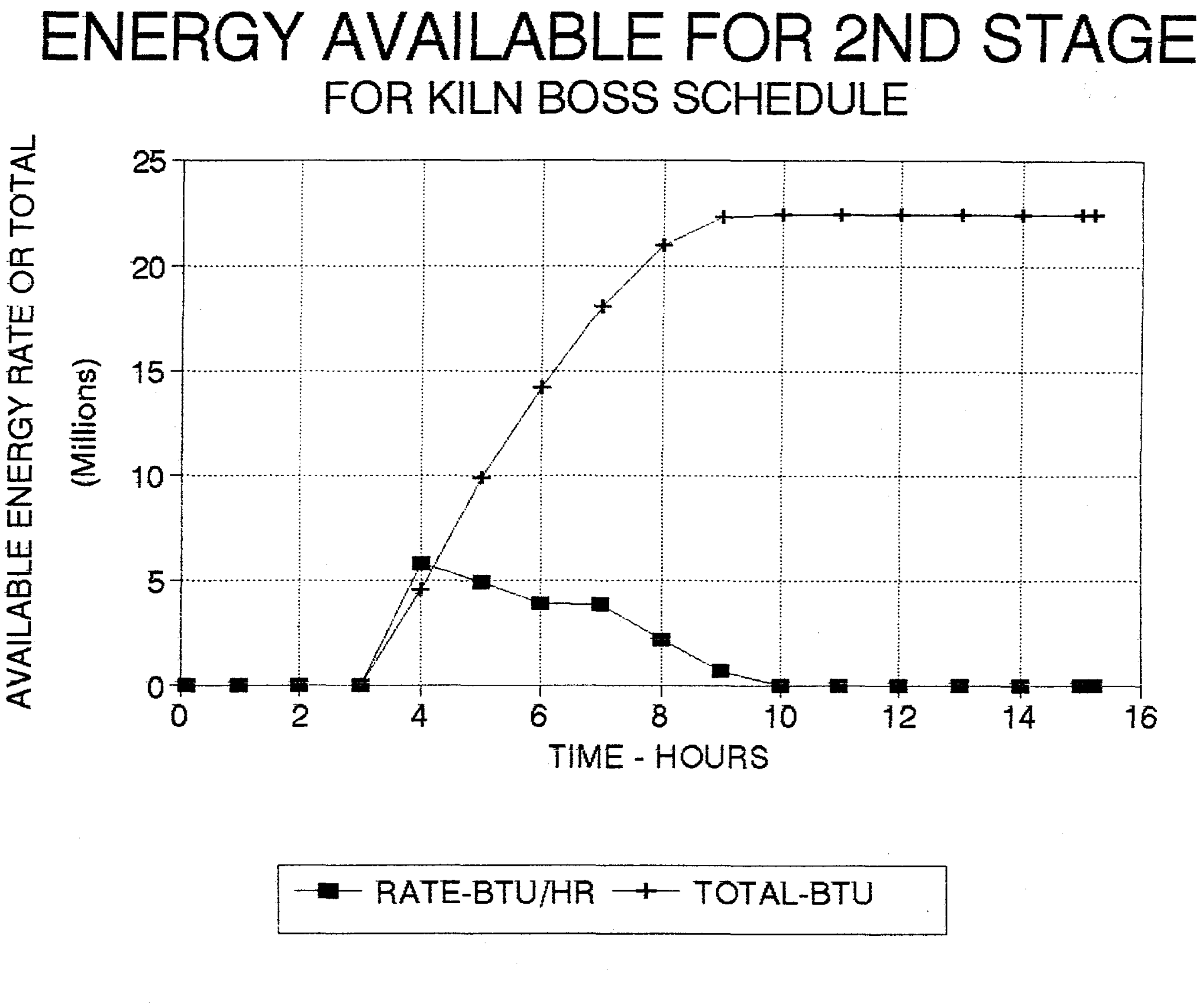



FIGURE 10. PREDICTED ENERGY RATE AND TOTAL ENERGY AVAILABLE FOR USE BY THE SECOND-STAGE KILN - KILN-BOSS SCHEDULE.

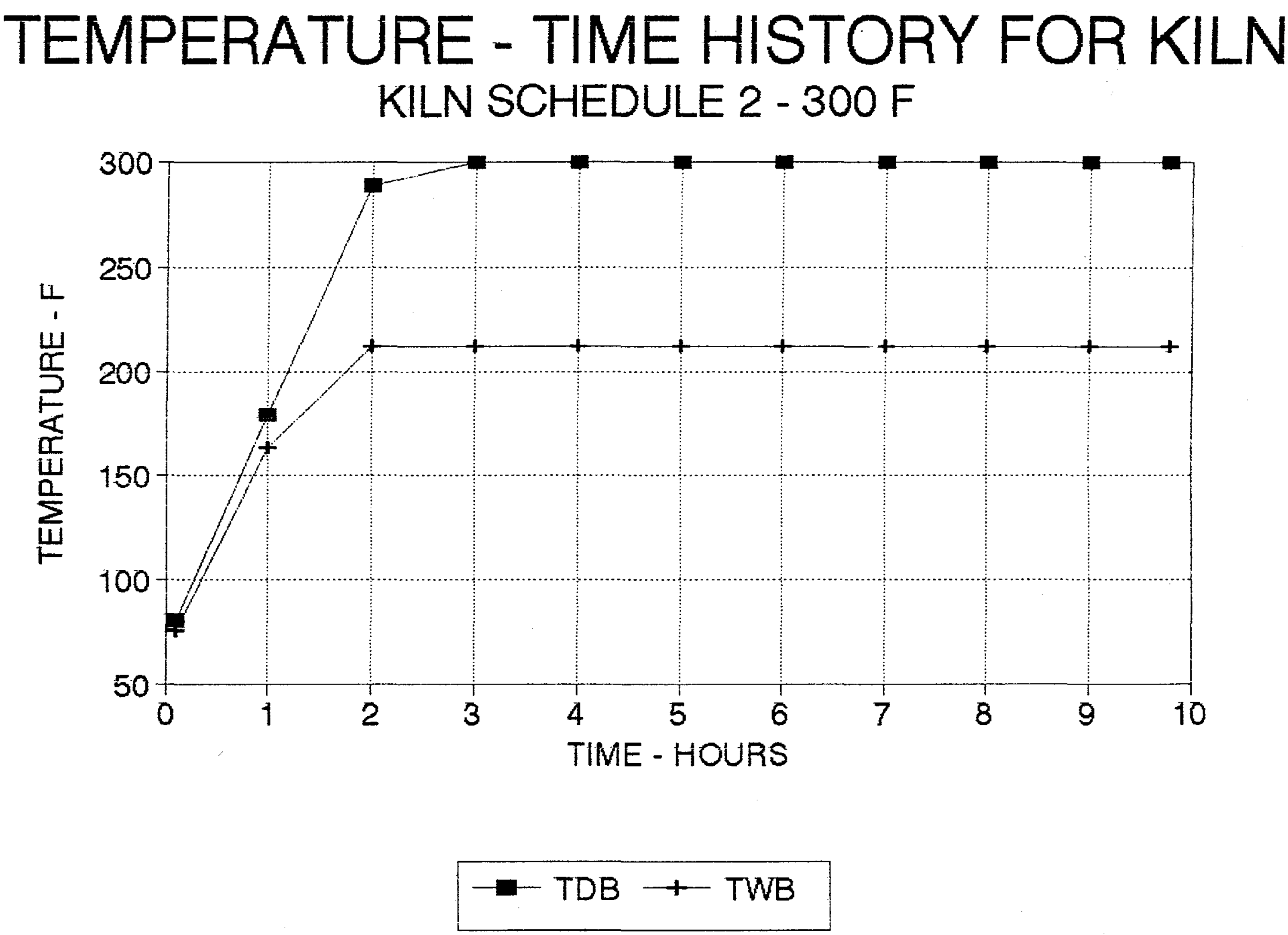



FIGURE 11. TEMPERATURE-TIME HISTORY FOR SCHEDULE 2 DRYING SCHEDULE.

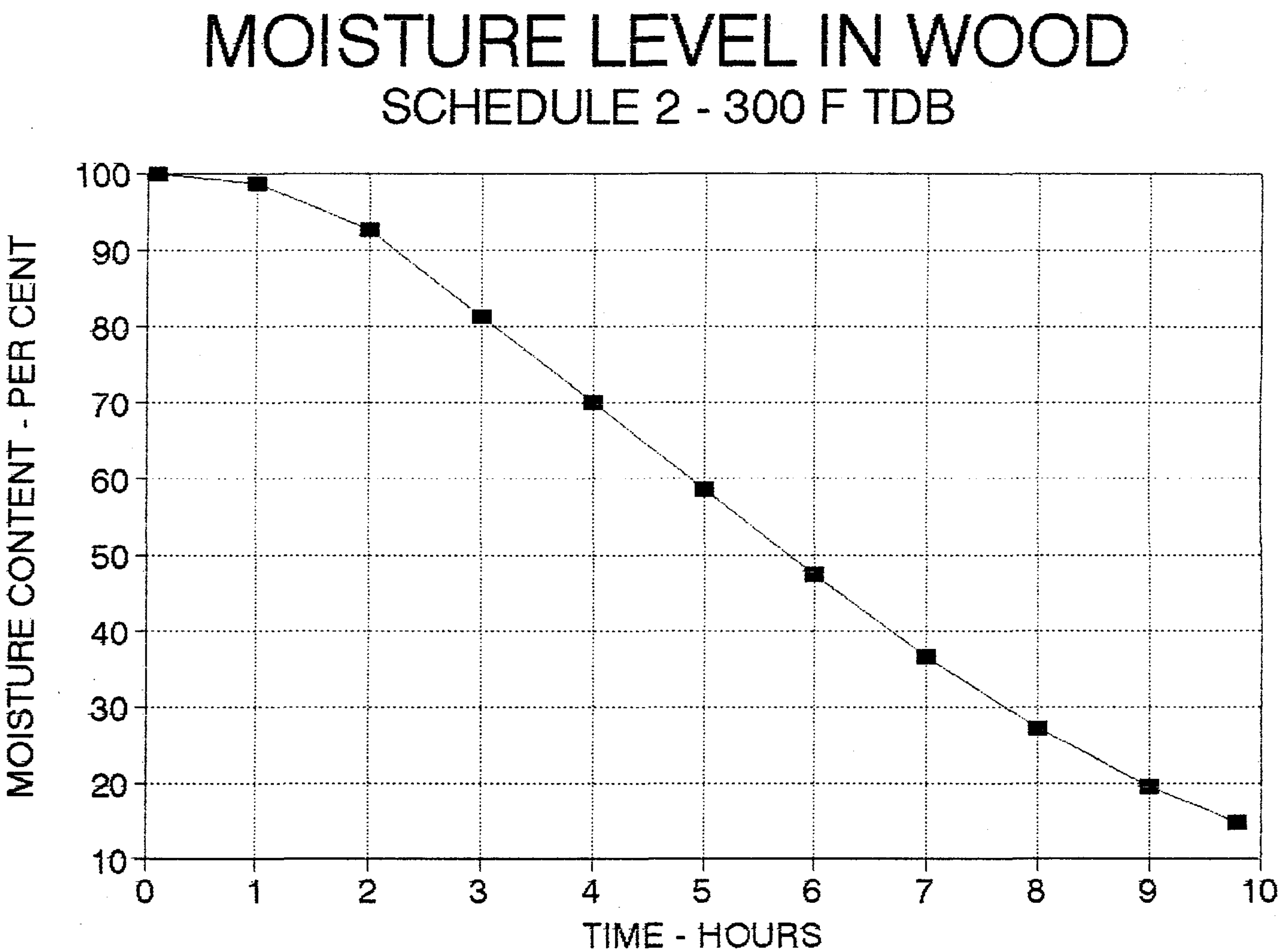



FIGURE 12. PREDICTED AVERAGE MOISTURE IN LUMBER IN DRY KILN SCHEDULE 2 DRYING SCHEDULE.

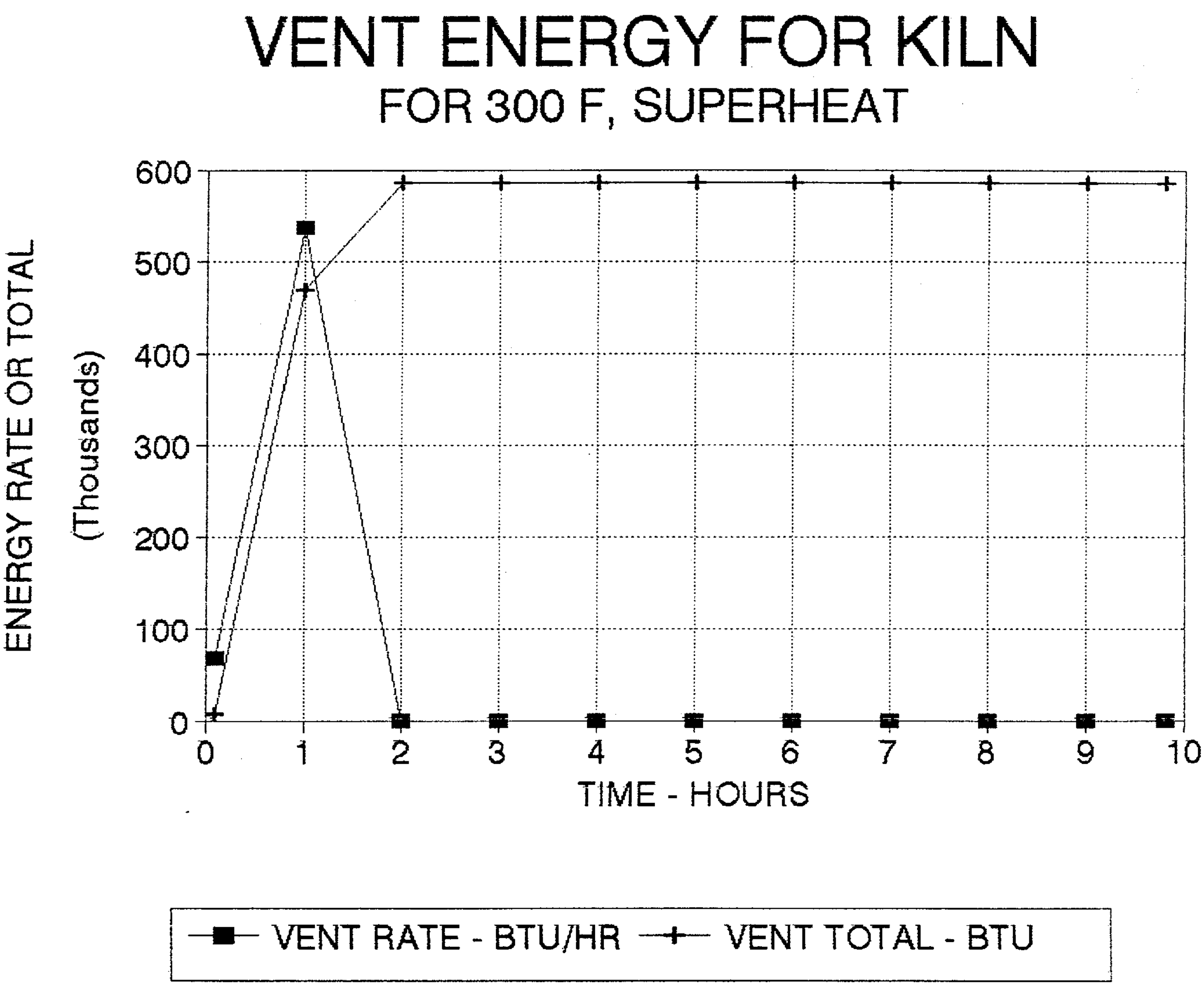



FIGURE 13. PREDICTED ENERGY RATE AND TOTAL ACCUMULATED FOR HEATING THE VENT AIR FOR SCHEDULE 2 DRYING SCHEDULE.

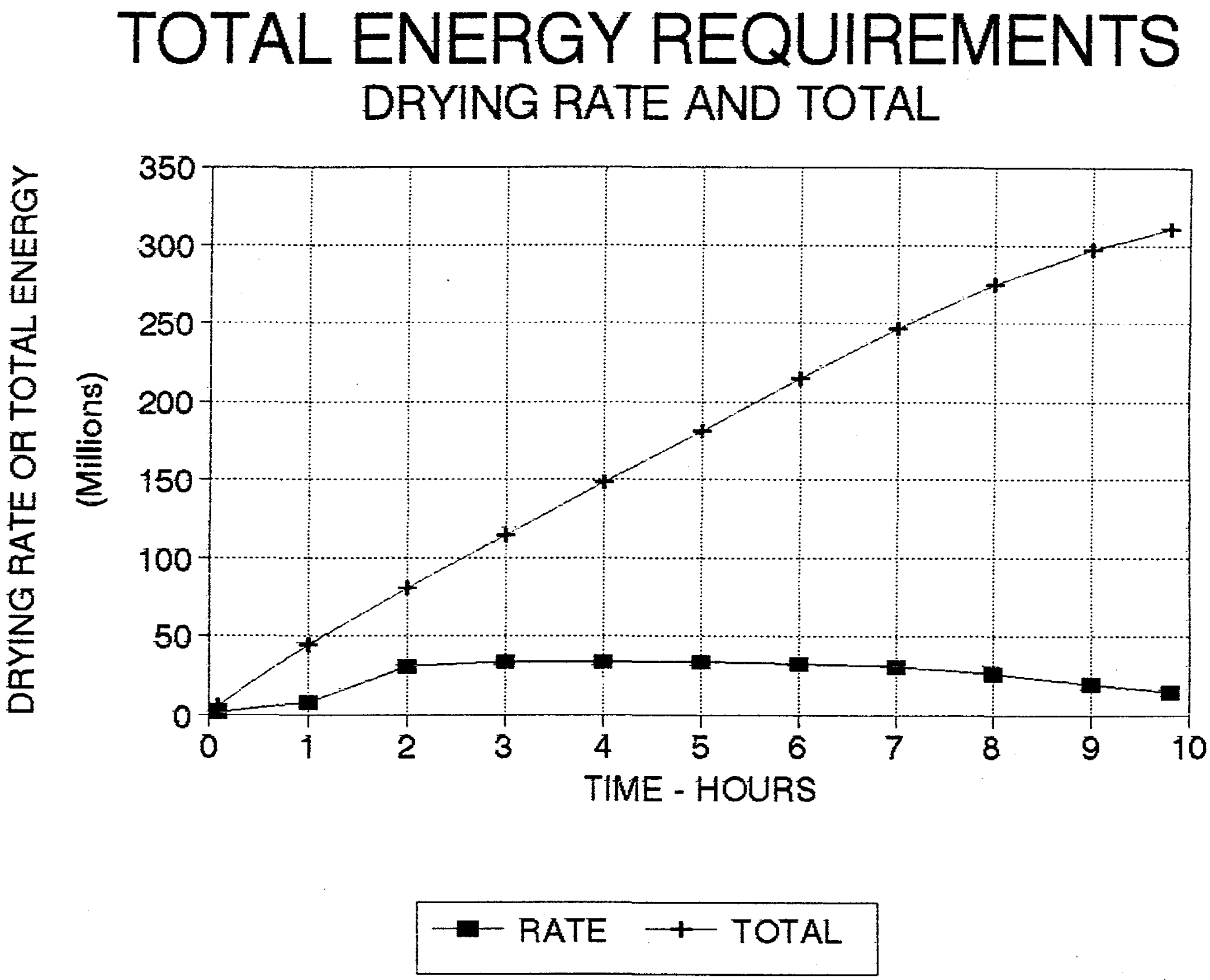



FIGURE 14. PREDICTED HEAT RATE FOR EVAPORATION AND TOTAL ACCUMULATED ENERGY FOR SCHEDULE 2 DRYING SCHEDULE.

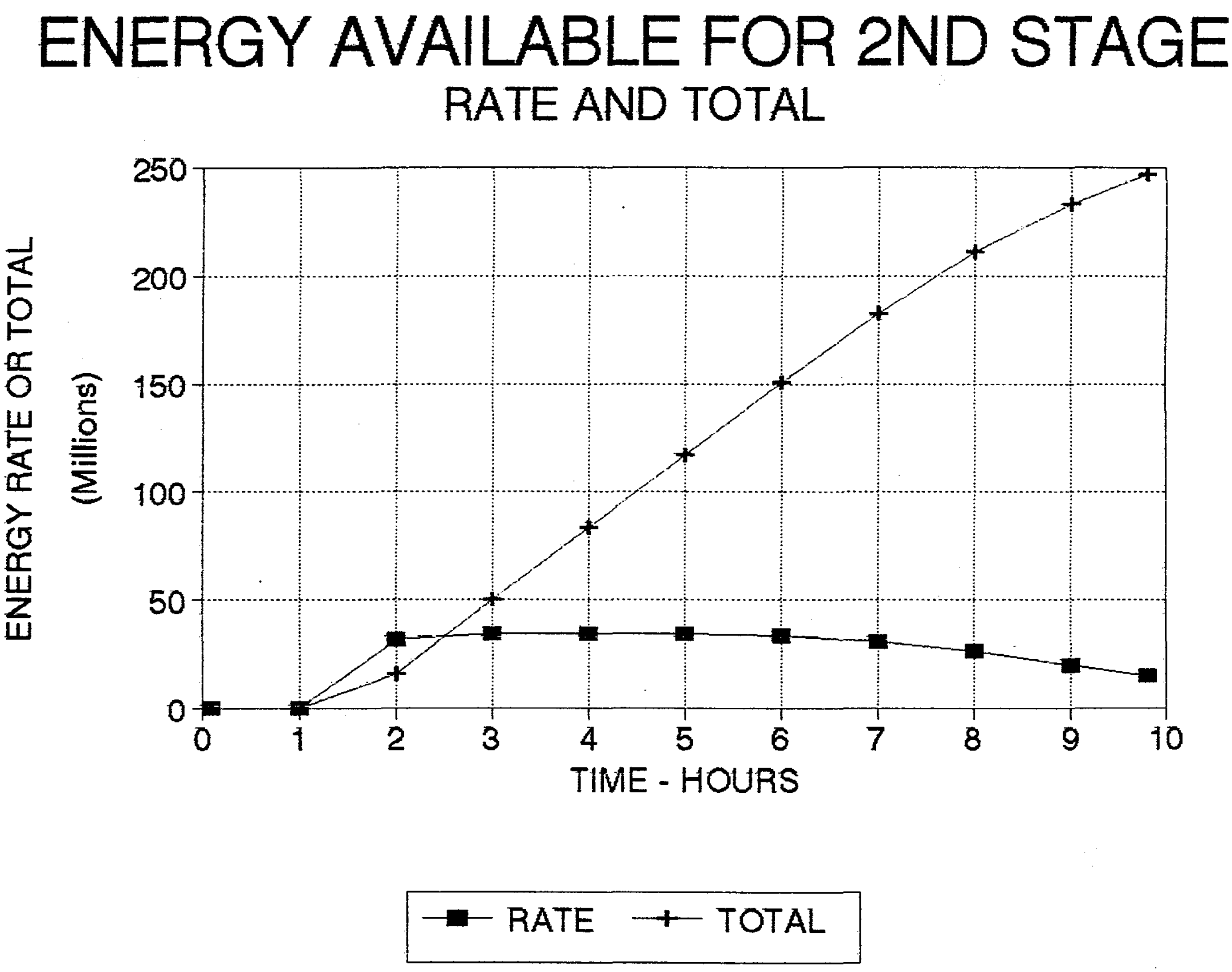



FIGURE 15. PREDICTED ENERGY RATE AND TOTAL ENERGY AVAILABLE FOR USE BY THE SECOND-STAGE KILN - SCHEDULE 2 DRYING SCHEDULE.

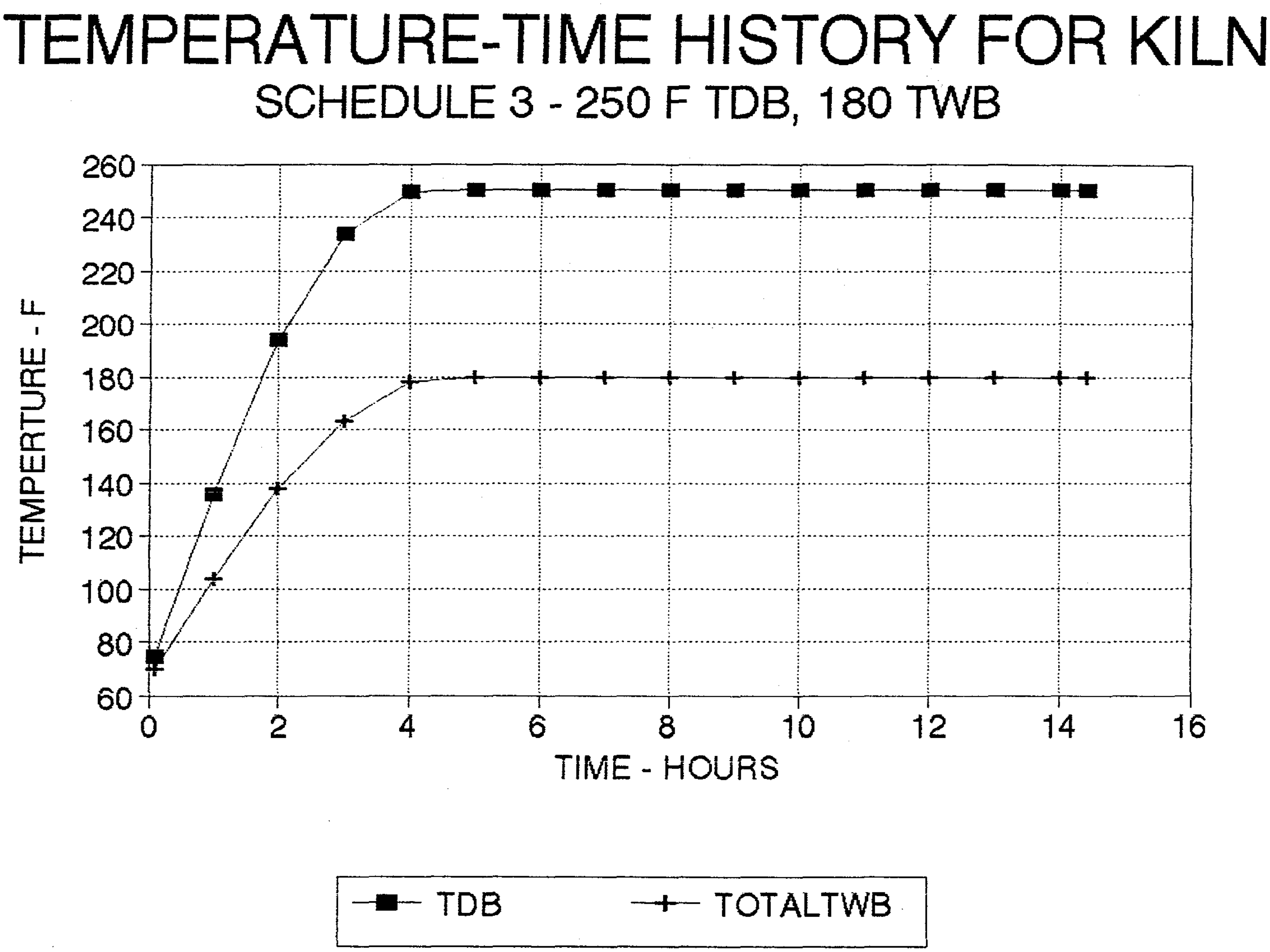



FIGURE 16. TEMPERATURE-TIME HISTORY FOR SCHEDULE 3 DRYING SCHEDULE.

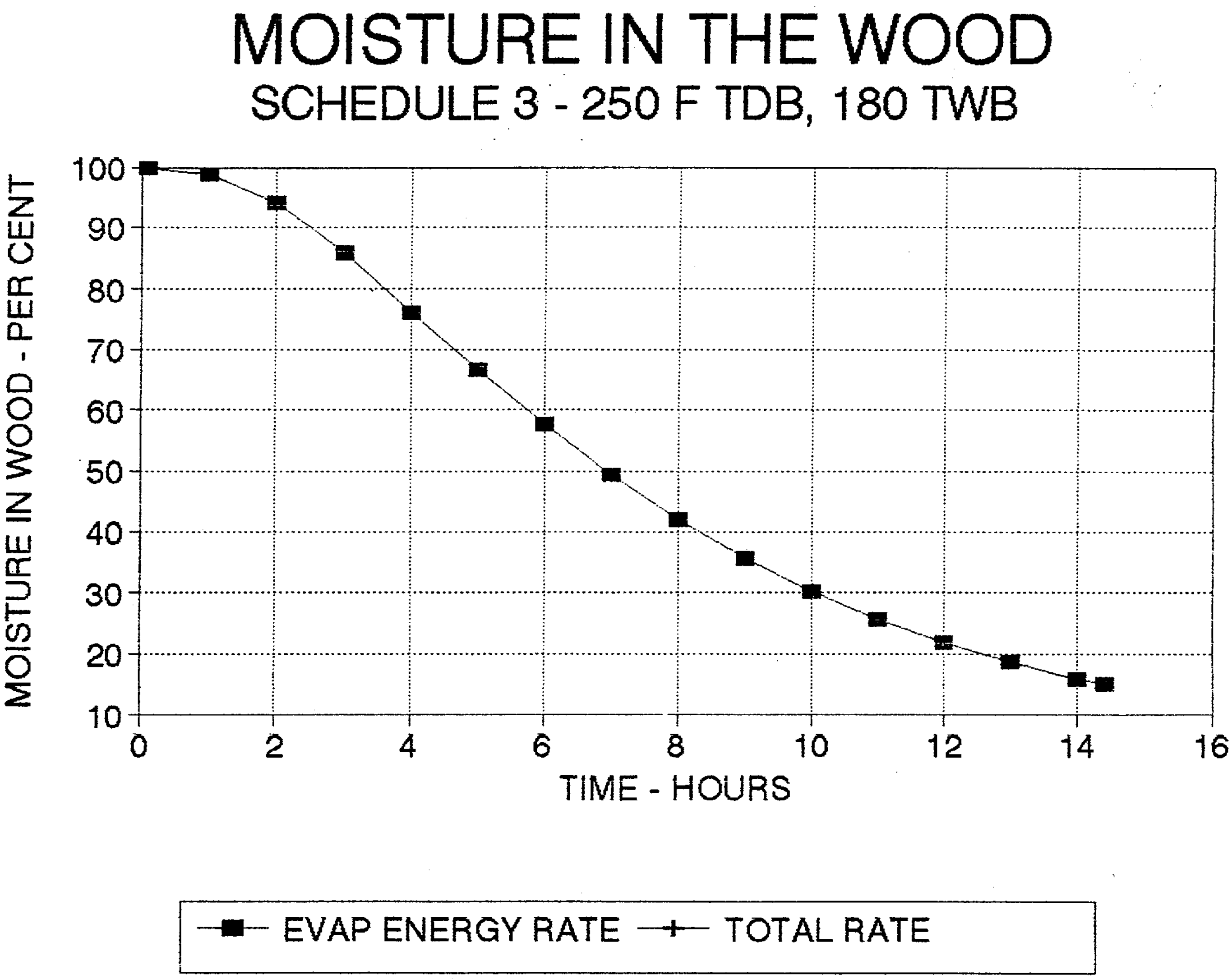



FIGURE 17. PREDICTED AVERAGE MOISTURE IN LUMBER IN DRY KILN SCHEDULE 3 DRYING SCHEDULE.

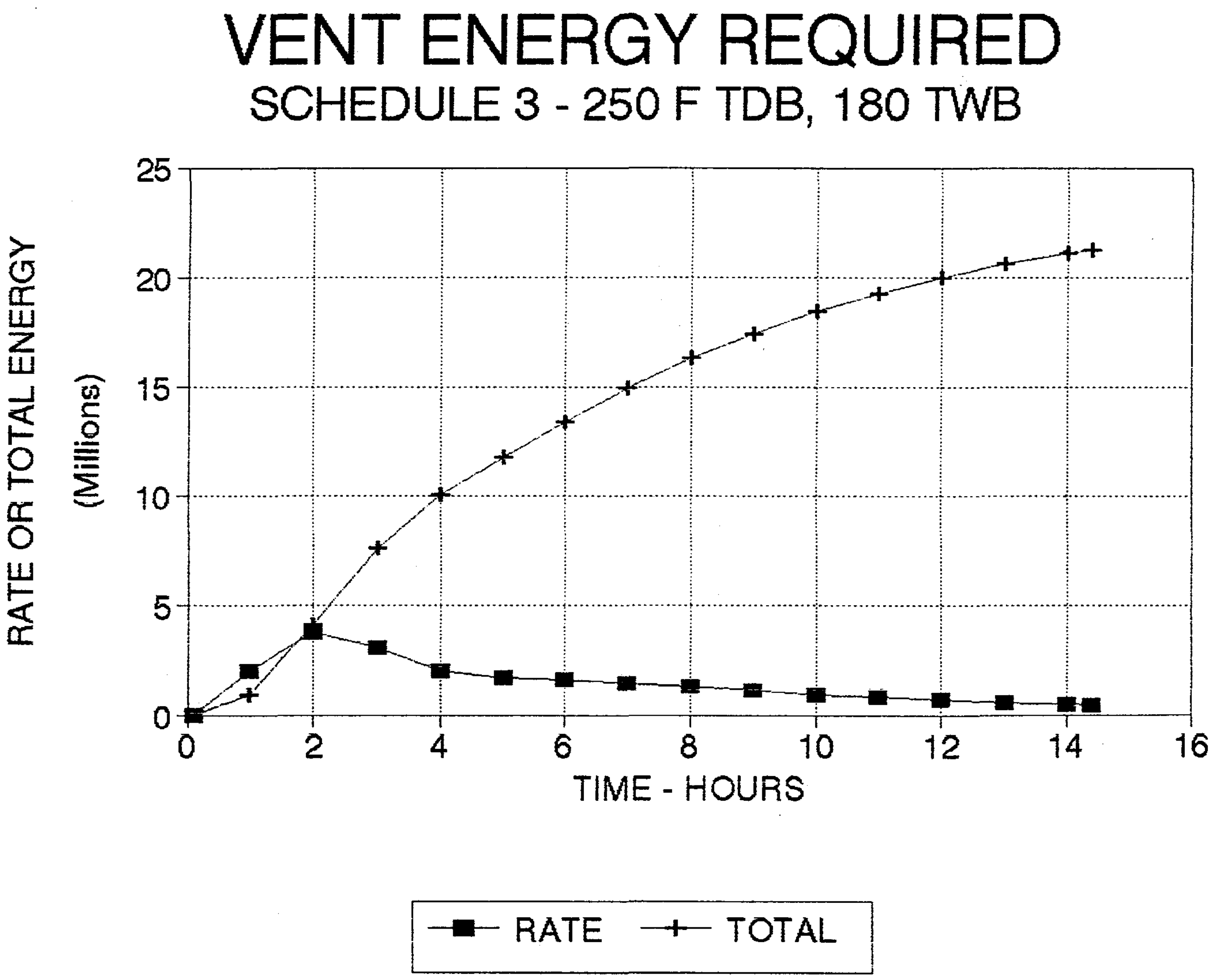



FIGURE 18. PREDICTED ENERGY RATE AND TOTAL ACCUMULATED FOR HEATING THE VENT AIR FOR SCHEDULE 3 DRYING SCHEDULE.

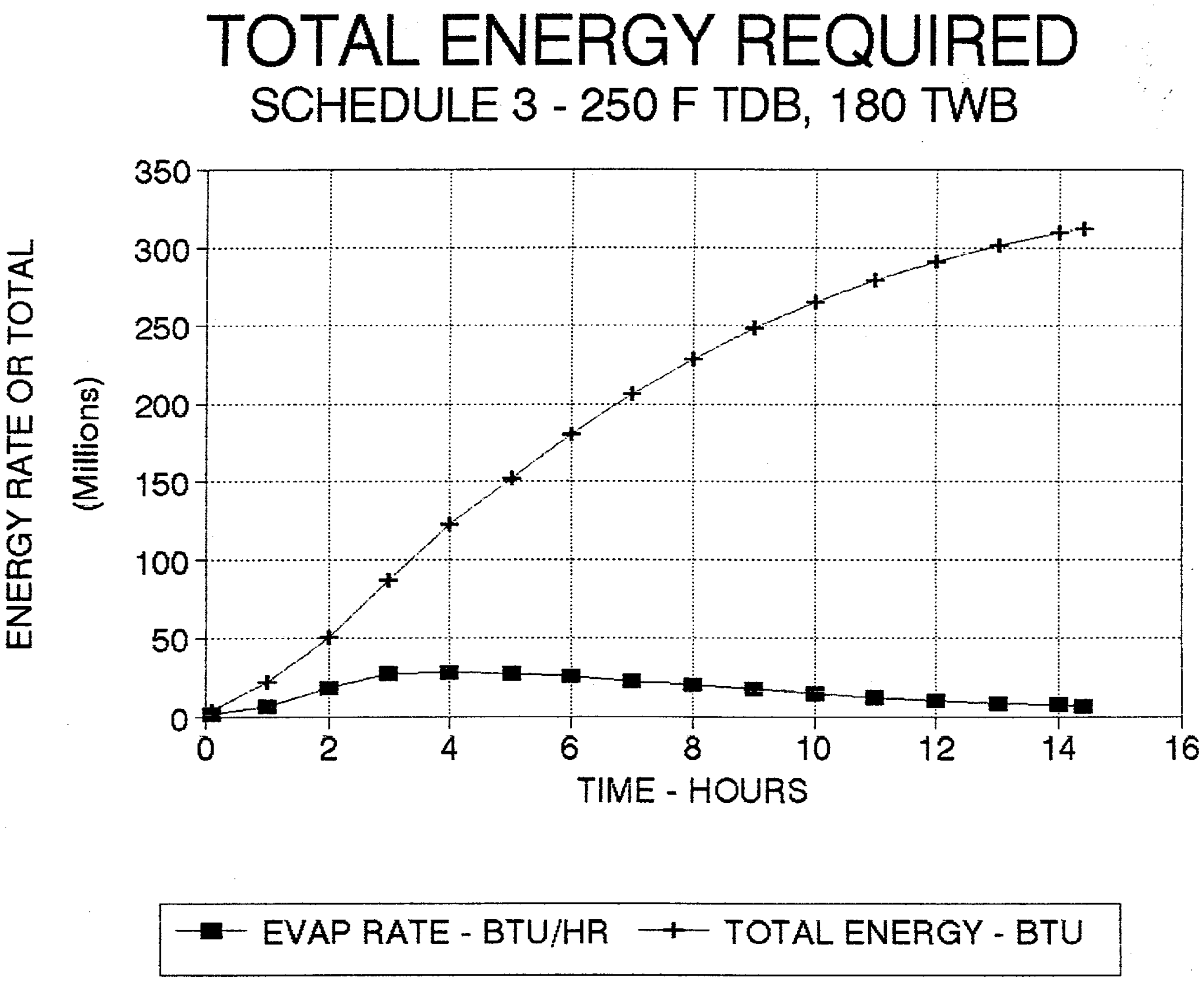



FIGURE 19. PREDICTED HEAT RATE FOR EVAPORATION AND TOTAL ACCUMULATED ENERGY FOR SCHEDULE 3 DRYING SCHEDULE.

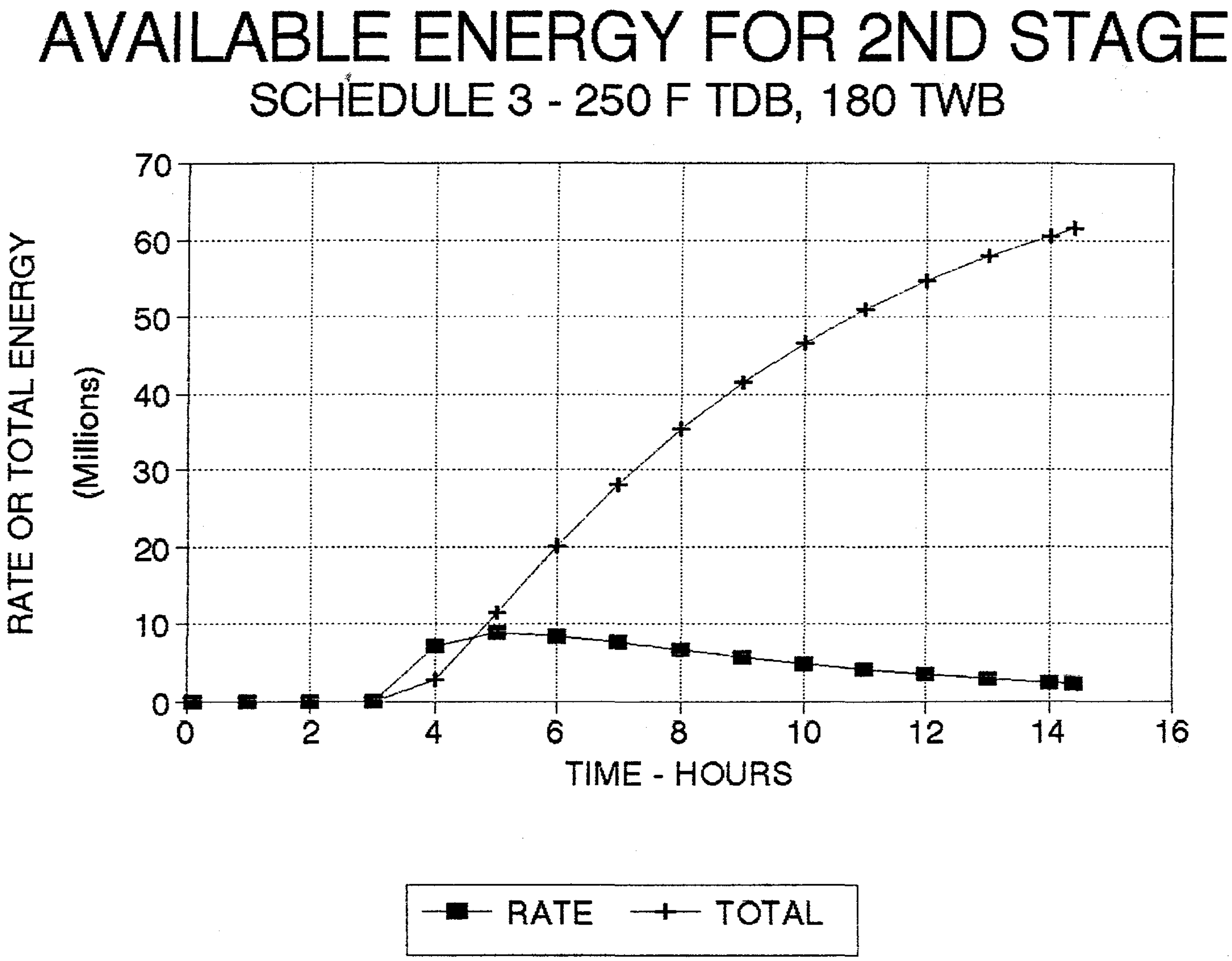



FIGURE 20. PREDICTED ENERGY RATE AND TOTAL ENERGY AVAILABLE FOR USE BY THE SECOND-STAGE KILN - SCHEDULE 3 DRYING SCHEDULE.

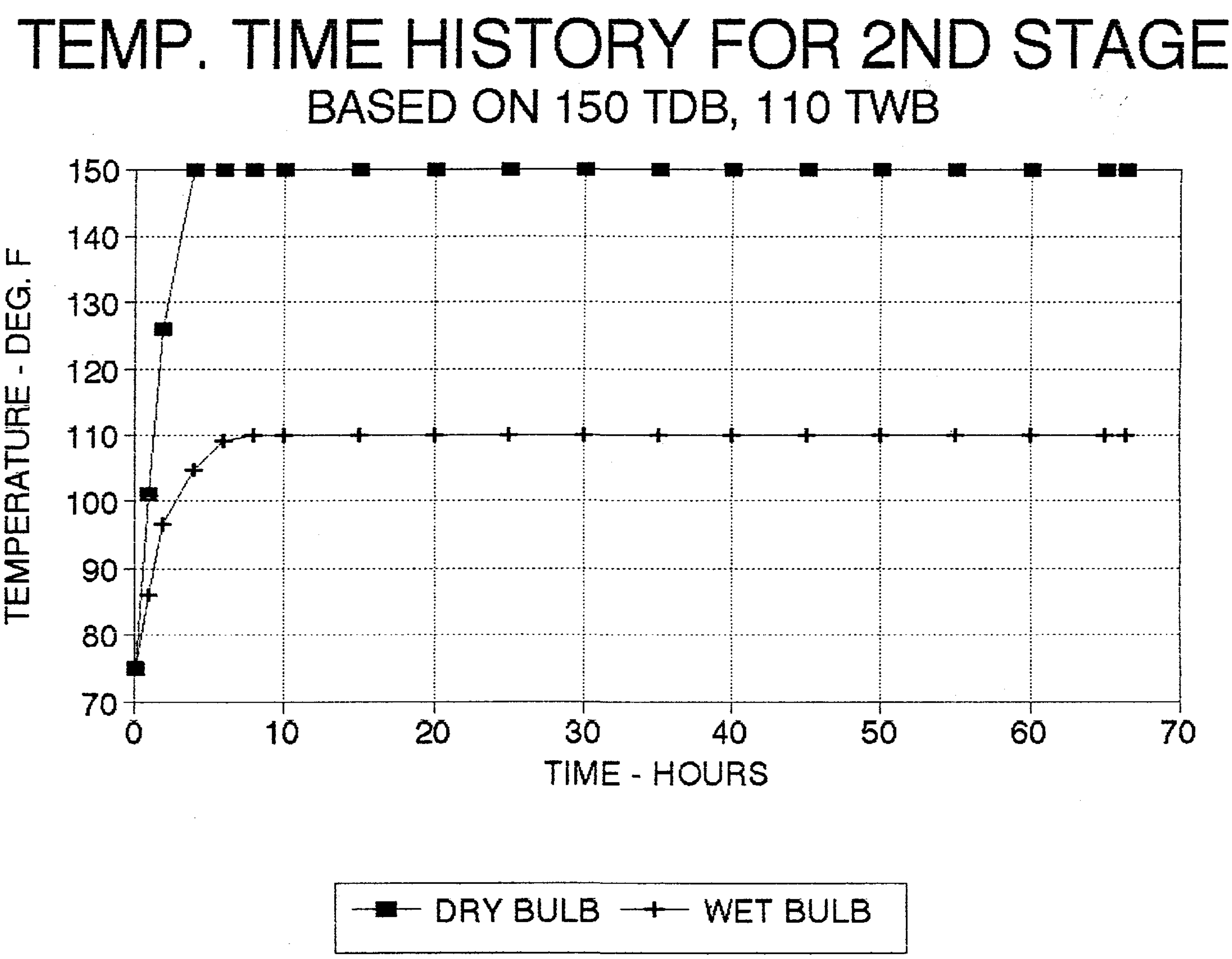



FIGURE 21. TEMPERATURE-TIME HISTORY FOR SECOND-STAGE KILN DRYING SCHEDULE.

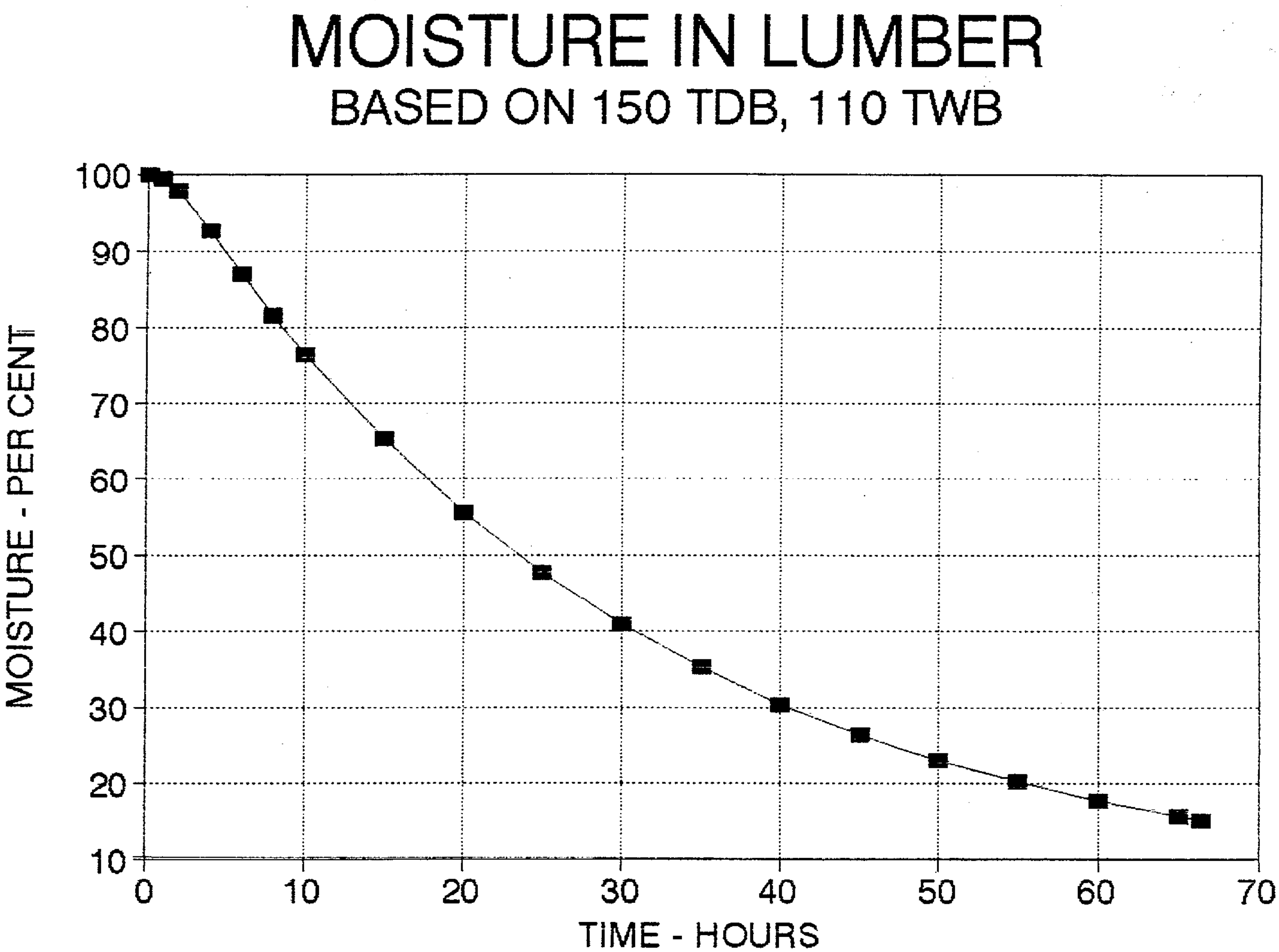



FIGURE 22. PREDICTED AVERAGE MOISTURE IN LUMBER IN SECOND-STAGE DRY KILN FOR SECOND-STAGE DRYING SCHEDULE.

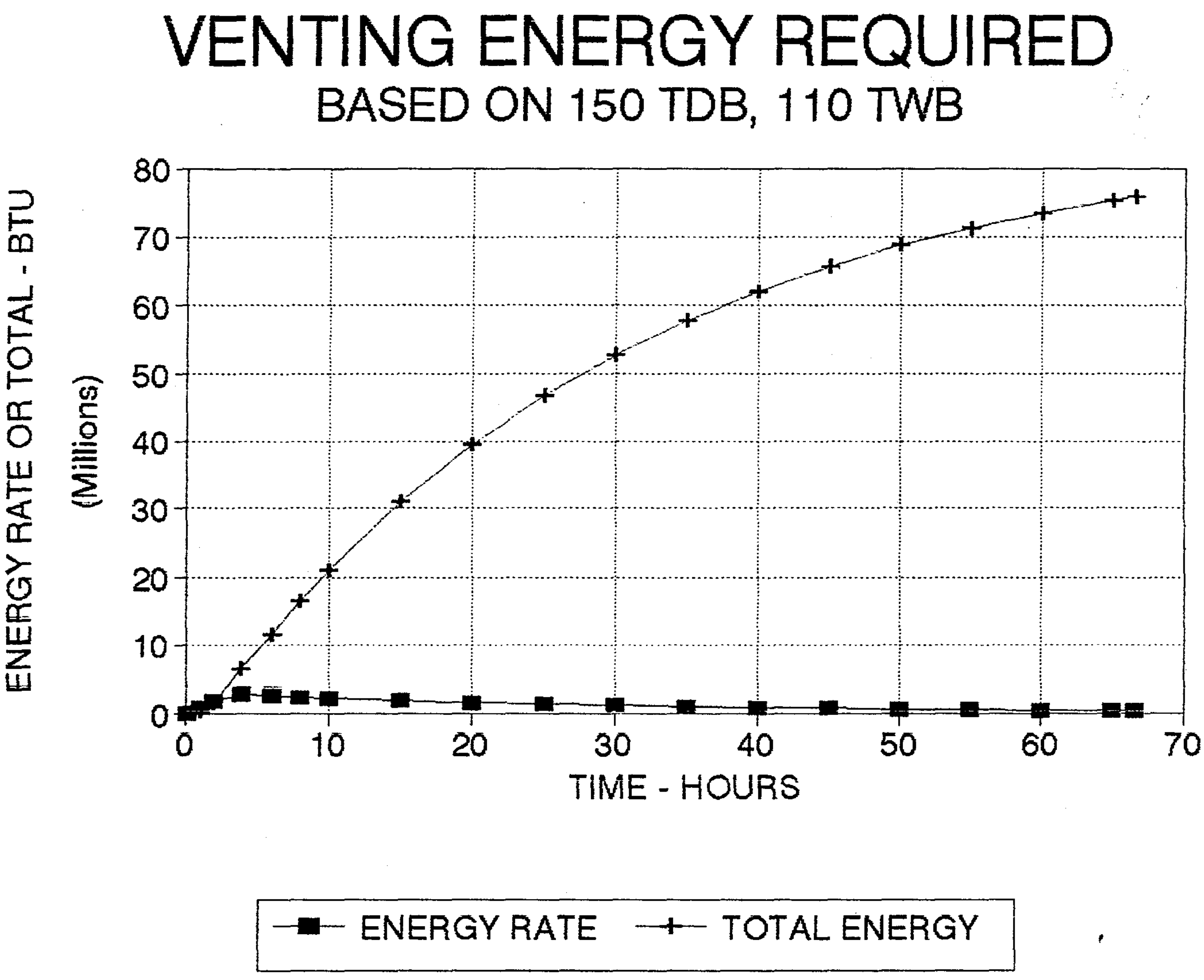



FIGURE 23. PREDICTED ENERGY RATE AND TOTAL ACCUMULATED FOR HEATING THE VENT AIR FOR SECOND-STAGE KILN DRYING SCHEDULE.

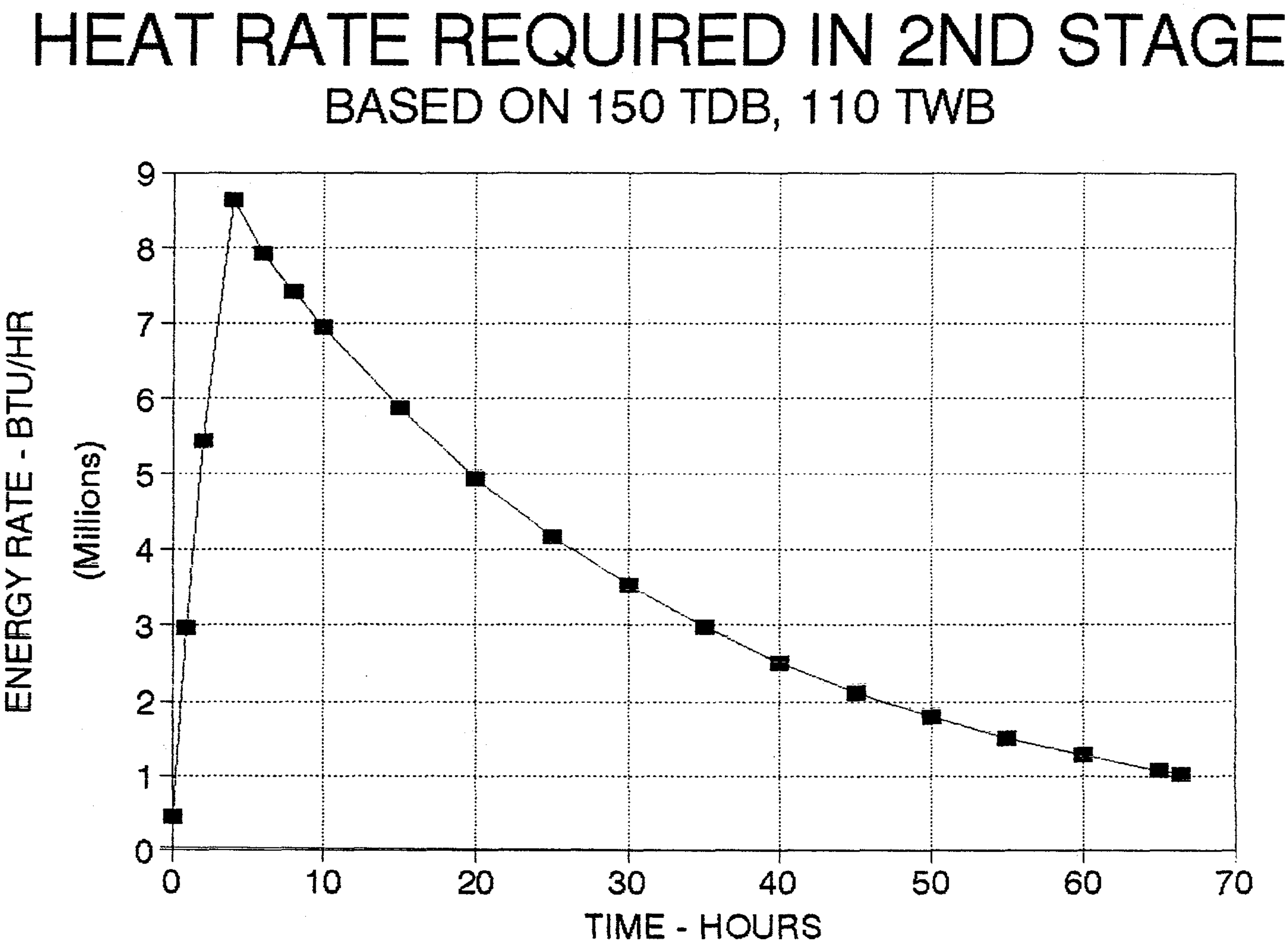



FIGURE 24. PREDICTED HEAT RATE FOR EVAPORATION FOR SECOND-STAGE DRY KILN DRYING SCHEDULE.

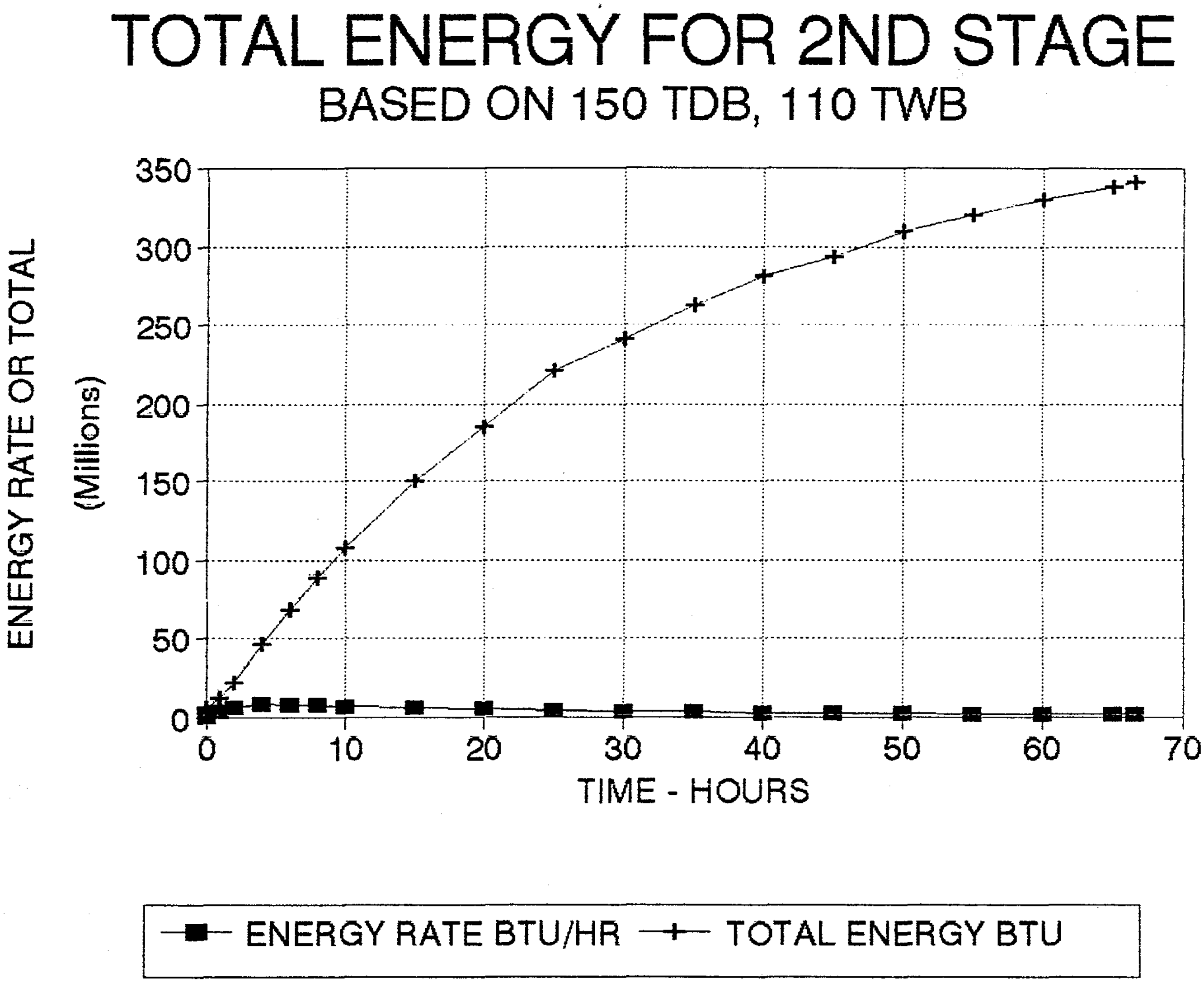



FIGURE 25. PREDICTED TOTAL ENERGY REQUIRED BY THE SECOND-STAGE KILN - SECOND-STAGE DRYING SCHEDULE.

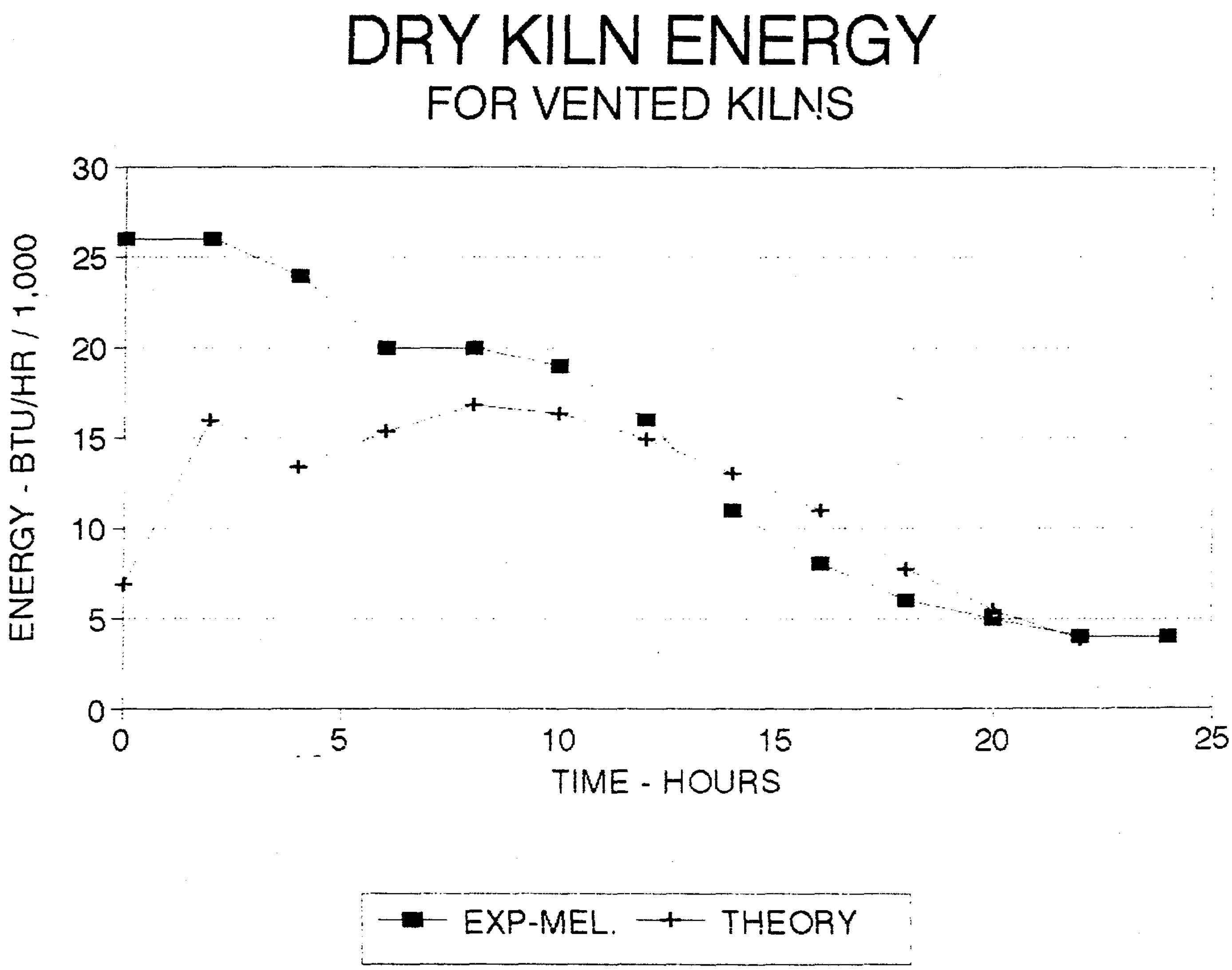



FIGURE 26. COMPARISON OF DESIGN AND THEORETICAL ENERGY REQUIREMENTS FOR A CONVENTIONAL DRY KILN.

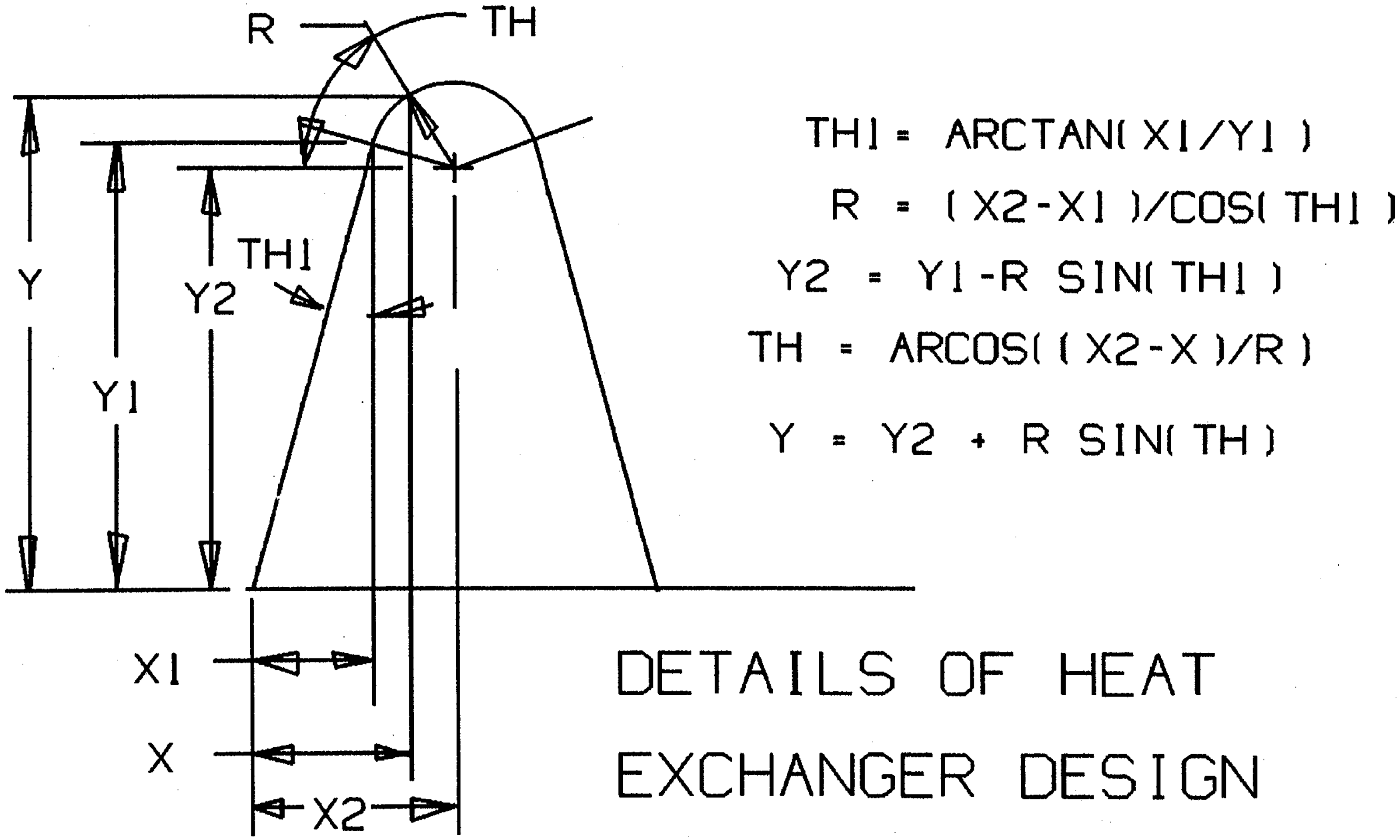



FIGURE 27. PRELIMINARY DESIGN OF PROTOTYPE HEAT EXCHANGE EQUIPMENT FOR SECOND-STAGE DRY KILN APPLICATIONS.

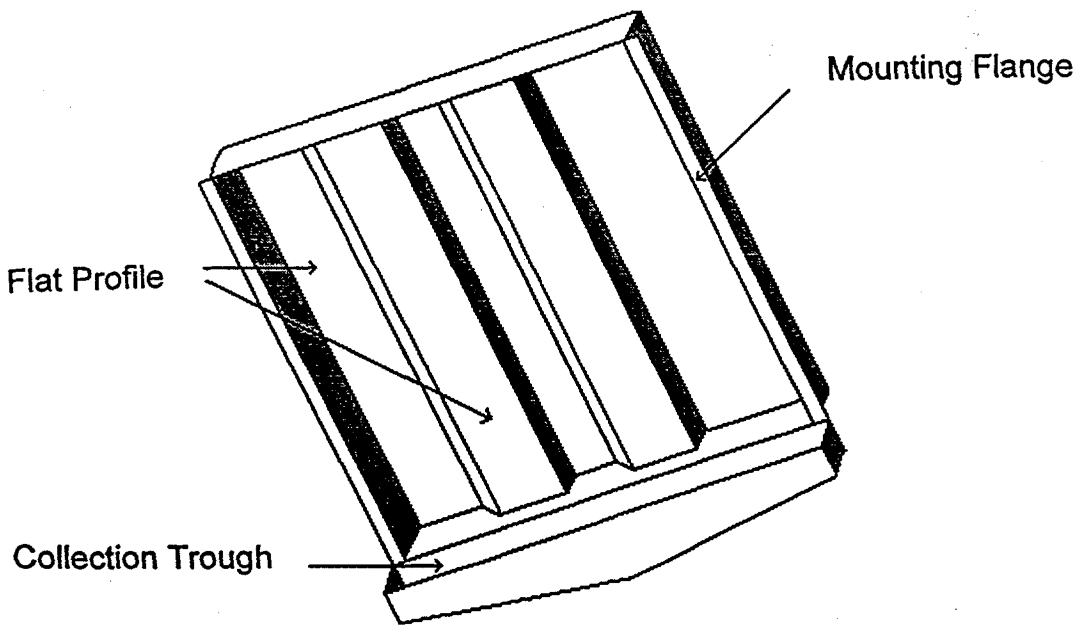



FIGURE 28. PERSPECTIVE DRAWING OF PILOT-SCALE HEAT EXCHANGER PANEL WITH COMMERCIALLY AVAILABLE ALUMINIZED SHEET METAL.

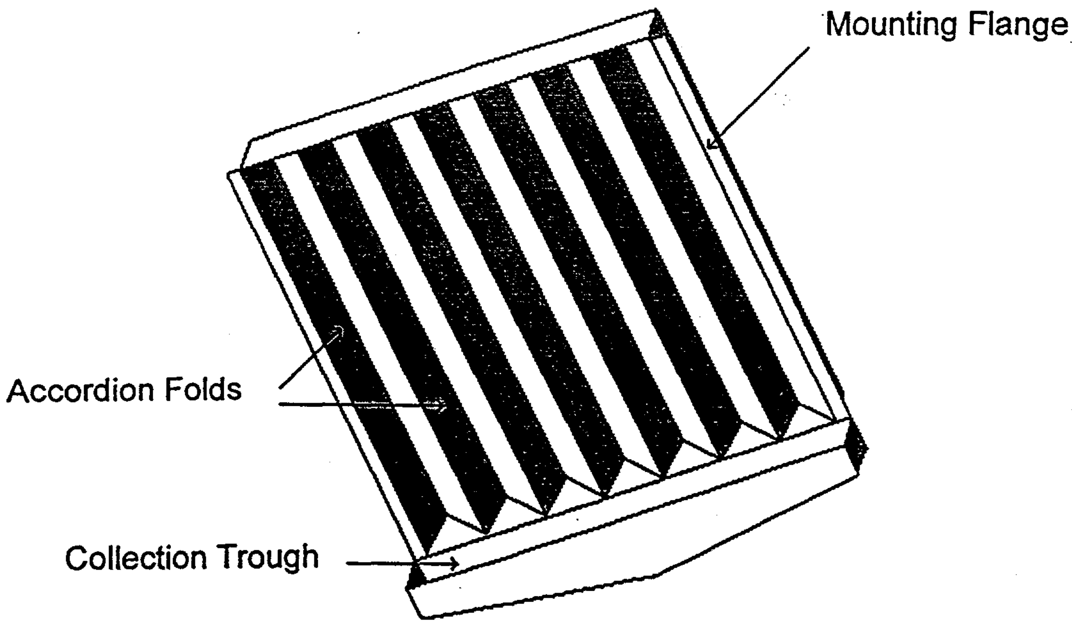



FIGURE 29. PERSPECTIVE DRAWING OF PILOT-SCALE HEAT EXCHANGER PANEL WITH DEEP SQUARE GROOVES TO ENHANCE SURFACE AREA.

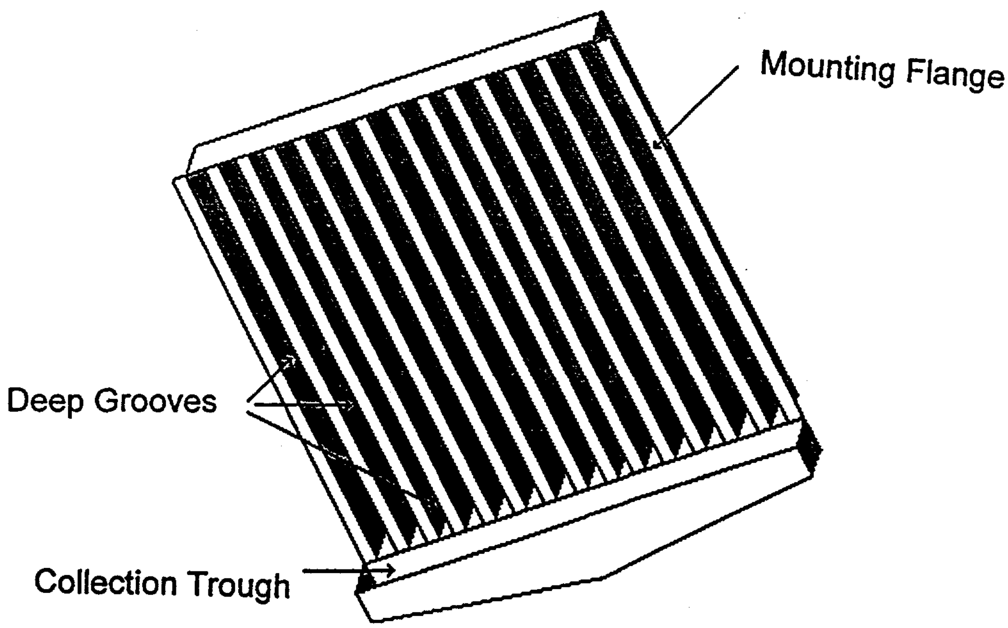
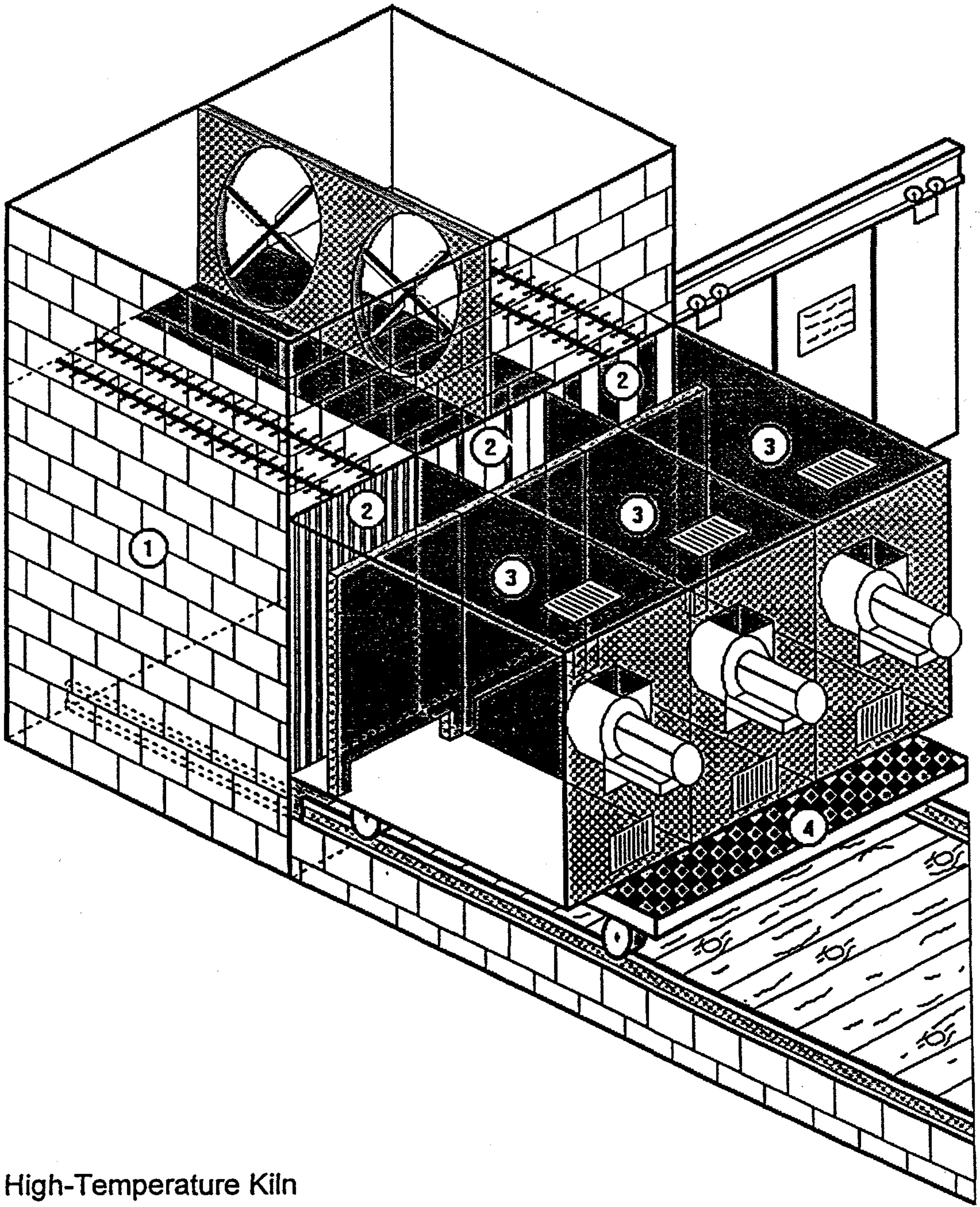



FIGURE 30. PERSPECTIVE DRAWING OF PILOT-SCALE HEAT EXCHANGER PANEL WITH DEEP FOLDED "V" GROOVES TO ENHANCE SURFACE AREA.




1. High-Temperature Kiln
2. Heat Exchangers
3. Second-Stage Chambers
4. Kiln Tram

FIGURE 31. PERSPECTIVE DRAWING OF TEST CELLS FOR THE EXPERIMENTAL EFFORT ON THIS PROJECT.

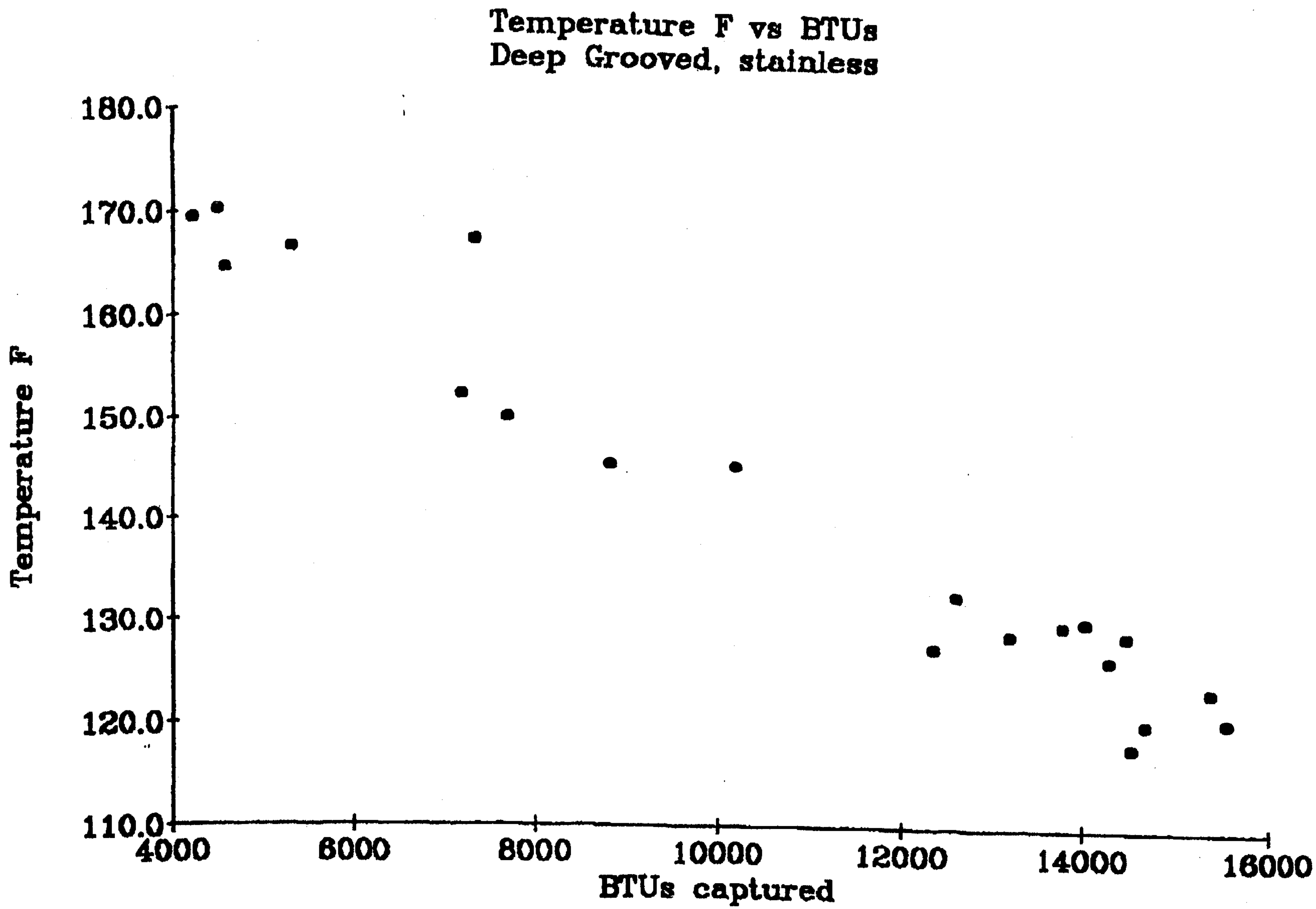



FIGURE 32. CORRELATION OF HEAT TRANSFER RATE FOR CELL 1.

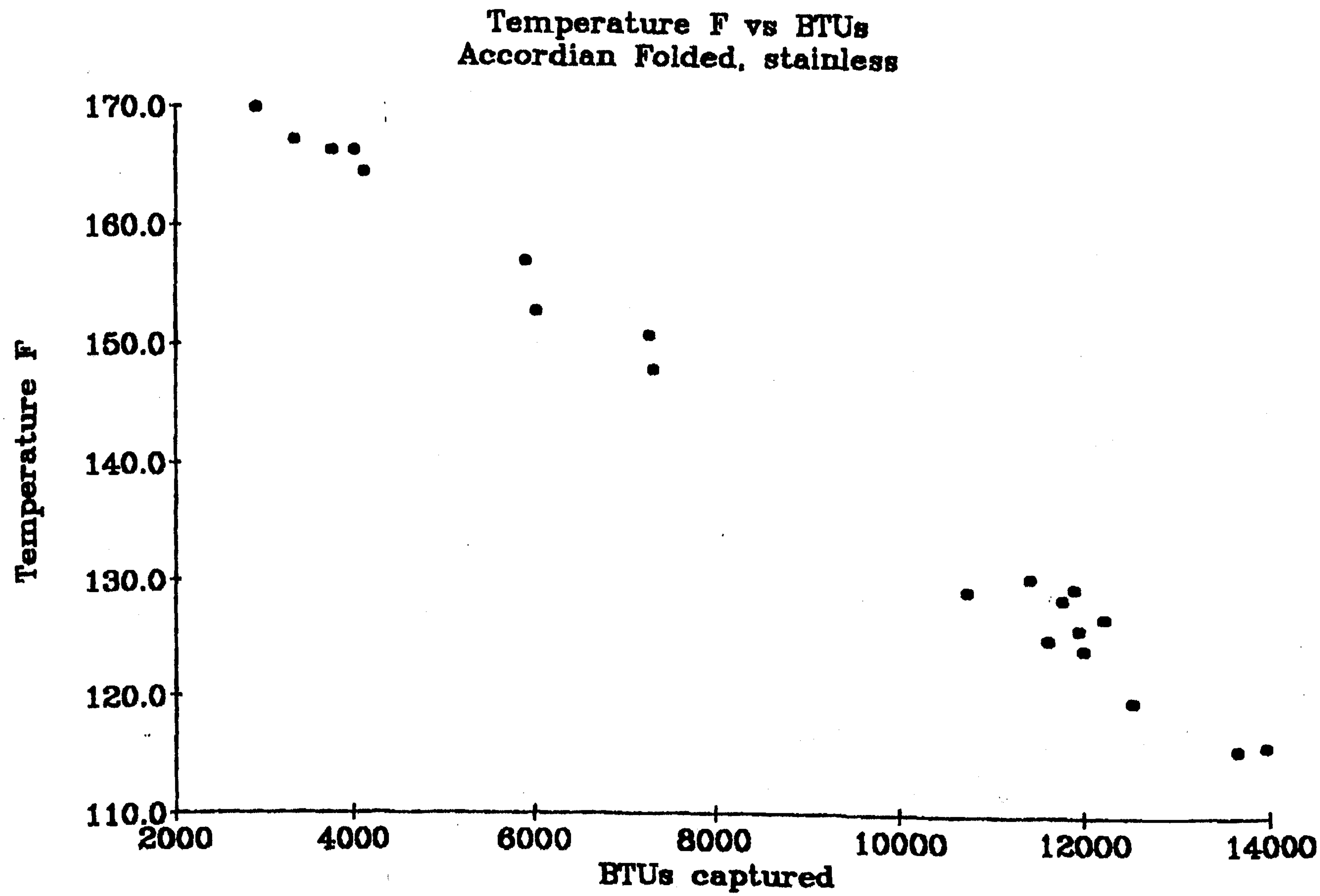



FIGURE 33. CORRELATION OF HEAT TRANSFER RATE FOR CELL 2.

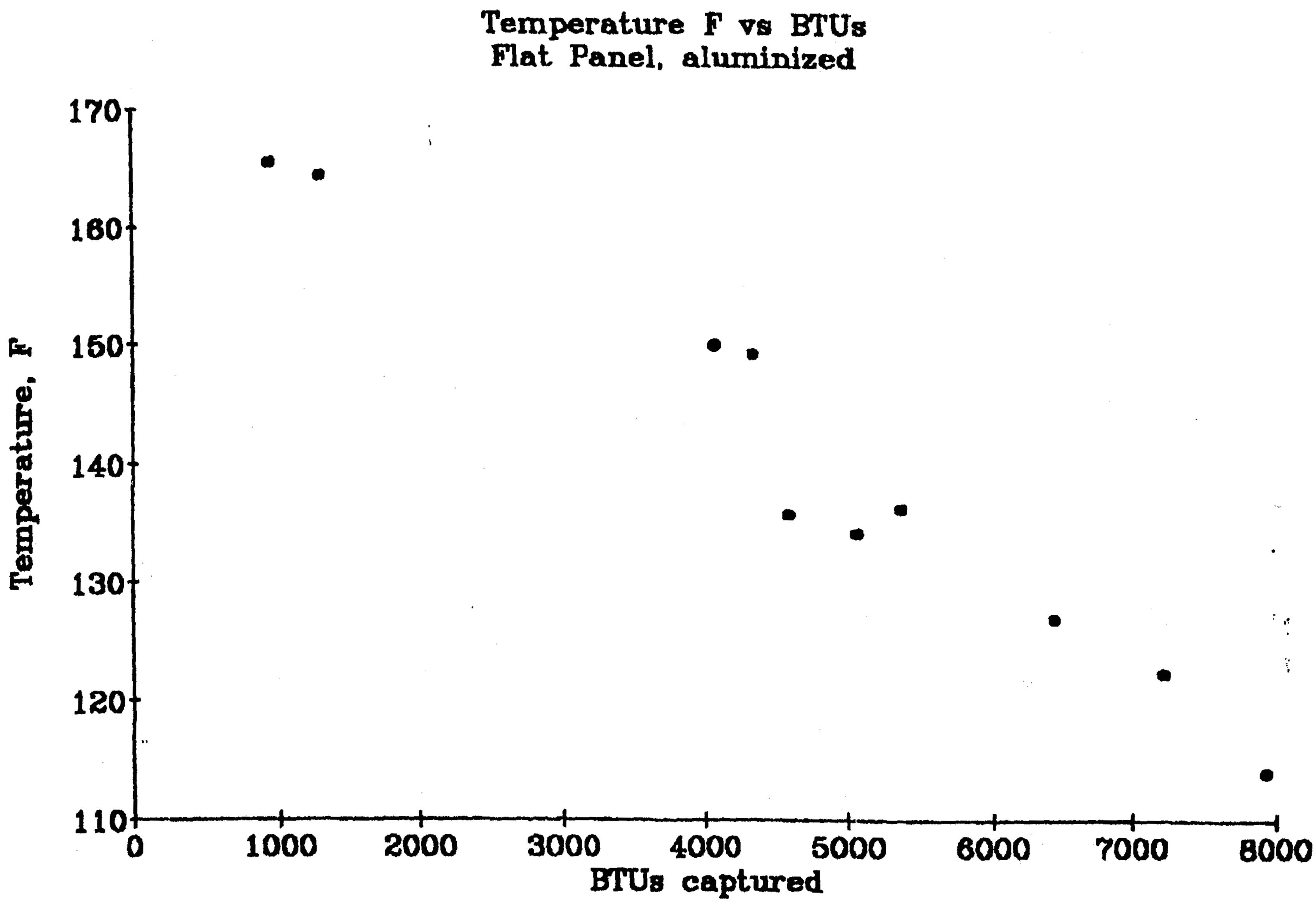



FIGURE 34. CORRELATION OF HEAT TRANSFER RATE FOR CELL 3.

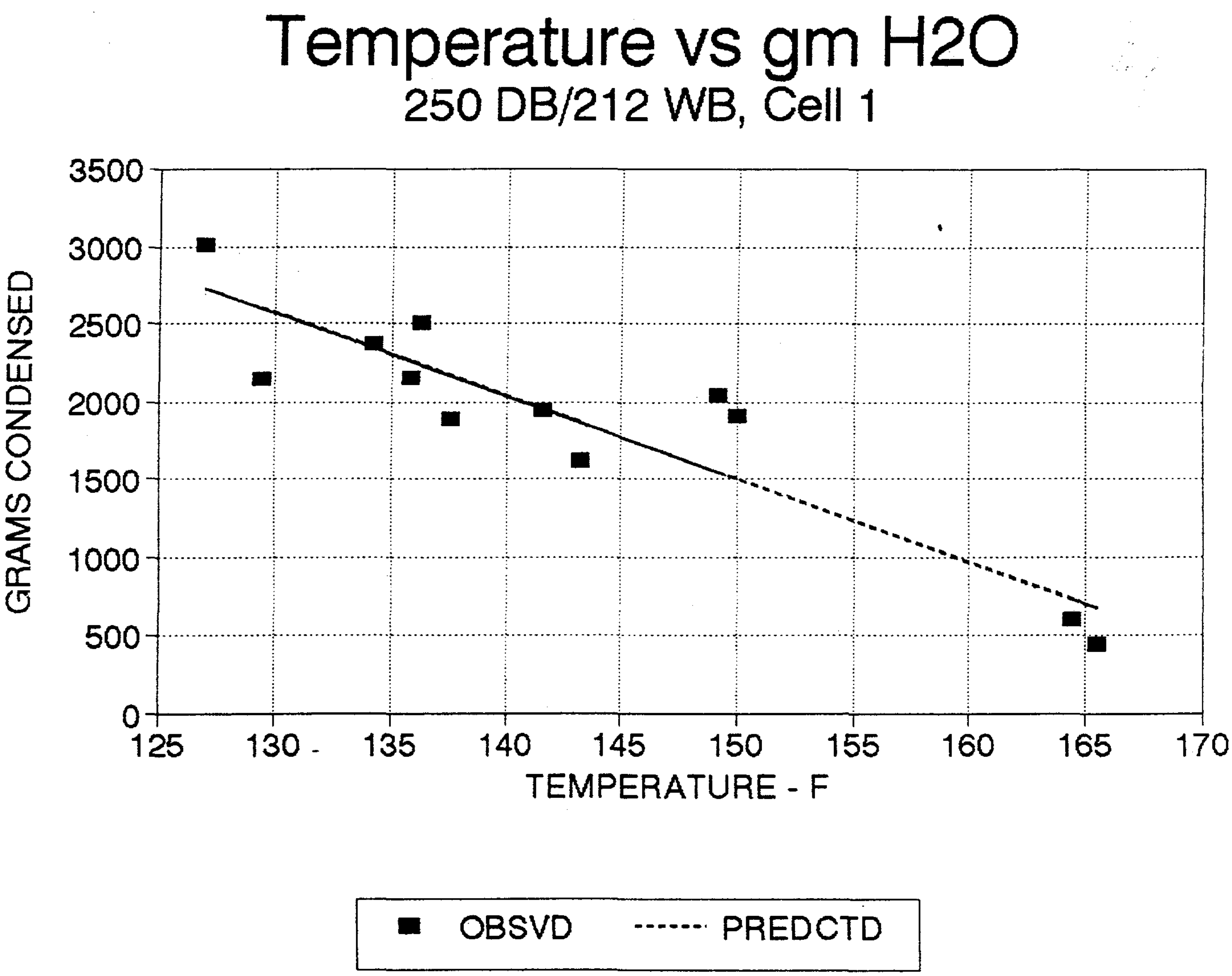



FIGURE 35. CORRELATION OF HEAT TRANSFER RATE FOR THE DEEP GROOVED STAINLESS STEEL PANEL

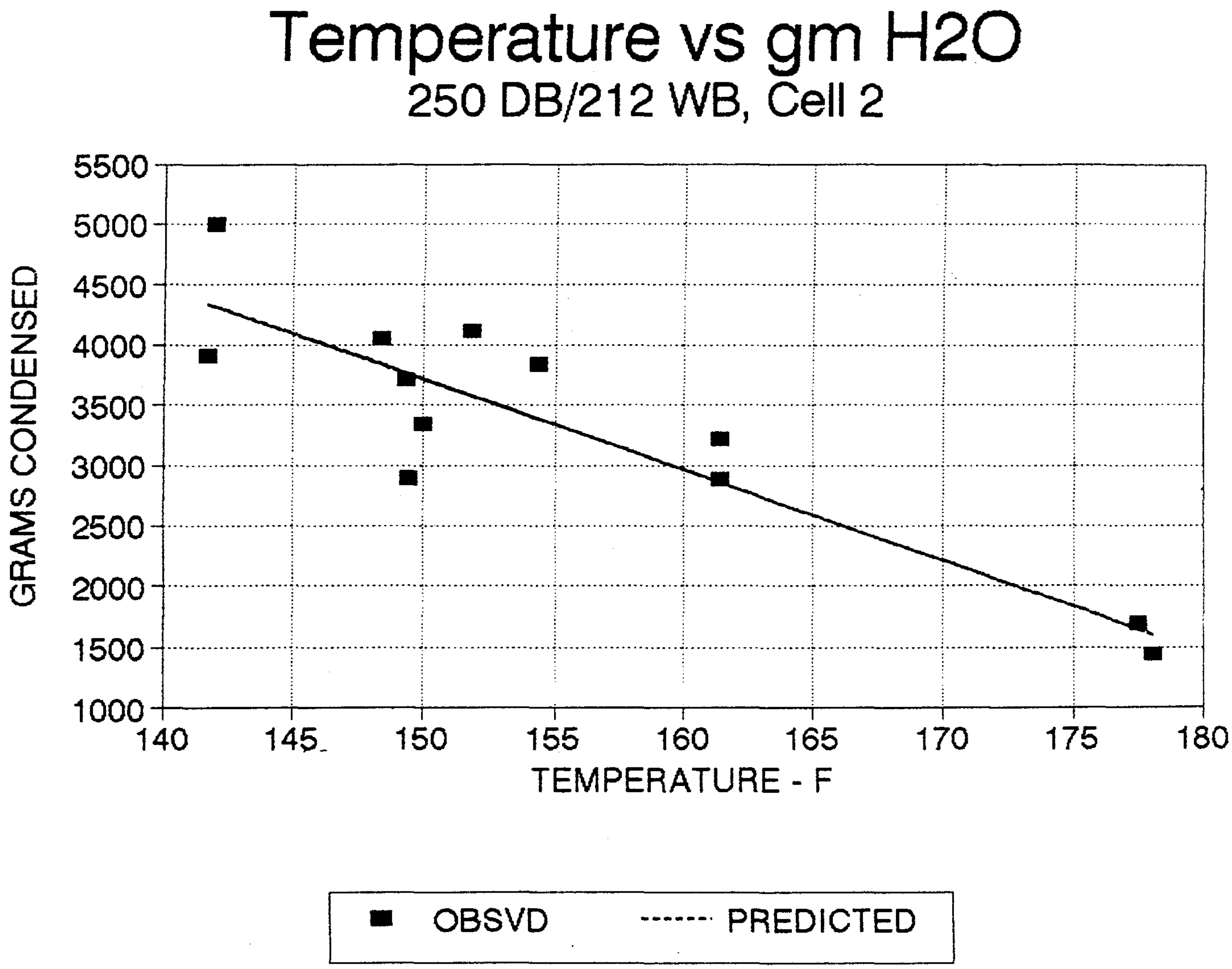



FIGURE 36. CORRELATION OF HEAT TRANSFER RATE FOR THE ACCORDION FOLDED STAINLESS STEEL PANEL

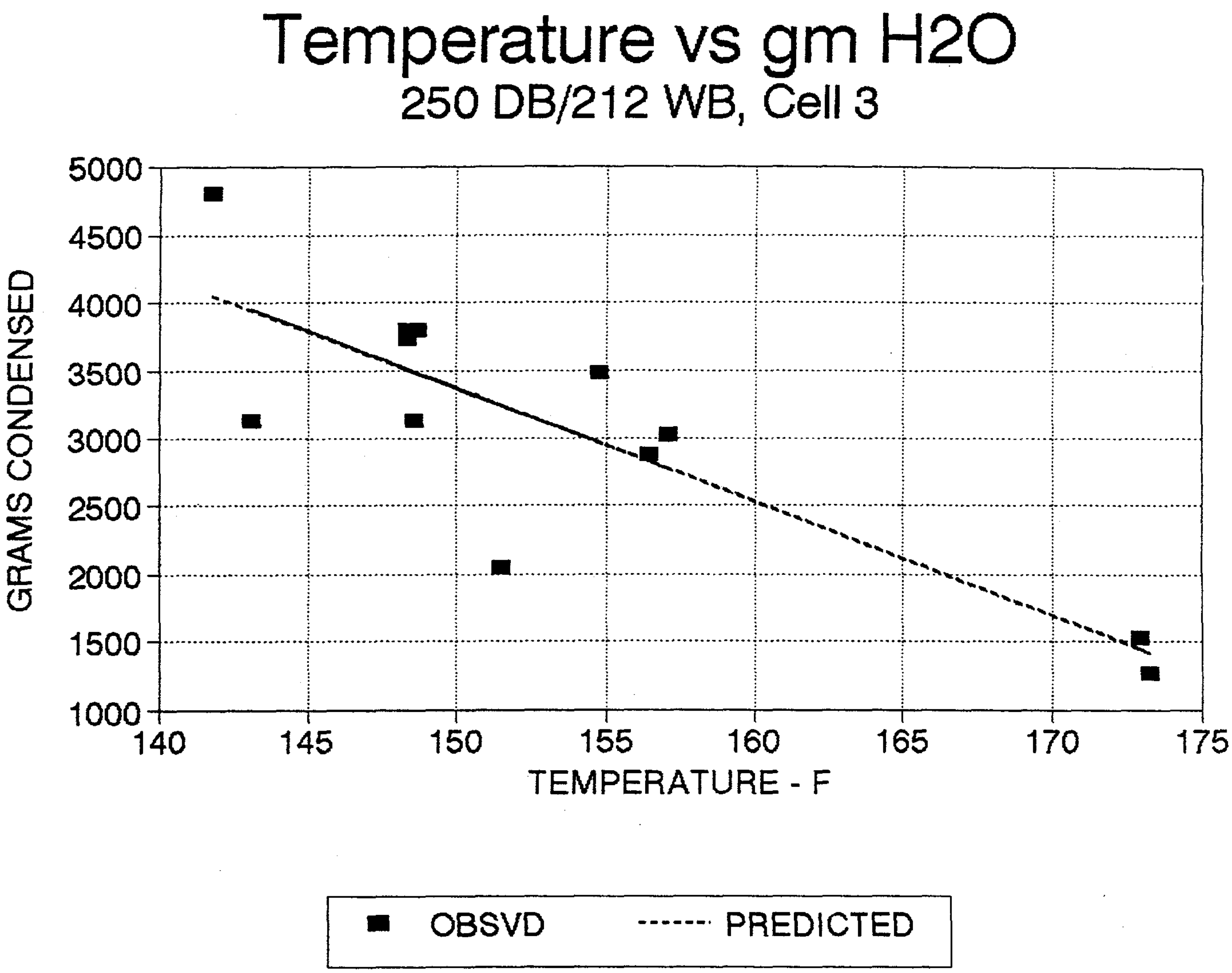
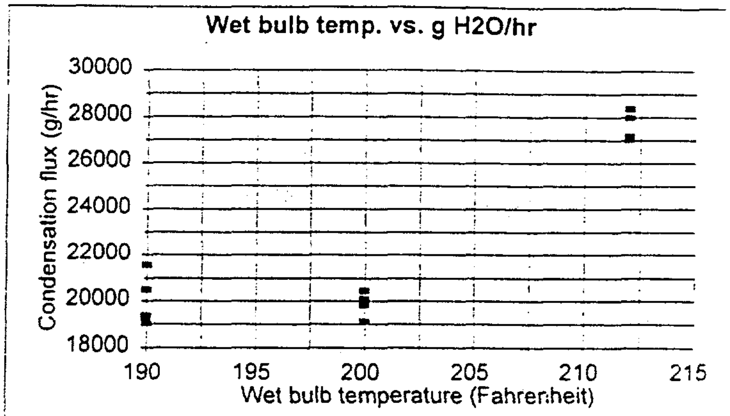



FIGURE 37. CORRELATION OF HEAT TRANSFER RATE FOR THE FLAT ALUMINIZED STEEL PANEL

Water Spray Results
May 17, 1996

Heat exchanger with deep grooved profile

| test # | db | wb | h2o initial | h2o final | h2o total | g/hour |
|---|---|---|---|---|---|---|
| 1 | 250 | 190 | 1431 | 10961 | 9530 | 19060 |
| 2 | 250 | 190 | 1351 | 11039 | 9688 | 19376 |
| 3 | 250 | 190 | 1398 | 11650 | 10252 | 20504 |
| 4 | 250 | 190 | 1507 | 12293 | 10786 | 21572 |
| 5 | 250 | 200 | 1459 | 6238 | 4779 | 19116 |
| 6 | 250 | 200 | 1437 | 6551 | 5114 | 20456 |
| 7 | 250 | 200 | 1449 | 6412 | 4963 | 19852 |
| 8 | 250 | 200 | 1533 | 6560 | 5027 | 20108 |
| 9 | 250 | 212 | 1459 | 8556 | 7097 | 28388 |
| 10 | 250 | 212 | 1409 | 8203 | 6794 | 27176 |
| 11 | 250 | 212 | 1417 | 8414 | 6997 | 27988 |
| 12 | 250 | 212 | 1432 | 8194 | 6762 | 27048 |




| test # | db | wb | Heat transfer rate BTUs/hr * sq ft |
|---|---|---|---|
| 1 | 250 | 190 | 7653.2 |
| 2 | 250 | 190 | 7780.1 |
| 3 | 250 | 190 | 8233.0 |
| 4 | 250 | 190 | 8661.9 |
| 5 | 250 | 200 | 7675.7 |
| 6 | 250 | 200 | 8213.8 |
| 7 | 250 | 200 | 7971.2 |
| 8 | 250 | 200 | 8074.0 |
| 9 | 250 | 212 | 11398.7 |
| 10 | 250 | 212 | 10912.1 |
| 11 | 250 | 212 | 11238.1 |
| 12 | 250 | 212 | 10860.7 |

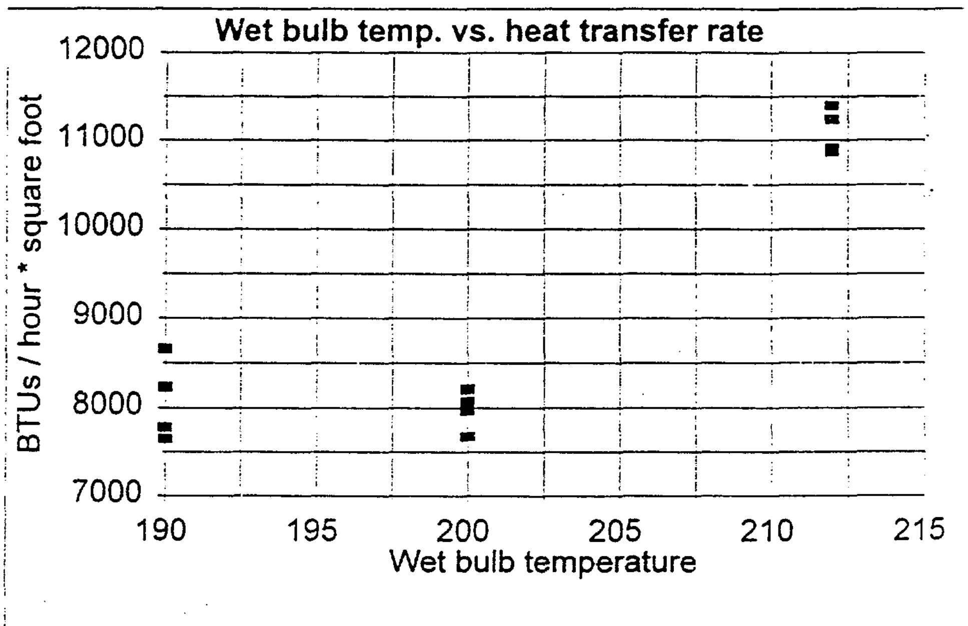
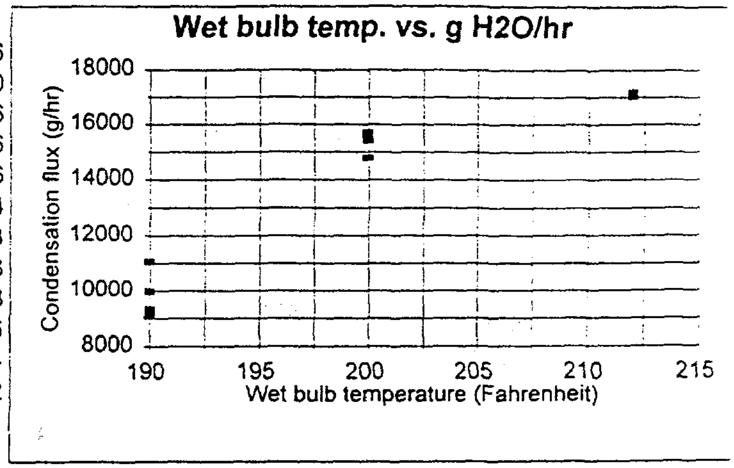



FIGURE 38. HEAT TRANSFER RATE AS A FUNCTION OF WET-BULB TEMPERATURE FOR THE HEAT EXCHANGER WITH DEEP GROOVED SQUARE PROFILE - WITH WATER-SPRAY COOLING.

Heat exchanger with accordion profile

| test # | db | wb | h2o initial | h2o final | h2o total | g/hour |
|---|---|---|---|---|---|---|
| 1 | 250 | 190 | 1340 | 6013 | 4673 | 9346 |
| 2 | 250 | 190 | 1304 | 5849 | 4545 | 9090 |
| 3 | 250 | 190 | 1317 | 6310 | 4993 | 9986 |
| 4 | 250 | 190 | 1380 | 6913 | 5533 | 11066 |
| 5 | 250 | 200 | 1332 | 5031 | 3699 | 14796 |
| 6 | 250 | 200 | 1320 | 5226 | 3906 | 15624 |
| 7 | 250 | 200 | 1325 | 5182 | 3857 | 15428 |
| 8 | 250 | 200 | 1354 | 5281 | 3927 | 15708 |
| 9 | 250 | 212 | 1344 | 5601 | 4257 | 17028 |
| 10 | 250 | 212 | 1338 | 5632 | 4294 | 17176 |
| 11 | 250 | 212 | 1383 | 5679 | 4296 | 17184 |
| 12 | 250 | 212 | 1297 | 5470 | 4173 | 16692 |




| test # | db | wb | Heat transfer rate BTUs/hr * sq ft |
|---|---|---|---|
| 1 | 250 | 190 | 4239.6 |
| 2 | 250 | 190 | 4123.4 |
| 3 | 250 | 190 | 4529.9 |
| 4 | 250 | 190 | 5019.8 |
| 5 | 250 | 200 | 6711.8 |
| 6 | 250 | 200 | 7087.4 |
| 7 | 250 | 200 | 6998.5 |
| 8 | 250 | 200 | 7125.5 |
| 9 | 250 | 212 | 7724.3 |
| 10 | 250 | 212 | 7791.4 |
| 11 | 250 | 212 | 7795.0 |
| 12 | 250 | 212 | 7571.9 |

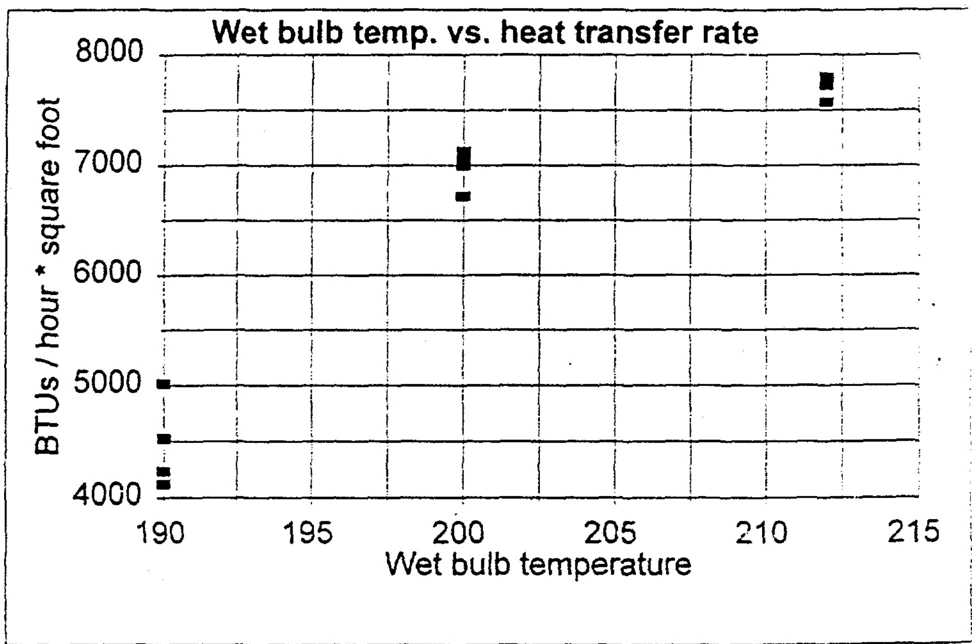
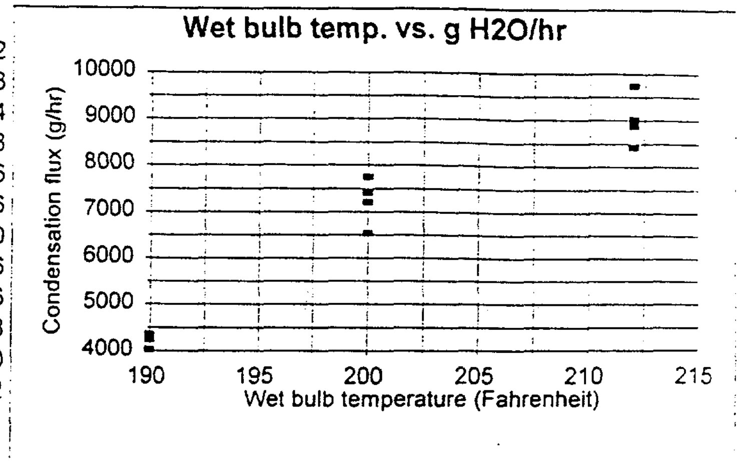



FIGURE 39. HEAT TRANSFER RATE AS A FUNCTION OF WET-BULB TEMPERATURE FOR THE HEAT EXCHANGER WITH DEEP GROOVED ACCORDION PROFILE - WITH WATER-SPRAY COOLING.

Heat exchanger with flat profile

| test # | db | wb | h2o initial | h2o final | h2o total | g/hour |
|---|---|---|---|---|---|---|
| 1 | 250 | 190 | 1405 | 3586 | 2181 | 4362 |
| 2 | 250 | 190 | 1314 | 3333 | 2019 | 4038 |
| 3 | 250 | 190 | 1317 | 3444 | 2127 | 4254 |
| 4 | 250 | 190 | 1365 | 3534 | 2169 | 4338 |
| 5 | 250 | 200 | 1377 | 3316 | 1939 | 7756 |
| 6 | 250 | 200 | 1371 | 3225 | 1854 | 7416 |
| 7 | 250 | 200 | 1337 | 2972 | 1635 | 6540 |
| 8 | 250 | 200 | 1440 | 3244 | 1804 | 7216 |
| 9 | 250 | 212 | 1351 | 3570 | 2219 | 8876 |
| 10 | 250 | 212 | 1507 | 3614 | 2107 | 8428 |
| 11 | 250 | 212 | 1338 | 3593 | 2255 | 9020 |
| 12 | 250 | 212 | 1371 | 3809 | 2438 | 9752 |




| test # | db | wb | Heat transfer rate BTUs/hr * sq ft |
|---|---|---|---|
| 1 | 250 | 190 | 1751.5 |
| 2 | 250 | 190 | 1621.4 |
| 3 | 250 | 190 | 1708.1 |
| 4 | 250 | 190 | 1741.9 |
| 5 | 250 | 200 | 3114.3 |
| 6 | 250 | 200 | 2977.8 |
| 7 | 250 | 200 | 2626.0 |
| 8 | 250 | 200 | 2897.5 |
| 9 | 250 | 212 | 3564.0 |
| 10 | 250 | 212 | 3384.1 |
| 11 | 250 | 212 | 3621.8 |
| 12 | 250 | 212 | 3915.8 |

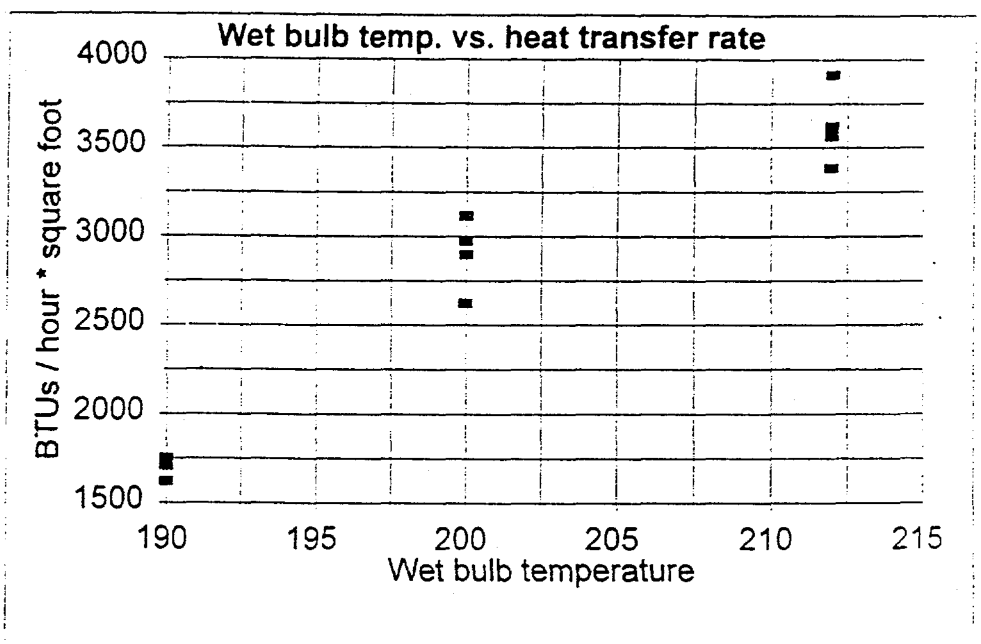
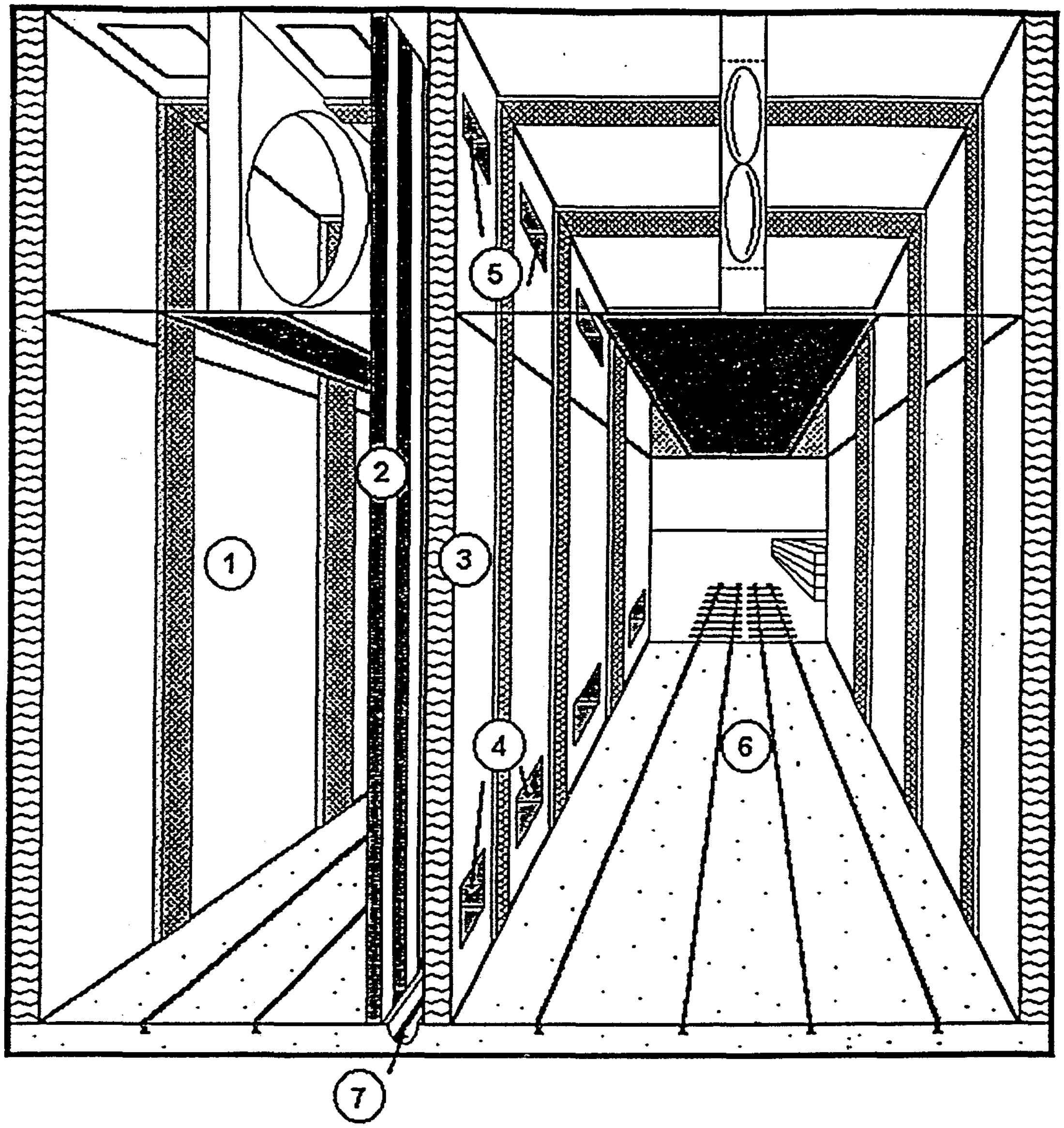



FIGURE 40. HEAT TRANSFER RATE AS A FUNCTION OF WET-BULB TEMPERATURE FOR THE HEAT EXCHANGER WITH A FLAT PROFILE - WITH WATER-SPRAY COOLING.




1. Second-Stage Drying Chamber
2. Heat Exchanger
3. Insulated Wall
4. Air / Steam Inlets
5. Air Outlets
6. Primary Kiln
7. Collection Trough

FIGURE 41. PERSPECTIVE SKETCH OF ONE TRACK SECONDARY KILN ADJACENT TO DOUBLE-TRACK PRIMARY KILN.

# APPENDIX A

COMPUTER PROGRAM IN FORTRAN
FOR
DRY KILN SIMULATION WITH VENTILATION

```
C 10 REM  THIS IS A PROGRAM TO CALCULATE THE MOISTURE CONTENT OF
C WOOD
C 20 REM  AT VARIOUS WET BULB, DRY BULB, AND GAS VELOCITY
C CONDITIONS
C 30 REM  FOR VENTED DRY KILN ENERGY PREDICTIONS
C 40 REM      FOR SIMULATION OF KILN SCHEDULE 3
C   FOR PREDICTING AVAILABLE ENERGY FOR SECOND STAGE
      PROGRAM DRYVA91
   41 REAL MCE,MCI,MOIST
      DIMENSION QRATE(150),TIEMPO(150),MOIST(150),QTOTAL(150)
      DIMENSION TTDBF(150),TTWBF(150)
      CHARACTER*12 FFILE
      INTEGER CNT,CNTP
      WRITE(*,*)'    ENTER THE FILE NAME FOR THIS CALC'
      READ(*,43) FFILE
   43 FORMAT(1X,A12)
      OPEN(6,FILE= FFILE,STATUS='UNKNOWN')
      WRITE(*,*)'    ENTER THE AMBIENT DRY BULB TEMPERATURE IN F '
      READ(*,*) TDBA
      WRITE(*,*)'    ENTER THE AMBIENT WET BULB TEMPERATURE IN F '
      READ(*,*) TWBA
   50 WRITE(*,*)' ENTER THE 2ND STAGE DRY BULB TEMPERATURE IF F '
   55 READ(*,*) TDB2
   60 WRITE(*,*)' ENTER THE 2ND STAGE WET BULB TEMPERATURE IN F '
   65 READ(*,*) TWB2
   70 WRITE(*,*)'    ENTER THE AIR VELOCITY IN FT/MIN  '
   75 READ(*,*) VEL
   80 WRITE(*,*)' ENTER THE INITIAL MOISTURE CONTENT IN PER CENT '
   82 READ(*,*) MCI
   85 WRITE(*,*)'ENTER THE MOISTURE CONTENT FOR ENDING THE CALCS '
   87 READ(*,*) MCE
      WRITE(*,*)'    ENTER THE FRACTION TIMES MOISTURE EVAPORATED'
      READ(*,*) FMIN
   90 WRITE(*,*)'    ENTER THE THICKNESS OF THE WOOD IN INCHES '
   95 READ(*,*) THK
  100 WRITE(*,*)' ENTER THE DENSITY OF THE DRY WOOD IN LBM/FT3 '
  105 READ(*,*) RHO
  110 WRITE(*,*)'    ENTER THE BOARD FEET OF WOOD IN THE KILN '
  112 READ(*,*) BFT
      WRITE(*,*)'    ENTER THE LENGTH OF THE KILN IN FEET'
      READ(*,*) FLNK
      WRITE(*,*)'ENTER THE HEIGHT OF THE KILN SIDEWALLS IN FEET'
      READ(*,*) FLHW
      WRITE(*,*)'    ENTER THE HEIGHT OF THE KILN CENTER IN FEET'
      READ(*,*) FLHC
      WRITE(*,*)'    ENTER THE WIDTH OF THE KILN IN FEET'
```

```
      READ(*,*) FLWD
      ARF = 2*(((FLWD/2)**2+(FLHC-FLHW)**2)**0.5)*FLNK
      AKLN = 2*(FLNK*FLHW)+ (FLHW+FLHC)*FLWD+ARF
      FPER = 2*(FLWD+FLNK)
  115 WRITE(*,*)'   ENTER THE CALCULATION TIME INTERVAL IN HOURS '
  117 READ(*,*) DT
  120 WRITE(*,*)'    ENTER THE PRINT INTERVAL IN NO. TIME STEPS '
  125 READ(*,*) CNTP
      WRITE(6,*)' TDB = ',TDB,'   TWB = ',TWB,'   MCI = ',MCI
      WRITE(6,*)' BFT = ',BFT,'   THK = ',THK,'   RHO = ',RHO
      WRITE(6,*)'  T,  FMC,  QVENT,   QVT,   QR,   QAVL, QAVLT, QT,
     +TDB,  TWB'

      J=0
C   130 REM
  140 STCOEFF = 150.4
  145 STRATE = 7156.5
C   150 REM
C  160 REM CALCULATE THE MOISTURE FLUX FOR THE CONSTANT RATE DRYING
C   170 REM
C   180 REM CALCULATE THE St FOR THE DRYING RATE APPROACHINE EMC
C   190 REM
C   200 REM CALCULATE THE TIME REQUIRED FOR DRYING
C   210 REM
C   220 REM THIS NOW CALCULATES THE EQUILIBRIUM MOISTURE CONTENT OF
C   WOOD
C   230 REM AS A FUNCTION OF WET BULB, DRY BULB TEMPERATURES
C   240 REM
       TDBAC = (TDBA - 32) * 5 / 9 + 273.19
       TDBAR = TDBA + 460
       TWBAC = (TWBA - 32) * 5 / 9 + 273.19
       TWBAR = TWBA + 460
       TC = 647.27
       PC = 218.167
       A = 3.2437814
       B = 5.86826E-03
       C = .0000000111702379
       D = 2.187462E-03
       X = (TC - TDBAC)
       PDA = 10**(.4343*LOG(PC)-(X/TDBAC)*(A+B*X+C*X**3)/(1+D*X))
       X = (TC - TWBC)
       PWA = 10**(.4343*LOG(PC)-(X/TWBAC)*(A+B*X+C*X**3)/(1+D*X))
       FPVA = PWA - (TDBA - TWBA) / 2700

       HA = FPVA / PDA
       GAMA = 0.622*FPVA/(1-FPVA)


       FMC = MCI
       CNT = 0
       PRT = 0
       FM = 0
```

```
      T = 0
      I = 1
      QTOTAL = 0
      QRATE =.0
      TIEMPO = 0
      MOIST = MCI
      QT = 0
      ABF = BFT * 2 / (THK )
      FMC = MCI
      THK = THK / 12
      QATT = 0.0
      QVT = 0.0
      TWB1 = TWBA
      QAVLT = 0
 250  IF(T.LE.4.0) TDB = 75 + 175*SIN(.3927*T)

      IF(T.GT.4.0) TDB = 250
      IF(T.LE.4.5) TWB = 70 + 110*SIN(.34906*T)

      IF (T.GT.4.5)  TWB = 180
      TDBC = (TDB - 32) * 5 / 9 + 273.19
 255  TDBR = TDB + 460
 260  TWBC = (TWB - 32) * 5 / 9 + 273.19
 270  TWBR = TWB + 460

 300  TC = 647.27
 301  PC = 218.167
 310  A = 3.2437814
 311  B = 5.86826E-03
 312  C = .0000000111702379
 320  D = 2.187462E-03
 330  X = (TC - TDBC)
 340  PD = 10**(.4343*LOG(PC)-(X/TDBC)*(A+B*X+C*X**3)/(1+D*X))
 350  X = (TC - TWBC)
 360  PW = 10**(.4343*LOG(PC)-(X/TWBC)*(A+B*X+C*X**3)/(1+D*X))
 365  FPV = PW - (TDB - TWB) / 2700

 366  H = FPV / PD
      GAM = 0.622*FPV/(1-FPV)

 370  FK1 = 3.73 + .03642 * TDB - .0001547 * TDB**2.
 380  FK2 = .674 + .001053 * TDB - 1.714E-06 * TDB**2
 390  W = 216.9 + .01961 * TDB + .00572 * TDB**2
 400 EMC = ((FK1*FK2*H)/(1+(FK1*FK2*H))+(FK2*H/(1-FK2*H)))*1800/W

 420  RH = H * 100

C   430 REM THIS IS THE END OF THE MOISTURE CALCULATIONS
C   440 REM
 445  FV = 1
 450  IF (VEL.LT.1329)  FV = (VEL / 1329)**0.3
 460  IF (VEL.GT.1329)  FV = (VEL / 1329)**0.5
```

```
470  FCR=(.01208+.006797* (TDB-TWB)-2.482E-05*(TDB - TWB)**2)*FV
480  ST = STCOEFF * EXP(-STRATE / TDBR)
485  FN = 5.
490  IF ((TDB - TWB).LT.46.) FN = .75 + (.093 * (TDB - TWB))

530  IF (FMC.LT.MCE) GO TO 690

540  QRH = 5000 * (TDB - 40)
545  FM = ((ST * (FMC - EMC))**(-FN) + FCR**(-FN))**(-1.0/FN)


     FM = FMIN*FM



560   FMC = FMC - 200 / (THK * RHO) * FM * DT


        FFM = FM*ABF
        FFMDDAIN = FFM/(GAM-GAMA)
        IF (TWB.GE.212) FFMDDAIN = 0
       QVENT = FFMDDAIN*(0.24*(TDB-TDBA)+GAMA*(0.44*(TDB-TDBA)))
        IF (TWB.GT.212) QVENT = 0
       QVT = QVT + QVENT*DT


570    QR = (FM * (1062 + (.45 * (TDB - 212))) * ABF )

       IF(TDB.LE.212) QR=FM*1062*ABF
       QMFS = FM * ABF
       QWLOS = AKLN*(TDB-TDBA)/10
       QPERLS = FPER*(TDB-TDBA)/5
       QLOSS = (QWLOS+QPERLS)*1.2
       QHT = (BFT/12)*31.2*(FMC)/100*(TWB-TWB1)
       IF(TWB.LE.TWB1) QHT = 0.0
       QHT = QHT + (BFT/12)*31.2*(TWB-TWB1)*0.5

       TWB1 = TWB
580    QT = QT + QR * DT + QVENT * DT +QLOSS*DT + QHT

C NOW MAKE A PREDICTION OF ENERGY AVAILABLE FOR SECOND STAGE


     TDB2C = (TDB2 - 32) * 5 / 9 + 273.19
     TDB2R = TDB2 + 460
     TWB2C = (TWB2 - 32) * 5 / 9 + 273.19
     TWB2R = TWB2 + 460

     TC = 647.27
     PC = 218.167
     A = 3.2437814
```

```
      B = 5.86826E-03
      C = .0000000111702379
      D = 2.187462E-03
      X = (TC - TDB2C)
      PD = 10**(.4343*LOG(PC)-(X/TDB2C)*(A+B*X+C*X**3)/(1+D*X))
      X = (TC - TWB2C)
      PW = 10**(.4343*LOG(PC)-(X/TWB2C)*(A+B*X+C*X**3)/(1+D*X))
      FPV = PW - (TDB2 - TWB2) / 2700

      H = FPV / PD
      GAM2 = 0.622*FPV/(1-FPV)
      QSREC2 = FFMDDAIN*(0.24*(TDB - TDB2)+GAM*(0.44*(TDB-TDB2)))

      IF (FFMDDAIN.EQ.0) QSREC2 = (0.44*(TDB-TDB2)*QMFS)
      QLREC2 = (QMFS - FFMDDAIN*(GAM2))*1062

      QAVL = QSREC2 + QLREC2
      IF (QAVL.LE.0) QAVL = 0
      QAVLT = QAVLT + QAVL*DT
         T = T + DT
600      IF (T.EQ.DT) WRITE(6,665)
   +T,MCI,QVENT,QVT,QR,QT,QAVL,QAVLT,TDB,TWB

620      CNT = CNT + 1


635      IF(CNT.EQ.CNTP) THEN
         CNT = 0

655      I = I + 1
         TIEMPO(I) = T
         MOIST(I) = FMC
660      QRATE(I) = QR
         QTOTAL(I) = QT
         TTDBF(I) = TDB
         TTWBF(I) = TWB

      WRITE(6,665)T,FMC,QVENT,QVT,QR,QT,QAVL,QAVLT,TDB,TWB


       ENDIF
680 GOTO 250
690  WRITE(*,*)'  QR,QT,T,FMC', QR, QT,QAVL, QAVLT, T, FMC
     WRITE(6,665)T,FMC,QVENT,QVT,QR,QT,QAVL,QAVLT,TDB,TWB

665 FORMAT(1X,2F7.1,6(2X,E9.4),1X,2F7.1)
     ENDFILE 6
     REWIND 6
     CLOSE (6)

720  END
```