ENERGY QUANTIFICATION IN KILN DRYING

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Introduction

Energy use in the kiln drying of lumber is one of the "hot" items of the current era. This is understandable since according to Comstock (2) approximately 60 to 70 percent of the total energy required from "woods to warehouse" in the production of lumber is used in the drying.

A number of publications are available on energy use and drying. Some of these offer "common sense" suggestions on steps to employ in order to conserve energy in the kiln, ranging from the use of preliminary air drying to the addition of more insulation to kiln walls and roofs. Other publications illustrate methods for estimating the required energy for drying a charge of lumber by utilizing the known thermal properties of air, wood, water and the materials of which the kiln is constructed.

These publications are all worthwhile and can make a valuable contribution to many individual situations. A few of them are hereby cited for easy reference (3, 4, 5, 6, 7, 8, 10, 11).

The literature does not, however, contain much information on the direct quantification of energy use in lumber drying. Cech and Pfaff (1) compared total energy consumption for dehumidification and steam-heated kiln drying of spruce studs but their article is without references. Comstock's paper (2) discusses energy requirements for the drying of wood products and it contributes much valuable information, but there is no data given that is based upon the direct determination of energy use in lumber drying.

Taylor (9) determined steam energy consumption in two high temperature and two conventional temperature commercial kilns in the drying of southern pine lumber. He did not find a distinct energy advantage for either type of kiln in drying southern pine. The highest energy requirement, approximately 1900 Btu/lb. of water removed, was for the smallest kiln, a 25,000 bd. ft. H. T. kiln. Taylor explained this on the basis of the large surface area of the kiln in relation to holding capacity and the resulting large conductive losses through the walls and roof, plus the fact that this kiln apparently operated with constant venting during the drying schedule. Total drying time for the conventional kilns was in the range of 3 to 4 days while for the H. T. kilns it was 24 to 30 hours.

As Taylor points out, southern pine kilns dry without the use of steam spray. This is true for all softwood kilns in a general sense and consequently it is a somewhat "different ballgame" than the drying of refractory hardwoods with kiln residence times running into weeks and even months.

In view of the lack of data on direct quantification of energy in kiln drying, especially for hardwood lumber, it was deemed desirable to embark upon such a research program. This was done in recognition of the inequalities of an experimental laboratory kiln and industrial kilns. Rosen (5) has addressed the implications of kiln size on such correlations. In spite of this, we felt that much of value might be learned and that possibly new and profitable insights could be gained with regard to saving energy in commercial lumber drying processes.

Objectives

1. To develop a reliable experimental apparatus and procedure for the continuous quantification of energy consumption in the experimental kiln drying of lumber.
2. To dry a hardwood lumber species according to the recommended FPL schedule and relate the energy consumed to various levels of wood moisture content and segments of the kiln schedule.

Experimental Materials and Procedures

Experimental Kiln and Associated Equipment

A steam heated, 500 bd. ft. Moore Oregon experimental dry kiln has been specially instrumented for this research. The kiln is equipped with two reversing 36" fans and vapor filled capillary tubes and temperature sensors for sensing both the dry bulb and wet bulb temperatures. The remaining details of the experimental equipment are perhaps best described through reference to Figure 1.

As shown in Figure 1, a pressure reducer is used to drop the saturated 100 psi steam to the desired pressure. In the drying of hardwoods the pressure we normally use is 30 psi. The steam next encounters a temperature transmitter and then flows through a circular orifice that is installed in a split flange in the steam line. The steam flow through the orifice is measured by a flow transmitter. The signal from the temperature transmitter plus the signal from the flow transmitter are sent to an integrator and multiplier. The net result is that a given amount of steam flow translates into an electrical signal that drives an event counter. The events are then calibrated in terms of Btu/event by the use of a water barrel calorimeter.

There are separate steam supply tanks for the heating coils and the humidification. Since the kiln is quite tight with little loss of water vapor around the door, etc., it is possible to maintain the desired humidity conditions in the kiln for a good share of the run without the use of the steam spray. Under this operating condition, the measure of condensate from the heating coils serves as the primary method of quantifying the steam consumed for a given period of drying. When it becomes necessary to use the steam spray during equalizing and conditioning, total steam consumption then has to be determined from the event counter.

Eventually we hope to instrument the vents and wall surfaces in such a manner that we can accurately quantify the energy losses through these avenues. At the present time, however, we can only correlate total energy consumption to the various stages of the drying process without being able to quantify individually the losses due to venting, conduction through the walls, etc. By making assumptions as to the R value of various kiln components and then measuring surface temperatures, one can estimate the conductive losses. However, it obviously would be better to use a guarded hot box to make such an evaluation and that is our projection for the future. We also project installation of the necessary equipment for measuring the temperature, relative humidity and velocity of the vented air. We presently do not have these capabilities to the degree of sophistication and accuracy deemed desirable.

Lumber

We employed 4/4 American elm lumber in the several runs, about 500 bd. ft. in each run. The use of American elm was somewhat incidental to the proliferation of Dutch elm disease and the research being conducted on various aspects of utilizing the lumber from disease killed trees. We found it to be a hardwood species that dries fairly rapidly and uniformly by comparison to our experience with many others. It is, however, a species that tends to warp excessively in drying.

It is our intent to continue our energy quantification research in the future with oak species being used for the experimental lumber. Oak is a refractory, slow drying hardwood with high energy requirements. Oak species also constitute one-half to two-thirds of the hardwood lumber kiln dried in the nation.

Experimental Procedures

Upon bringing the fresh sawn lumber to the laboratory, it was immediately end trimmed to 8'. In this process we obtained moisture content sections from about one-half the total number of boards. This made it possible to obtain an accurate estimate of the average initial MC of the entire charge. The lumber was block piled in the coldroom during the short-term storage period prior to construction of the kiln charge.

During construction of the charge the green weight of all boards was obtained. This total green weight, in combination with the aforementioned estimate of green MC, made it possible to estimate the ovendry weight of the charge.

The lumber was stacked in a 4' wide charge, using 3/4" by 1.5" sticks placed on 2' centers. Six end coated sample boards were employed. They were placed in pockets built into the center of the charge and were accessible through the front end of the charge. There were sample boards at 3 levels; two 42" long boards per level. During the kiln run the fans were shut down, the main door was opened, the samples were quickly removed for weighing and the door was again closed. The removal and reinstallation of the kiln samples had an insignificant effect upon kiln conditions. In addition to monitoring the charge MC through use of sample boards, we also employed a strain gauge load cell. The load cell is placed under the front axle of the kiln car so that in effect about one-half of the charge is being weighed. Knowing the tare weight of the kiln car, stickers, etc., plus having knowledge of load distribution on the kiln car, an estimate of the current total lumber weight is obtainable from the digital readout for the load cell.

A technique we found useful in the handling of the sample boards was to clamp them in restraining devices. Each restraining device consisted of two iron straps with bolt holes in each end. A strap was placed on each face of the sample board near the end of the board. Bolts were then put through the holes and the nuts securely tightened to put contact pressure between the straps and the board faces. As the sample boards dried, the restraining devices prevented cup from occurring. This insured our ability to remove and replace the sample boards in the charge at all stages of drying. When the sample board was weighed, the tare weight of the two restraining devices was simply subtracted.

The sample boards were weighed with sufficient frequency to allow the drying to proceed in close correspondence with the recommended schedule. The recommended FPL schedule T6, D4 is given in Table 1.

As described above, estimated weight loss for the lumber was determined from load cell readings and/or sample board weighings. Correspondence of the estimated MC change by load cell and sample boards was fairly good. The comparison is shown in Table 2. Near the end of the run the sample boards were possibly more reliable for determining the relatively small changes in MC. Imperfect replacement of sample boards after their removal for weighing tends to have an effect on the load cell reading and the estimate of weight change.

We did experience a problem due to an apparent "moisture leak" for the load cell at high vapor pressure conditions for the kiln air. This resulted in a shorting of the electrical contacts and consequently erratic readings. We worked on a solution to this problem through the use of a silicon type of sealer and as a result the performance was adequate in runs 2 and 3.

During the part of the kiln run in which w.b.t. could be maintained from the moisture evaporated from the wood, the total steam consumption could be obtained from the condensate meter. When the steam spray humidification was operating, however, this was no longer possible and it was then necessary to rely solely upon the event counter for total steam consumption. In any case, we were always able to correlate the steam consumption to the pounds of water removed from the charge, or to specific features of the drying process such as the equalizing or conditioning treatments.

Results and Discussion

Preliminary Comments

Before examining the research results, it is appropriate to discuss some of the energy values pertinent to the removal of water from wood.

The heat of vaporization for water varies as a function of temperature (9). To vaporize one pound of water at 212°F requires 970 Btu (12). At 50°F the latent heat of vaporization for water is given as about 1070 Btu/lb. (10). Consequently, in a lumber-drying situation one should actually integrate over the ranges of drying temperature and MC involved. However, to avoid this busy work it is probably adequate to assume an average value for heat of vaporization of water over the range of temperature employed in the kiln run. About 1000 Btu/lb. should be sufficiently good. An average amount of 1135 Btu for each pound of water removed from the wood below the fiber saturation point (f.s.p.) is the accepted value. The figure 1135 Btu includes the energy required to overcome the molecular bonding of water molecules to the wood. Consequently the total energy of drying includes the heat of vaporization, 1000 Btu/lb. of water, plus the energy required to overcome molecular forces of attraction between wood and water molecules. In drying lumber to an average MC of say 10%, it seems reasonable to assume a minimum value of about 1100 Btu for each pound of bound water removed from the wood. Energy in excess of this is then assumed to result from the inherent inefficiencies in the process. Specific items are the heating and venting of excess fresh air and conductive losses through the kiln surfaces.

Background Information on the Kiln Runs

We dried three charges of elm lumber. Run No. 1 proved to be a "shakedown" run in which we encountered and then corrected certain problems that expressed themselves. One of these was calibration of the recorder and controller. We discovered that instead of drying at the initial settings of d.b.t. 120°F and w.b.t. 113°F, we were actually drying at only a 3°F depression with a d.b.t. of 120°F. We immediately calibrated the instrument so that there was correspondence between the setting and the actual wet bulb temperature.

The inadvertent high humidity condition in the kiln correspondingly caused a problem with the load cell as previously mentioned. Consequently, in preparation for Run No. 2 we dried the load cell by placing it in a bench oven and then used silicon seal at appropriate locations on the cell.

Analysis of the Data

A summary of the data collected in the second and third runs is given in Tables 3 and 4 respectively.

Figures 2 and 3 illustrate the level of Btu's required as a function of average MC of the charge. The curves have a familiar and expected shape. Above 30% MC the curve is quite flat with a use of about 2900 Btu/lb. of water removed (rough average for both runs). At about the f.s.p. the use begins to increase at an increasing rate, and at 10% average MC the amount is near 8,000 Btu's/lb. of water removed. In Run No. 3 the lumber was dried to a lower average MC of about 6% at which the use of energy was 13,500 Btu's/lb. of water removed. These are values that are strictly applicable to this experimental kiln plus the specific kiln schedule and the lumber being dried, but they do dramatically illustrate the added "energy expense" at low moisture contents.

During the removal of free water the energy use is about 2900 Btu's/lb. of water removed. This is 1900 Btu's more per pound of water removed than the 1000 Btu's needed for water vaporization. This is due to the conductive losses through the walls, roof and floor plus the loss of sensible heat due to the intermittent venting required for maintaining the w.b.t. setting, and any air leakage that occurred past the closed vent and around the door.

Figures 4 and 5 express the data in another manner. Here it is possible to relate the slope of the drying rate curve to the steam consumption. During drying to about the f.s.p., there is a decreasing rate of Btu use per hour. During this period of drying, the steam spray was not used. Consequently the decreasing Btu consumption resulted from a slight decrease in the rate of water removal per hour, but possibly even more so from a decrease in the amount of venting. Early in the runs there was a high rate of steam use because of the "constant rate" drying period, which can be likened to the evaporation of water from a free surface, plus the heat load required for bringing everything up to temperature. As the drying rate decreased, the amount of venting needed to expel humid air also decreased, causing a reduction in the loss of heated air.

In both runs at about 35 hours of drying time the kiln conditions became a 15°F wet bulb depression (w.b.d.) with a 120°F d.b.t. The reduced relative humidity caused an upward inflection in the Btu/hour curve. This was no doubt due to the effect of increased venting losses upon steam consumption. In each run the highest use of Btu's/hour occurred with a d.b.t. of 180°F and a w.b.d. of 50°F. Again, this results from the almost continuous venting that was required to maintain the 50°F w.b.d.

It is appropriate to make some additional comments about Figure 5. During the drying time interval of about 55 to 85 hours there is a "scatter" of the coordinates for the Btu/hour curve. We have concluded that this is not just random experimental variation. For both sets of kiln conditions, i.e. 150°F d.b.t. with a 50°F w.b.d. and a 180°F d.b.t. with a 50°F w.b.d., the highest plot of energy use is nearest the start of each particular set of temperatures. We concluded that this is due in large part to the need for more frequent venting at the beginning of the drying step. As the amount of drying time in the step increased, the need for venting decreased and thus reduced steam consumption along with the reduced rate of drying.

In both runs the highest use of Btu's per hour occurred during equalizing at 180°F d.b.t. with a 152°F w.b.t. and conditioning at 180°F d.b.t. with a w.b.t. of 170°F (Table 5). This was due to the necessity of steam spray for maintaining the 6% equilibrium moisture content (e.m.c.) during equalizing and the 11% e.m.c. during conditioning. (It also resulted in part from the fact that the spray and venting functions were "fighting" each other to some extent. The vent would start to open just before the spray was completely off. In other words, they are set too close together. It has illustrated to us another factor in kiln drying that can conceivably have a significant effect on energy consumption.)

One more way of presenting some of the data is illustrated in Figures 6 and 7, which show Btu's/lb. of water removed as a function of drying time. It is quite apparent that the final stage of drying requires a high expenditure of energy per pound of water. It certainly seems appropriate to seek methods to reduce this energy consumption through modified kiln schedules, heat exchangers or whatever.

Conclusions

The drying of 4/4 American elm lumber from the green condition in a steam heated experimental kiln required a comparatively high expenditure of energy. The total use of energy for the kiln runs, including the equalizing and conditioning treatments, amounted to about 8500 Btu's per pound of water removed. The removal of the free water required about 3000 Btu's per pound. The energy required for the removal of bound water increased as the bound water moisture content decreased. This was due in large part to the increased venting losses plus additional conductive losses through the kiln walls and the roof.

The equalizing and conditioning treatments utilized about one-half the total energy used in the kiln runs. Since these are essential treatments for the quality drying of hardwood lumber, additional research should be conducted on means to accomplish them with a lower expenditure of energy.

The drying of oak lumber requires a kiln residence time much greater than that for elm. The implications for energy use in relationship to the various steps of the kiln schedule are therefore evident.

Literature Citations

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TABLE 1: THE RECOMMENDED FPL SCHEDULE T6, D4 FOR 4/4 AMERICAN ELM LUMBER.

MC AT START OF STEP (%)	DRY BULB TEMPERATURE (D.B.T.)(°F)	WET BULB TEMPERATURE (W.B.T.)(°F)
ABOVE 50	120	113
50 TO 40	120	110
40 TO 35	120	105
35 TO 30	120	95
30 TO 25	130	90
25 TO 20	140	90
20 TO 15	150	100
15 TO FINAL	180	130

EQUALIZING TREATMENT: THE RECOMMENDATIONS GIVEN IN THE KILN OPERATOR'S MANUAL, U.S.D.A. AGRI. HANDBOOK NO. 188, WERE FOLLOWED. CONSEQUENTLY, WE USED 180°F D.B.T. AND 152°F W.B.T. FOR AN EQUILIBRIUM MOISTURE CONTENT OF 6%.

CONDITIONING TREATMENT: AGAIN THE AGRI. HANDBOOK RECOMMENDATIONS WERE FOLLOWED AND WE USED A D.B.T. OF 180°F AND A W.B.T. OF 170°F.

TABLE 2: COMPARISON OF ESTIMATED MC CHANGES OF THE LUMBER CHARGES AS DETERMINED BY THE LOAD CELL AND THE USE OF SIX SAMPLE BOARDS.

RUN NO. 2

	ESTIMATED MOISTURE CONTENT (%)	
DRYING TIME (HOURS)	LOAD CELL	SAMPLE BOARDS
21.9	51.5	46.3
46.0	26.7	25.8
56.3	18.2	18.9
67.2	10.1	11.9
74.1	6.0	8.4
94.3	2.9	5.5

RUN NO. 3

22.0	44.9	42.4
29.2	40.1	38.3
35.0	35.4	32.8
43.3	29.1	25.2
53.5	21.2	19.5
59.3	16.4	13.8
66.5	13.1	13.2
74.0	8.8	8.2

Table 3: Summary of the Data Collected in Kiln Run No. 2

Drying Interval in Hours	Hours	Kiln Setting	Average M.C. for Interval %	Δ M.C.%	Pounds of Water	BTUs Used	BTUs per Lb. of Water	BTUs per Hour
1.25 - 3.75 (2.5)[1]	2.50	120°-DB 113°-WB	78.4 - 75.1 (76.8)[2]	3.3	35.6	122,014	3,427	48,806
3.75 - 9.25 (6.5)	5.50	120°-DB 113°-WB	75.1 - 66.3 (70.7)	8.8	96.5	259,645	2,691	47,208
9.25 - 23.42 (16.3)	14.17	120°-DB 113°-WB	66.3 - 50.7 (58.5)	15.6	169.4	503,672	2,973	35,555
23.42 - 32.33 (27.9)	8.90	120°-DB 110°-WB	50.7 - 39.3 (45.0)	11.3	123.6	323,092	2,614	36,302
32.33 - 43.83 (38.1)	11.50	120°-DB 105°-WB	39.3 - 28.1 (33.7)	11.2	122.0	371,898	3,048	32,339
43.83 - 46.53 (45.2)	2.70	120°-DB 105°-WB	28.1 - 26.1 (27.1)	2.0	22.0	78,089	3,549	28,922
46.53 - 57.00 (51.8)	10.47	130°-DB 90°-WB	26.1 - 17.7 (21.9)	8.4	91.5	405,085	4,427	38,701
57.00 - 68.25 (62.6)	11.25	150°-DB 100°-WB	17.7 - 9.6 (13.6)	8.1	88	580,785	6,600	51,625
68.25 - 74.33 (71.3)	6.08	180°-DB 130°-WB	9.6 - 8.4 (9.0)	3.5	44	349,447	7,942	57,446
74.33 - 94.33 (84.3)	20.00	180°-DB 152°-WB	8.4 - 5.5 (7.0)	2.9	28.8	1,855,742	64,435	92,787

[1] The midpoint of the interval was used for plotting data shown in Figure 4.

[2] The average MC interval was used for plotting data shown in Figure 2.

Table 4: Summary of the Data Collected in Kiln Run No. 3.

Drying Interval in Hours	Hours	Kiln Setting	Average M.C. for Interval %	Δ M.C.%	Pounds of Water	BTUs Used	BTUs per Lb. of Water	BTUs per Hour
0.00 - 2.00 (1.0)[1]	2.00	120°-DB 113°-WB	69.8 - 68.1 (69.0)[2]	1.8	20.8	148,369	7,133	74,184
2.00 - 4.00 (3.0)	2.00	120°-DB 113°-WB	68.1 - 65.8 (67.0)	2.3	27.1	73,208	2,701	36,604
4.00 - 10.25 (7.1)	6.25	120°-DB 113°-WB	65.8 - 55.7 (60.8)	10.1	116.7	293,809	2,518	41,236
10.25 - 22.00 (16.1)	11.75	120°-DB 113°-WB	55.7 - 44.9 (50.3)	10.8	125	350,423	2,803	29,823
22.00 - 24.00 (23.0)	2.00	120°-DB 113°-WB	44.9 - 43.5 (44.2)	1.4	16.7	49,782	2,981	24,891
24.00 - 28.00 (26.0)	4.00	120°-DB 113°-WB	43.5 - 41.0 (42.2)	2.5	29.2	100,539	3,443	25,135
28.00 - 29.50 (28.8)	1.50	120°-DB 113°-WB	41.0 - 39.9 (40.4)	1.1	12.5	45,877	3,670	30,585
29.50 - 35.25 (32.4)	5.75	120°-DB 110°-WB	39.9 - 35.4 (37.7)	4.5	52.13	162,034	3,108	28,180
35.25 - 43.50 (39.3)	8.25	120°-DB 105°-WB	35.4 - 29.3 (32.4)	6.1	70.8	260,621	3,681	31,590
43.50 - 53.83 (48.7)	10.33	130°-DB 90°-WB	29.3 - 20.9 (25.1)	8.4	97.95	388,492	3,966	37,597
53.83 - 59.25 (56.5)	5.42	150°-DB 100°-WB	20.9 - 16.4 (18.7)	4.5	52.1	294,785	5,658	54,418
59.25 - 66.50 (62.9)	7.25	180°-DB 130°-WB	16.4 - 13.1 (14.8)	3.3	37.5	282,096	7,523	38,909
66.50 - 75.92 (71.2)	9.42	180°-DB 130°-WB	13.1 - 8.4 (10.8)	4.7	68.7	478,293	6,962	50,790
75.92 - 90.50 (83.2)	14.58	180°-DB 130°-WB	8.4 - 4.4 (6.4)	4.0	46	624,710	13,580	42,838

[1] The midpoint of the interval was used for plotting data shown in Figure 5.

[2] The average MC interval was used for plotting data shown in Figure 3.

TABLE 5: SUMMARY OF THE DATA FOR THE EQUALIZING AND CONDITIONING TREATMENTS OF RUNS 2 AND 3.

RUN 2

TREATMENT	TEMPERATURES	DURATION	WATER REMOVED	TOTAL BTU'S	BTU'S FOR HEAT	BTU'S FOR SPRAY	BTU'S/HOUR	TOTAL BTU'S USED IN RUN	% OF TOTAL USED FOR EQUALIZING TREATMENT
EQUALIZING	D.B.T. 180°F W.B.T. 152°F	41.5 HRS.	36 LBS.	3,698,000	1,850,000	1,848,000	89,000	7,796,000	47.4%
CONDITIONING	D.B.T. 180°F W.B.T. 152°F	10.0 HRS.	(NEGLIGIBLE)	985,000	317,500	667,000	98,500	7,796,000	12.6%

RUN 3

TREATMENT	TEMPERATURES	DURATION	WATER REMOVED	TOTAL BTU'S	BTU'S FOR HEAT	BTU'S FOR SPRAY	BTU'S/HOUR	TOTAL BTU'S USED IN RUN	% OF TOTAL USED FOR EQUALIZING TREATMENT
EQUALIZING	D.B.T. 180°F W.B.T. 152°F	16 HRS.	(NEGLIGIBLE)	2,028,500	960,500	1,068,000	126,750	6,557,000	30.9%
CONDITIONING	D.B.T. 180°F W.B.T. 152°F	10.1 HRS.	(NEGLIGIBLE)	976,000	320,000	656,000	96,650	6,557,000	14.9%

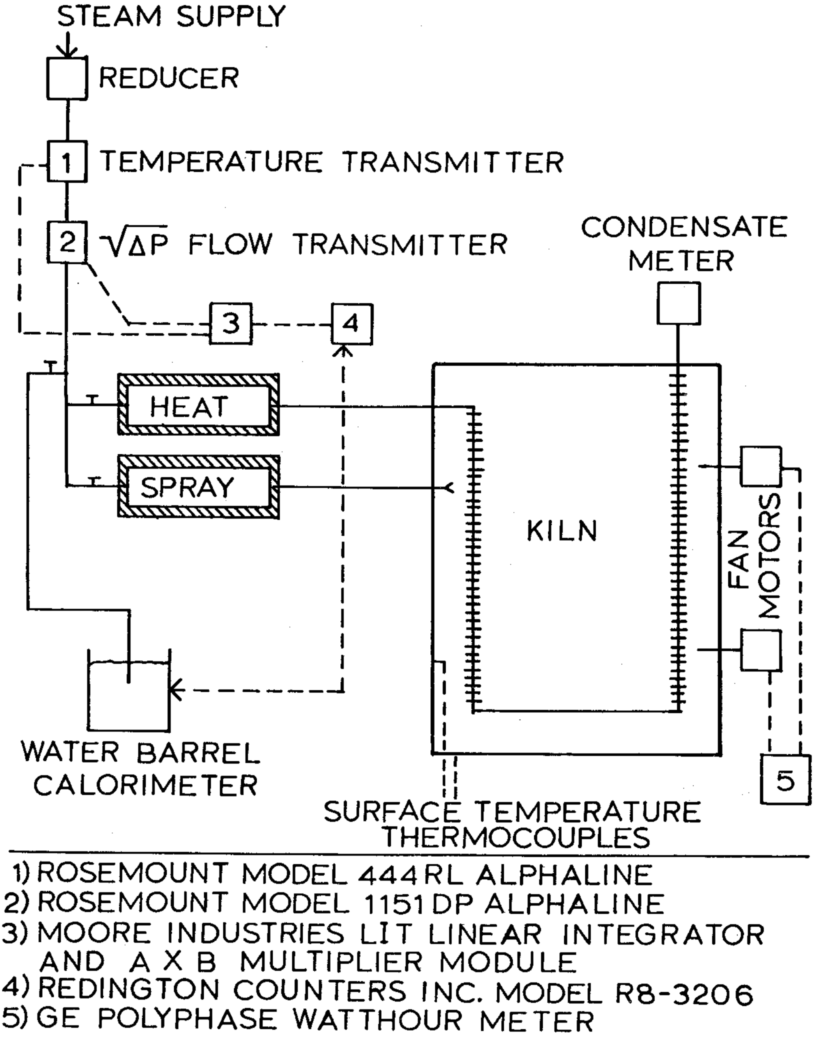

Figure 1. Schematic diagram of the kiln and energy quantification equipment.

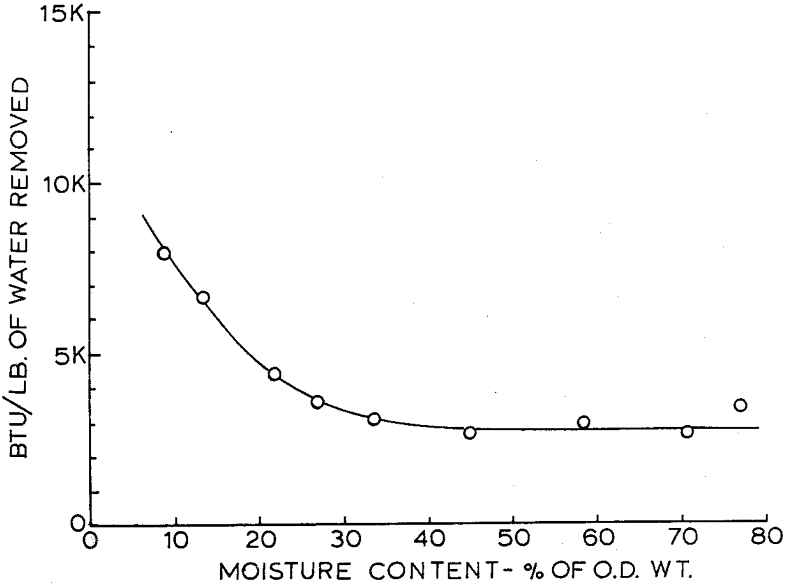

Figure 2. Btu's employed per lb. of water removed as a function of average MC for Run No. 2.

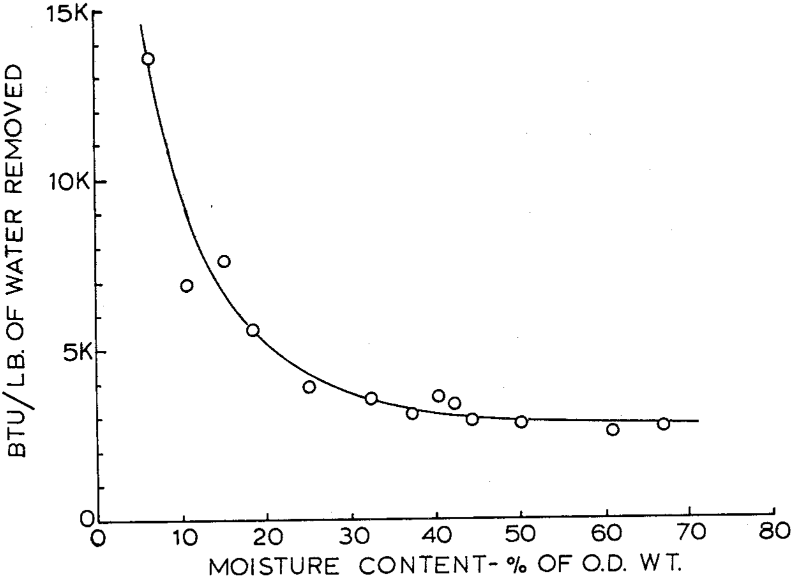

Figure 3. Btu's employed per lb. of water removed as a function of average MC for Run No. 3.

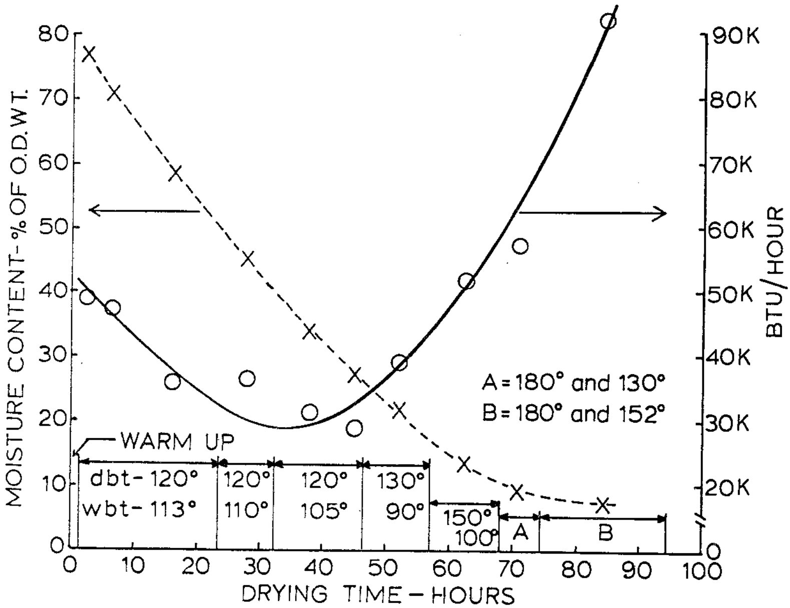

Figure 4. Average MC and Btu's of steam energy consumed as a function of drying time in hours for Run No. 2.

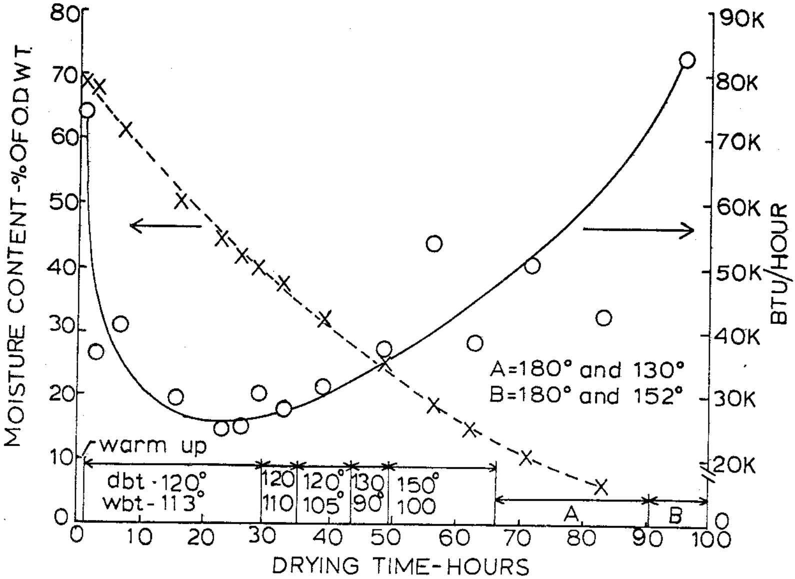

Figure 5. Average MC and Btu's of steam energy consumed as a function of drying time in hours for Run No. 3.

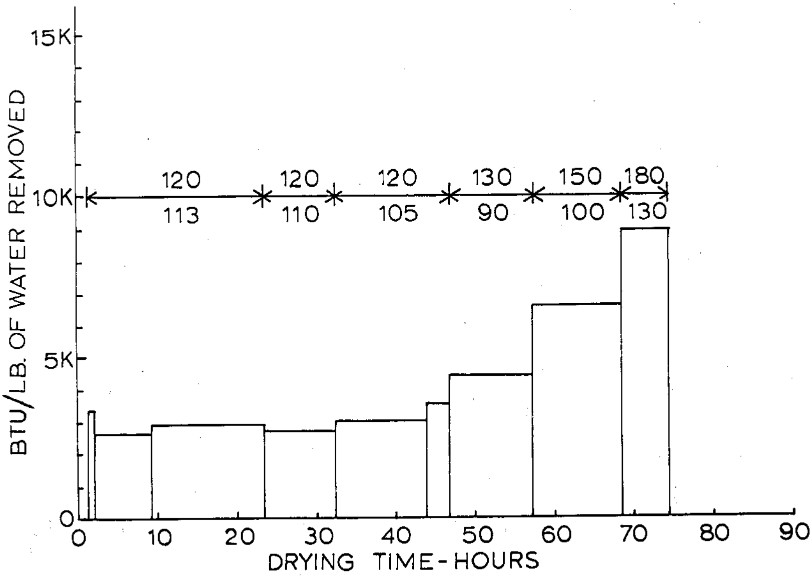

Figure 6. Btu's/lb. of water removed as a function of drying time and kiln conditions.

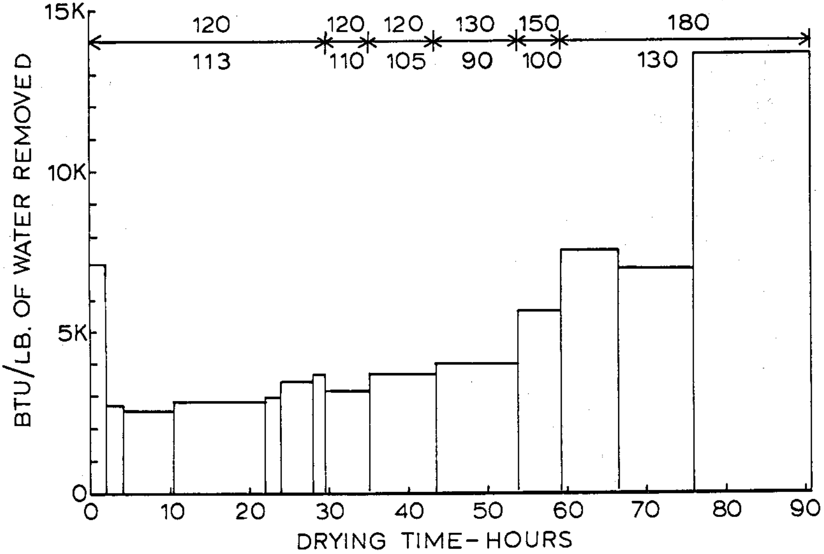

Figure 7. Btu's/lb. of water removed as a function of drying time and kiln conditions.