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Fan Cycling and Energy Consumption in Bulk Tobacco Curing

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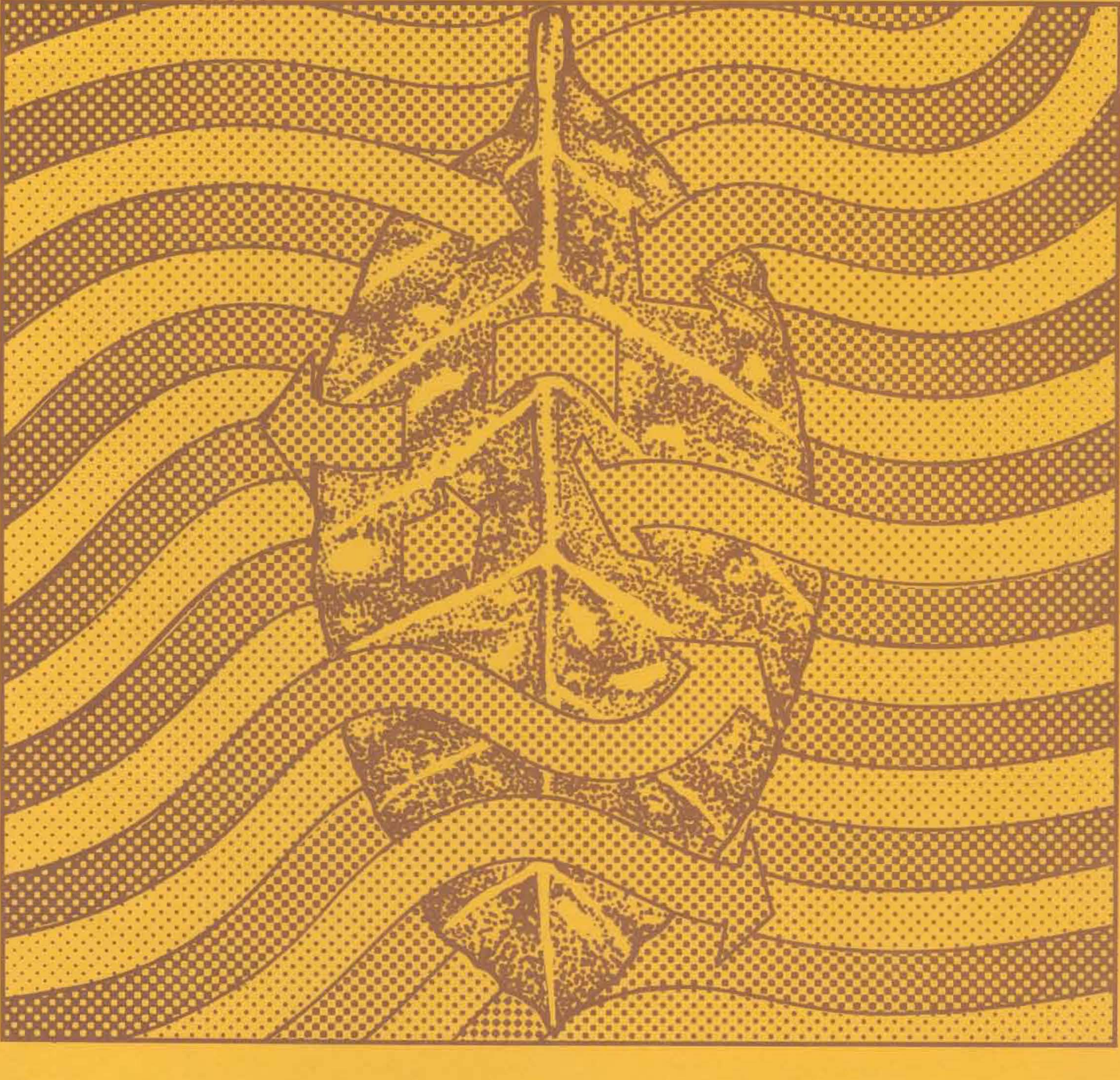

Acknowledgment

This work was supported in part by Georgia Power Company, Oglethorpe EMC, Powell Manufacturing Company and the Georgia Commodity Commission for Tobacco. This support, both financial and technical, is gratefully acknowledged. A special appreciation goes to Mr. C. L. Talley for the use of his barns and entire tobacco crop for this study. His excellent management and unswerving support insured the success of the entire project.

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Introduction

There is a continuing need to improve the efficiency and thus reduce the cost of tobacco curing. Rising energy costs have stimulated new interest in technology to reduce the consumption of petroleum fuels and electric power for the curing process. The "demand problem" which bulk curing creates for the electric power supplier is an immediate problem which is becoming more critical each year. The harvest season for Georgia bright leaf tobacco occurs during an eleven week period, June 15- September 1, which coincides with the yearly peak demand for electric power.

Georgia has an estimated 9000 bulk tobacco barns with 5 or 7.5 hp fan motors. (These represent a total capacity sufficient to cure 75% of the state's tobacco production). Using a 75% motor efficiency, and assuming that half have 5 hp fan motors and half have 7 hp fan motors, then the total demand, if all are operating simultaneously, is 56000 kw.

Most bulk barns are serviced by Electric Membership Cooperatives (EMCs) which have a primarily "rural" road. Some EMC's cannot, under the present rate structure, recover the demand charges they incur because of their bulk curing load. Electric power rates have been increased, and can be expected to continue to rise in the future. The tobacco grower, in response to these rate increases, is joining with the EMC's to seek ways to manage energy demand for bulk curing.

In Georgia the peak demand is most likely to occur between 1200-1700 hrs. on week days. It is appropriate to consider intermittent fan operation to reduce demand during this period.

Conservation of petroleum fuel used for tobacco curing is absolutely essential, consequently the influence of fan cycling on petroleum fuel consumption must be determined. If fan cycling causes a decrease in drying rate and thus an increase in curing time, this may result in increased structural heat losses and thus increase fuel consumption. On the other hand, the drying rate may be limited by the moisture release mechanisms of the leaf, and not by the drying potential of the circulated air. In this case fan cycling could actually have little effect on curing time. Any increase in curing time would reduce the seasonal capacity of the barn and increase the the grower's per acre investment in curing facilities.

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Review of Literature

Dodd and Cundiff (1977) found that 10-15% of the total energy input for containerized curing is electrical energy with the remainder being petroleum fuel energy. They developed a model to predict heat energy for the change in enthalpy in the exchanged air, E_x, the structural heat losses, E_s, and the energy to elevate and maintain the temperature of the tobacco material, E_m. Less than 1% of the energy was required for E_m, thus it can be neglected from practical consideration. The E_x component represented 60-70% of the petroleum fuel energy consumed, and the remaining 30-40% was E_s.

Structural Heat Loss

The Dodd-Cundiff model showed that 50-60% of the heat energy required for the coloring phase (cure hours when temperature, $T < 45^oC$) is a structural heat loss, and that this requirement is 30-40% of the heat energy for the stem drying phase (cure hours when $T > 60^oC$). During the leaf drying phase (cure hours when $45^oC < T < 60^oC$) the E_s component was 20-30% of the total heat energy for the phase. Comparable figures for bulk rack curing were not found in the literature.

Fan Cycling

Watkins (1975) used an ON 5 min. OFF 5 min. cycle in an uninsulated barn, and found that the ON interval was too short for the furnace to maintain the barn temperature at thermostat settings above 49^{o}C. This led to uneven heat distribution in the barn and curing problems resulted. In subsequent research Watkins (1976) used an ON 20 min. OFF 10 min. fan cycle on barns at 15 farm locations dispersed throughout the flue-cured production area of North Carolina. The barns were cycled during the six hour period, 1500-2100, daily. He found no difference in tobacco quality (subjective evaluation) or curing time for leaf cured with intermittent ventilation and those receiving continuous ventilation.

Cundiff (1977) cured tobacco in one-tenth scale chambers with an ON 15 min. OFF 45 min. fan cycle for seven hours daily. Chemical analysis showed no difference in this tobacco and that cured with continuous fan operation. He found the curing time was slightly extended, and a 4% increase in petroleum fuel consumption. He concluded that this small difference was not significant due to possible differences in combustion efficiency of the furnace units.

Objectives

1. Conduct an on-farm test of the ON 20 min OFF 25 min fan cycle for five hours (1200-1700) each day of the cure.
2. Determine petroleum fuel and electrical energy consumption in the cycled barn for comparison with the consumption in insulated and uninsulated barns with continuous fan operation.
3. Operate the barns empty for seven days using the same thermostat settings used for a "typical cure", and estimate the structural heat losses from the measured fuel consumption.
4. Evaluate cure acceptability with a chemical analysis of cured leaf samples from each cure.

Experimental Methods

An agreement was made with a tobacco grower to conduct an on-farm test using four mobile style curing barns located on his farm. The grower retained full management control. He loaded the barns in response to the harvest requirements of his tobacco, and used his own judgement in selecting the curing schedule for each cure.

Barns 1, 2 and 3 were Powell Model 88-648 barns, and had no factory installed insulation. The walls, doors and ceiling of Barns 1 and 2 were insulated for the test, and Barn 3 was left as an uninsulated check. Barn 4 was a Powell MaxiMiser 126, a new experimental model with factory installed insulation. It was possible to insulate under the concrete slab for this barn as it was installed just prior to the start of the 1977 season. The thermal resistance of all the curing compartment surfaces is given in Table 1 for each of the four barns.

Each barn was operated with continuous fan operation for cure 1. During cure 2 Barn 1 was operated with an ON 15 min OFF 45 min fan cycle during the 5 hour period, 1200-1700, each day of the cure. For cures 3-7 an ON 20 min. Off 25 min. cycle was used. The fans operated continuously in Barns 2, 3 and 4 during all cures.

The barns had equal capacity, 126 bulk racks. Tobacco was hand harvested and placed in bulk racks in an aligned leaf configuration.

Each barn was instrumented to record temperature in the lower plenum, T_ℓ, and in the upper plenum, T_u. A seven day circle chart recorder (Minneapolis-Honeywell Regulator, Brown Instrument Division) was mounted in a cabinet on the exterior wall. The lower plenum probe was positioned at the centerline of the lower plenum under the right room (as viewed from the furnace compartment) approximately 3 m from the fan. The upper plenum probe was positioned directly above the lower probe at a point one-half the distance between the top of the tobacco and the ceiling.

Petroleum fuel consumption was measured with a LP gas meter (REGO Model AL425-TC) installed in the supply line to each barn. The meters were calibrated for 395 kPa (11 in. WC) gas pressure and the barn pressure regulators were adjusted to obtain this pressure at the beginning of the season. The burner in each barn was adjusted by the manufacturer's representative to achieve maximum combustion efficiency measured with a combustion testing kit (FYRITE CO_2 Indicator Model CND). Fuel recordings were made at 0800 and 2000 hrs. daily.

The electric power supplier installed and serviced demand metering instrumentation on all four barns. This equipment automatically recorded the maximum demand in each 15 min. interval on magnetic tape.

The cycled barn was first wired with a time switch (Dayton Model 2E 213) to interrupt the coil voltage to the fan motor starter. This was changed after Cure 2 and rewired as shown in Figure 1. Here the time switch interrupts the coil voltage of a DPDT relay. One pole of this relay opens the burner solenoid and the other activates a "Delay on De-Energization" (solid state timer, General Time Series #2110) relay which delays interruption of the motor starter coil voltage for 5 min. This control circuit gave a burner cycle, ON 15 min. OFF 30 min. and a fan cycle, ON 20 min. OFF 25 min.

Each time a barn was filled, three samples of 10 leaves each were collected, one at 1000, one at 1300, and one at 1600 hrs. This was done to insure a representative sampling of all tobacco in the cure. These samples were sealed in individual plastic bags, and placed in an insulated container. The samples were weighed and placed in containers for oven drying. Samples were dried for 48 hrs at 74^{o}C and reweighed to the nearest 0.01 gm using a top loading electronic balance (Mettler P/200).

When a barn was unloaded three samples of 10 leaves each were again taken. Sample 1 was selected from a rack on the bottom tier in the middle of the barn. Sample 2 was selected from a rack on the middle tier and sample 3 was taken from the top tier. These samples were sealed in plastic bags and returned to the laboratory for weighing. They were destemed, redried at 74^{o}C for 48 hours, and reweighed. The lamina portion was then ground to pass a 40 mesh screen and placed in sealed sample bags for later chemical analysis. Total nitrogen, alkaloids, starch and sugar percentages were determined using standard laboratory procedures (Gaines, 1971).

The reordered tobacco from each barn was weighed with a spring scale as the barn was unloaded. The total moisture removed, W, was then determined using the following relation,

$$W = \frac{W_c}{0.95} \frac{\overline{w}_{co}}{\overline{w}_c} \left(\frac{\overline{w}_g}{\overline{w}_{go}} - 1\right), \qquad (1)$$

where

W_c = total mass cured leaf
$\overline{w}_c$ = average mass cured samples
$\overline{w}_{co}$ = average mass oven dry cured samples
$\overline{w}_g$ = average mass green samples
$\overline{w}_{go}$ = average mass oven dry green samples

The derivation of equation (1) includes the assumption of a 5% solids loss (Johnson, 1976) during the cure.

Analytical Methods

An experimental rate function for heat losses, dE_{se}/dt (empty), was determined by operating each barn empty for seven days using the same thermostat settings used for a "typical cure". The vents were tightly closed to minimize leakage. Fuel usage was recorded every 12 hours, at 0800 and 2000 hrs. just as in the curing tests. The reading for each 12 hour interval was corrected for combustion efficiency and these points were connected with straight lines to define the dE_{se}/dt (empty) rate curve.

This rate curve was divided into a leaf coloring part, a leaf drying part and a stem drying part based on the temperature measured in the lower plenum. The leaf coloring phase is defined as curing time when $T < 45^oC$, and stem drying is defined as curing time when $T < 60^oC$. The intermediate phase, or leaf drying phase is defined as curing time when $45^oC < T < 60^oC$. The leaf coloring, leaf drying and stem drying hours were determined from the lower plenum temperature recordings for each cure. The three parts of the dE_{se}/dt (empty) curve were extended or shortened to obtain a computed dE_{se}/dt curve for each cure with the correct number of hours in each of the cure phases.

The rate function for energy to achieve the enthalpy change in the exchanged air, dE_x/dt, was estimated from

$$\frac{dE_x}{dt} = \frac{dE_f}{dt} - \frac{dE_{se}}{dt}, \qquad (2)$$

where dE_f/dt is a petroleum fuel rate function obtained by multiplying the fuel consumption by combustion efficiency.

Fuel consumption, heat loss and exhaust energy for the various cure phases was obtained from numerical integration of the respective rate functions. For example,

$$E_{x\ell c} = \int_{o}^{t_{\ell c}} \frac{dE_x}{dt} \qquad (3)$$

$$E_{x\ell d} = \int_{t_{\ell c}}^{t_{\ell d}} \frac{dE_x}{dt}\, dt \qquad (4)$$

$$E_{xsd} = \int_{t_{\ell d}}^{t_n} \frac{dE_x}{dt}\, dt \qquad (5)$$

Where $t_{\ell c}$ - leaf coloring upper bound
$t_{\ell d}$ - leaf drying upper bound
t_n - total cure time.

The percentage of E_f and E_x consumed in each cure phase was computed using the phase totals.

The time average exhaust energy per unit of water removed is given by,

$$e_{xw} = \frac{E_x}{W} \quad , \tag{6}$$

and in like manner,

$$e_{fw} = \frac{E_f}{W} \quad . \tag{7}$$

Water removal per cure phase is then,

$$W_{\ell c} = \frac{E_{x\ell c}}{e_{xw}} \tag{8}$$

$$W_{\ell d} = \frac{E_{x\ell d}}{e_{xw}} \tag{9}$$

$$W_{sd} = \frac{E_{xsd}}{e_{xw}} \tag{10}$$

The percentage of water removed during each phase was then computed.

Fuel energy per unit of cured leaf (oven dry) is given by:

$$e_{fo} = \frac{E_f}{W_{co}} \quad , \tag{11}$$

where $W_{co} = W_c \dfrac{\overline{w}_{co}}{\overline{w}_c}$.

Results and Discussion

Petroleum Fuel Energy

A comparison of the dE_f/dt functions for Barns 1 and 2 is given in Figure 2 for Cures 2-7. Cures 3-5 had similar consumption rates in both barns, however, in Cure 2 and Cure 6, Barn 1 has a particularly high rate of useage during the leaf drying phase. The higher useage rate in Barn 2 during the stem drying phase, Cure 7, suggests that the automatic vent control may have exhausted excessive air during this phase.

A comparison of the dE_f/dt functions for Barns 3 and 4 is given in Figure 3 for Cures 2-7. The curves for Cures 3-6 show that, in general, the consumption rate in Barn 4 was higher during the leaf drying and lower during stem drying. The cure 2 and 7 curves show a short interval high consumption rate for Barn 3 during stem drying, which suggests that the vent control may have exhausted excessive air at these times.

A comparison of the dE_x/ dt functions for Cures 2-7, Barns 1 and 2, is given in Figure 4. In this figure the dotted vertical lines mark the cure phases in Barn 1 and the solid lines mark phases in Barn 2. In Cures 3-5and 7, Barn 1 had a lower exhaust energy rate during leaf drying. Perhaps the wet bulb sensor for the vent control dried out and this caused a high exhaust rate. Water was added to the wick reservoir, or the system corrected itself, because the dE_x/dt function is similar to the Barn 2 function during stem drying.

A comparison of the dE_x/dt functions for Barns 3 and 4 is given in Figure 5 for Cures 2-7. As in Figure 4 the cure phases are denoted by vertical lines, dotted lines for Barn 4 and solid lines for Barn 3. Cures 3-5 had a higher exhaust energy rate in Barn 4 particularly during leaf drying and early stem drying. The Barn 4 venting seems to be more efficient during the last part of the stem drying phase. The Cure 2 curves show the high energy useage in Barn 3 during stem drying, which was first revealed in the Cure 2 dE_f/dt function shown in Figure 3. The dE_x/dt function gives a better definition of the effect of venting on fuel consumption.

The number of hours in each cure phase are summarized in Table 2 and a physical description of the tobacco in each cure is given in Table 3. Note in Table 3 that each barn was lightly loaded for Cure 5. A comparison of e_{fw} for the various cures (Table 4) shows the effect of light loading. It resulted in a high energy consumption per unit of water removed.

In Table 4, note the effect of stalk position on e_{fw}. In Barn 1, the lower stalk cures (Cures 2-3) required 58% more energy per unit of water removed than the upper stalk cures (Cures 6-7). The lower stalk cures required 1% more energy in Barn 2, 54% more in Barn 3, and 27% more in Barn 4.

Similar trends were noted in e_{fo}, Table 5. The lower stalk cures in Barn 1 used 104% more fuel energy per unit of cured leaf (oven dried) than the upper stalk cures. The energy percentages for upper versus lower leaves in Barns 2, 3 and 4 were 85%, 60% and 52% respectively.

Table 5 gives perhaps the best comparison of overall curing efficiency for the various barns. Using Barn 3 as a base for comparison of the mean e_{fo} for six cures, note that Barn 4 used 79% as much energy, Barn 2 92% as much, and Barn 1 95% as much. The energy savings were then 5% in Barn 1, 8% in Barn 2 and 21% in Barn 4. Apparently the savings in Barn 4 were obtained through a reduction in structural losses rather than in improved vent control.

Comparison of the fuel energy percentage and water removal percentage for the cure phases, given in Table 6 for Barn 1-4, shows that the fuel energy percentage is greater than the water removal percentage during the leaf coloring and stem drying phases, but that the reverse is true during leaf drying. The particular cure management used resulted in the following mean fuel energy percentages for the stem drying phase (six cures): 45% - Barn 1, 51% - Barn 2, 52% - Barn 3 and 37% - Barn 4. In explanation of the lower percentage in Barn 4, remember that Figure 5 did show that Barn 4 had a lower exhaust energy rate during the last portion of stem drying. In addition, the insulation under Barn 4 must have resulted in significant energy savings, particularly during the high temperature stem drying.

In Table 7, E_{se} and E_x are presented as a percentage of E_f. The insulation added to Barns 1 and 2 did little to reduce the heat loss percentages in comparison with those of Barn 3. Barn 4 showed a 16% improvement over Barn 3. Table 7 shows that 39% of the petroleum fuel consumed in a conventional barn is used to elevate and maintain the temperature of the curing structure. This is consistent with the results reported by Dodd and Cundiff (1977). In the factory insulated barn with insulation under the concrete slab (Barn 4) the losses were only 23% of the total petroleum fuel consumed.

Electrical Energy

Due to a malfunction in the data recording instrumentation on Barns 1 and 2, the demand data was not obtained, however accurate data was recorded on Barns 3 and 4. A comparison of the peak demand curves for Barns 3 and 4 is given in Figures 6-9 for Cures 4-7 respectively. The maximum 15 min. interval reading was plotted for each 24 hr. interval to obtain the curves.

For each of the cures the demand increases as the tobacco dries and the airflow resistance decreases. The energy requirement of the forward curve centrifugal fans used in the barns increases as the air volume increases. Note that the peak demand was less for Barn 3 than for Barn 4 during the last three days of the cure. A manufacturer's design change increased the volume of air moved by the fan in the new model barn. The same fan design and fan speed was used, but the flow pattern through the furnace was improved. The increased airflow resulted in a shorter curing time and an increased electrical demand. In general, the reduction in curing time was not sufficient to off set the increased usage rate and achieve a reduction in the total electrical energy required. Total electrical energy required for each cure (Table 8) was estimated by multiplying the peak demand each day by 24 hrs., and summing over the cure days.

A comparison of the peak demand for Barns 3 and 4 for the period July 15 - Aug. 14 is given in Figure 10. Barn 4 used less electrical energy, 2274 kw-hrs, than Barn 3, 2348 kw-hrs, during this period, however Barn 4 was off for three days (July 23-26) between cures. The harvest was managed such that Barn 3 was unloaded and refilled the same day, and thus was not turned off for the entire month. If Barn 4 had operated continuously, it would have used more electrical energy during this month interval than Barn 3.

Chemical Analysis

The chemical analysis of the cured leaf (Table 9) showed that the cures in Barn 3, in general, had a lower total nitrogen percentage. The means show Barn 1 cures were highest in total nitrogen followed by the Barn 4 and Barn 2 cures respectively. The total alkaloids were lower in the Cure 4 - Barn 3 and Cures 5, 6 - Barn 4 cured tobacco. These low values were characteristic of the tobacco and not caused by the curing envrionment.

The comparison between Barns 1 and 2 shows total alkaloids were generally higher in Cures 2 - 4, Barn 1, and lower in Cures 5 - 7. When the Barn 1 tobacco is compared with Barns 3 and 4 tobacco on the basis of total nitrogen or total alkaloids, it is difficult to define any consistant difference between the cycled airflow curing environment and the continuous airflow environment.

The best determination of cure acceptability can be gotten from the starch and reducing sugar percentages. High starch (>3.0%) and low reducing sugar (<8.0%) percentages indicate a reduction in cure quality. Cure 6 in Barns 2, 3 and 4 definitely has a high starch percentage and Cure 6 in Barn 1 had a low sugar percentage. The total cure time for Cure 6 was 122, 134, 144 and 120 hrs. in Barns 1-4 respectively (Table 2). The short cure time in Barns 1 and 4 is part of the explanation. The leaf was dried before the starch to sugar conversion was completed. The high starch content in Cure 6 tobacco from Barns 2 and 3 was not caused by accelerated drying because the cure time was similiar to that used for other cures. Each of the three samples from these cures showed a high starch percentage. The data is consistant, but is not readily explained.

Comparison of the starch percentage for Barn 1 cures with those in Barns 2-4 shows no real trend. The mean percentages are similiar for the cures in the various barns. A similiar comparison of the sugar percentages shows Barn 1 cures had a lower reducing sugar percentage than those in Barns 2, 3 and 4, Cure 5 - Barn 4 being the single exception. This indicates that the cycling procedure did cause a reduction in reducing sugars. It is possible that a reduced drying rate during leaf drying created an envrionment where the sugars were metabolized before drying arrested the chemical activity in the cure. The starch percentages do not show that the conversion was incomplete, thus the low reducing sugar percentages can not be explained simply by hypothesizing insufficient time in the coloring phase of the cure.

The tobacco industry uses the total nitrogen/total alkaloids (TN/TA) ratio and the reducing sugars/total alkaloids (RS/TA) ratio as an indication of quality. The TN/TA ratio should be less than 0.8 and the RS/TA ratio should be greater than 3.0. These ratios are given in Table 10. Note that the TN/TA ratios are acceptable where as the RS/TA ratio are generally low with the Barn 1 cures being lower than the others. The over-all low values are probably due to a drought during the growing season which generally reduced tobacco quality.

Summary and Conclusions

An on-farm test was conducted with four mobile style bulk rack barns. Barns 1 and 2 had insulation added to the side walls and ceiling. Barn 4 was a factory insulated, unmodified conventional barn. Each barn was operated with continuous fan operation except Barn 1 which was cycled ON 20 min OFF 25 min from 1200-1700 hrs. each day of the cure.

Averaged over six cures, the petroleum fuel consumption, expressed as MJ/kg cured leaf (oven dried), was 19.2 Barn 1, 18.6 Barn 2, 20.2 Barn 3 and 16.0 Barn 4. The lower stalk cures (Cures 2-3) required more energy than the upper stalk cures (Cures 6-7); 104% more in Barn 1, 85% more in Barn 2, 60% more in Barn 3, and 58% more in Barn 4.

Fan cycling had a negligible effect on petroleum fuel consumption. Barns 1 and 2 were quite similar in operation throughout. Barn 2 appeared to have a slightly more efficient vent control. The fuel energy savings in Barn 4 in comparison with Barn 3 were due to reduced structural heat losses.

Electrical demand data was not obtained on Barns 1 and 2 because of an equipment malfunction. Barn 4 had a higher demand than Barn 3 because the fan in Barn 4 moved more air. The same fan design and fan speed was used, however the manufacturer improved the airflow through the furnace and reduced the barn resistance. The resulting higher airflow required more electrical energy. Greater airflow did reduce the curing time, thus the electrical energy per cure in Barn 4 was not greater than Barn 3.

Chemical analysis of the cured leaf revealed a total nitrogen/total alkaloids ratio for all cures that is typical for type 14 tobacco. Starch percentages were in normal range for all cures. The reducing sugar percentages were lower in Barn 1 cures than in Barns 2, 3 and 4 cures. The fan cycling procedure did cause a reduction in reducing sugars in these tests. The reducing sugars/total alkaloids ratio was low for all cures, probably because of drought which generally reduced tobacco quality. The tobacco cured using the fan cycling procedure had a lower reducing sugar/total alkaloids ratio than tobacco cured with continuous fan operation.

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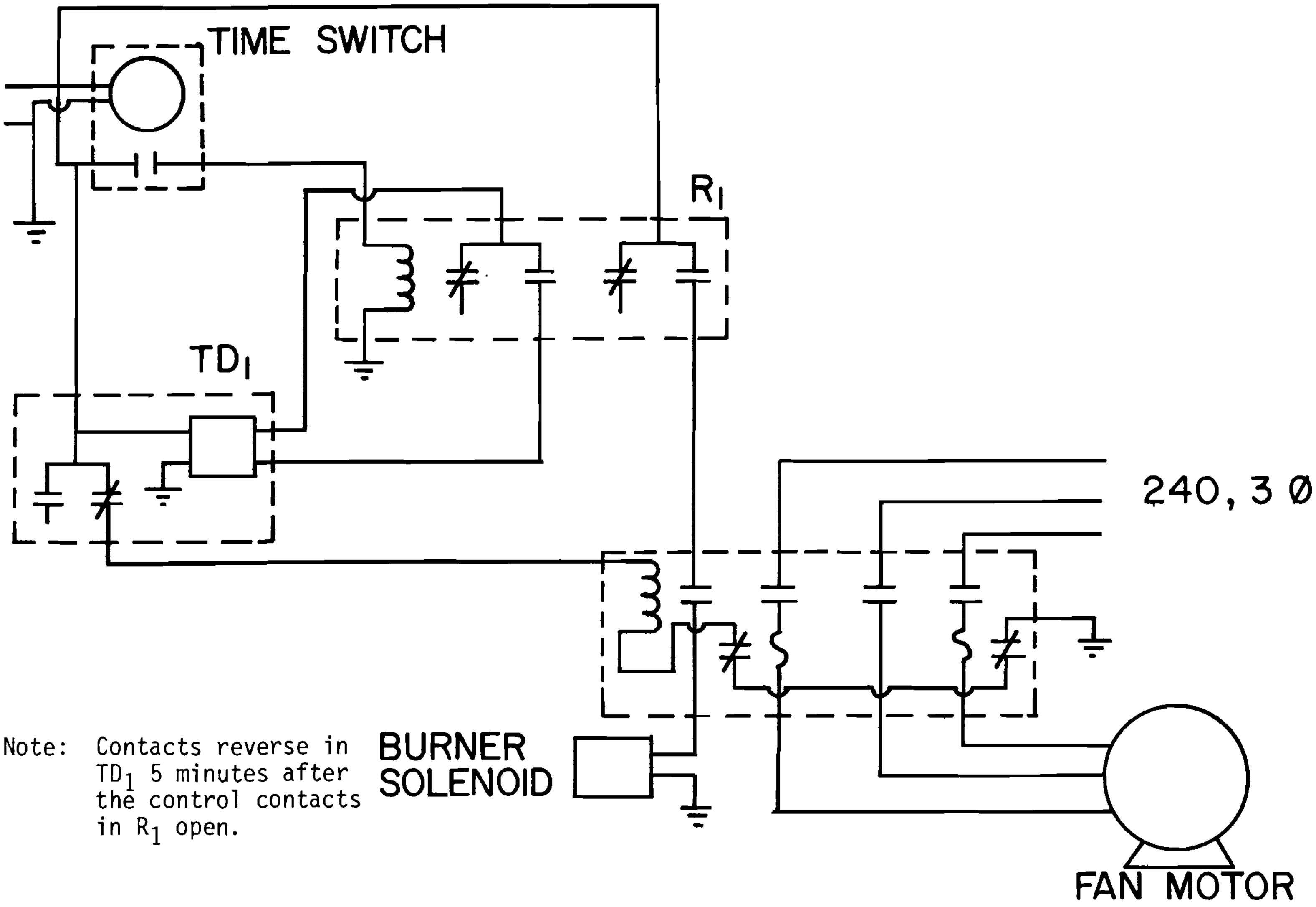

Note: Contacts reverse in TD_1 5 minutes after the control contacts in R_1 open.

Figure 1. Control circuit for cycled barn (Barn 1).

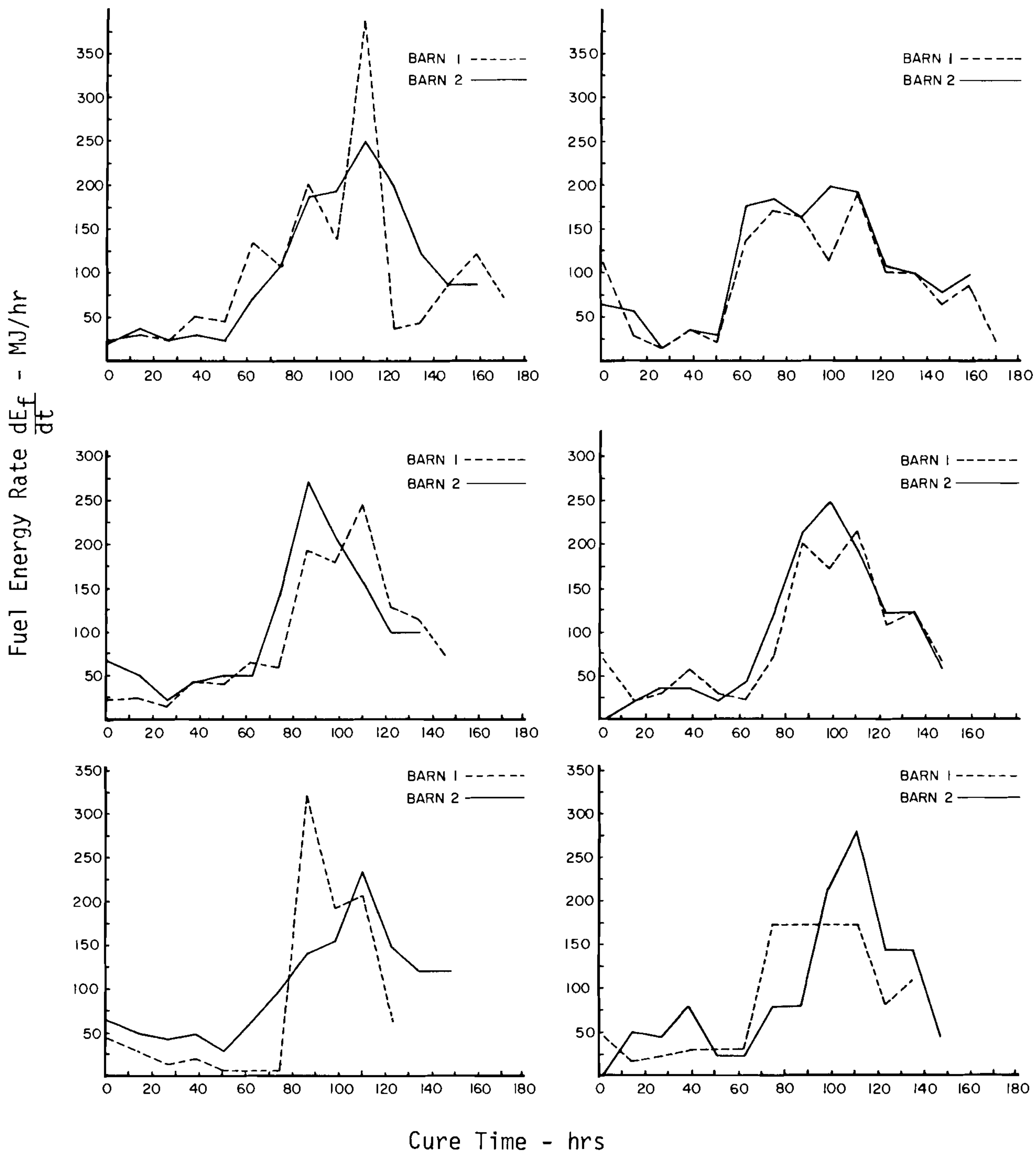

Figure 2. Fuel consumption rate for Barns 1 and 2, Cures 2-7 respectively.

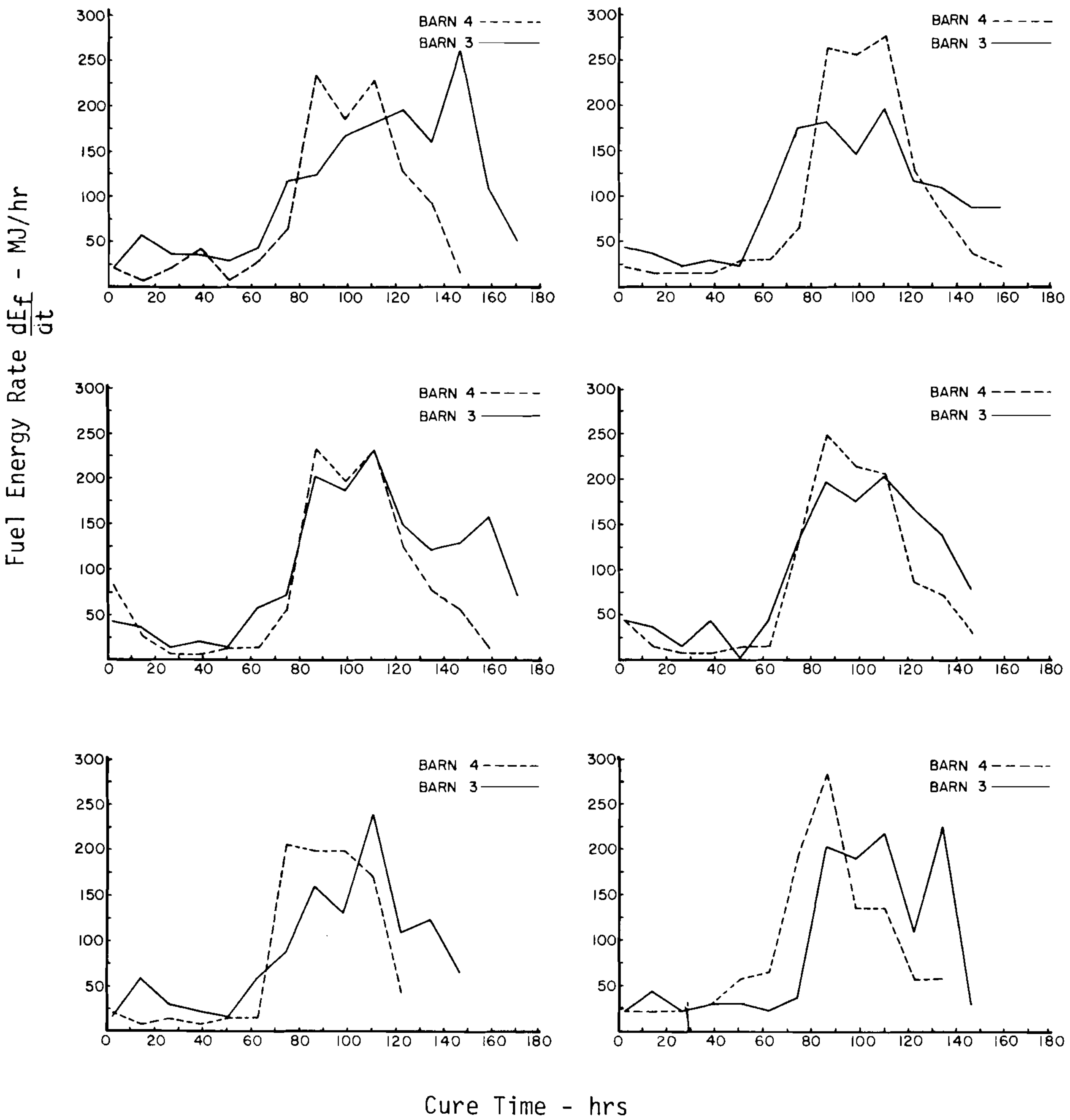

Figure 3. Fuel consumption rate for Barns 3 and 4, Cures 2-7 respectively.

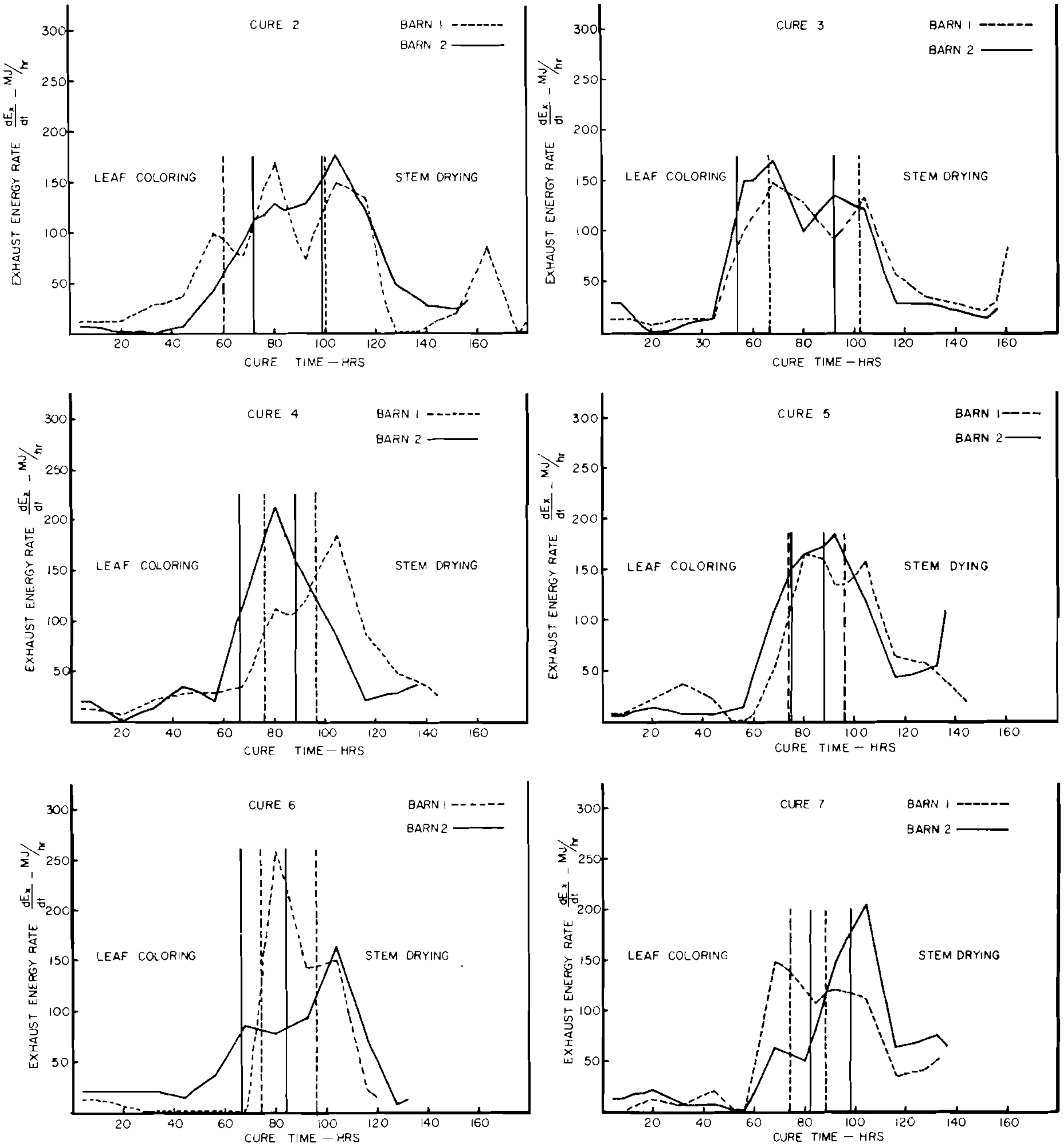

Figure 4. Exhaust energy rate for Barns 1 and 2, Cures 2-7 respectively.

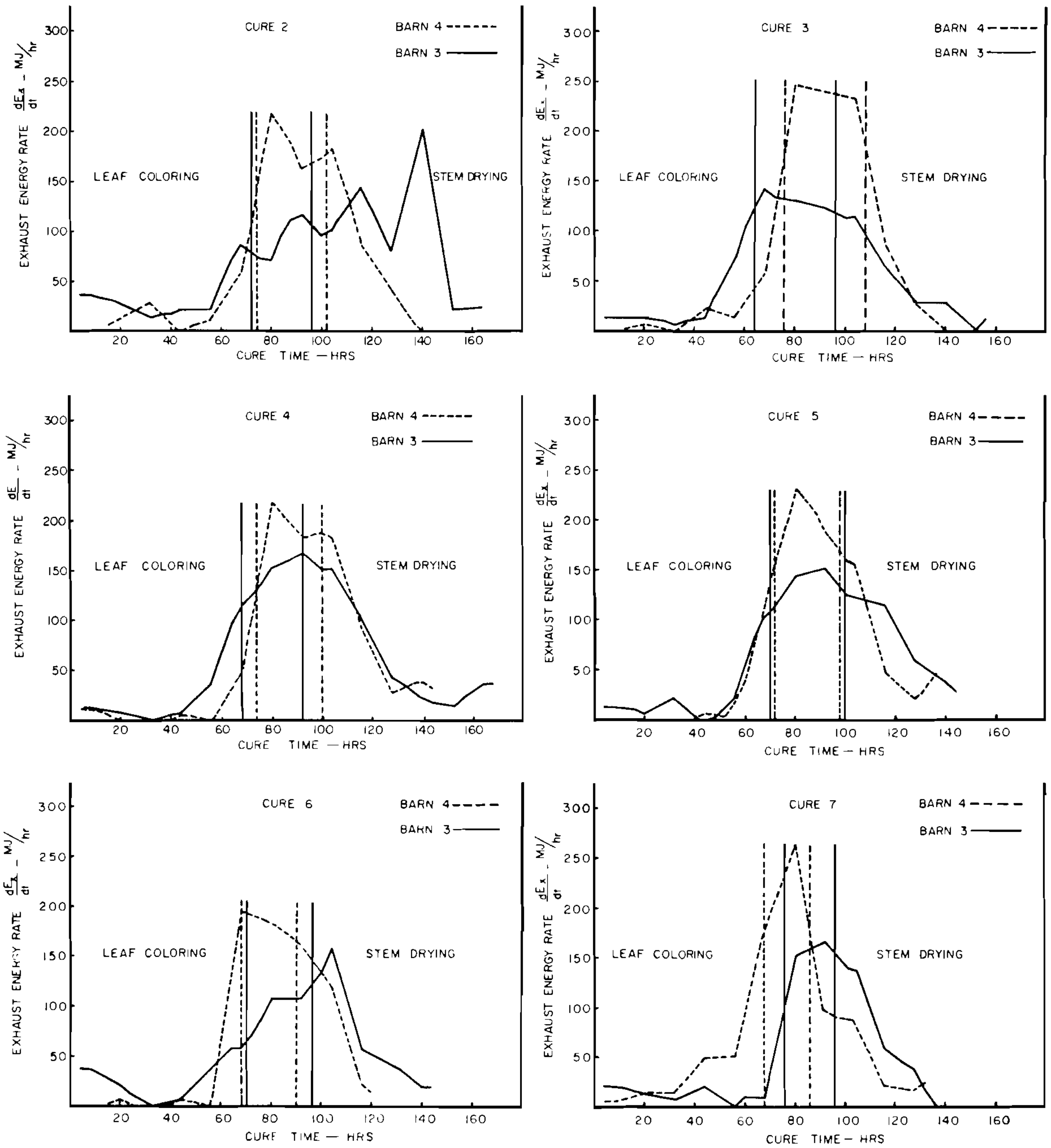

Figure 5. Exhaust energy rate for Barns 3 and 4, Cures 2-7 respectively.

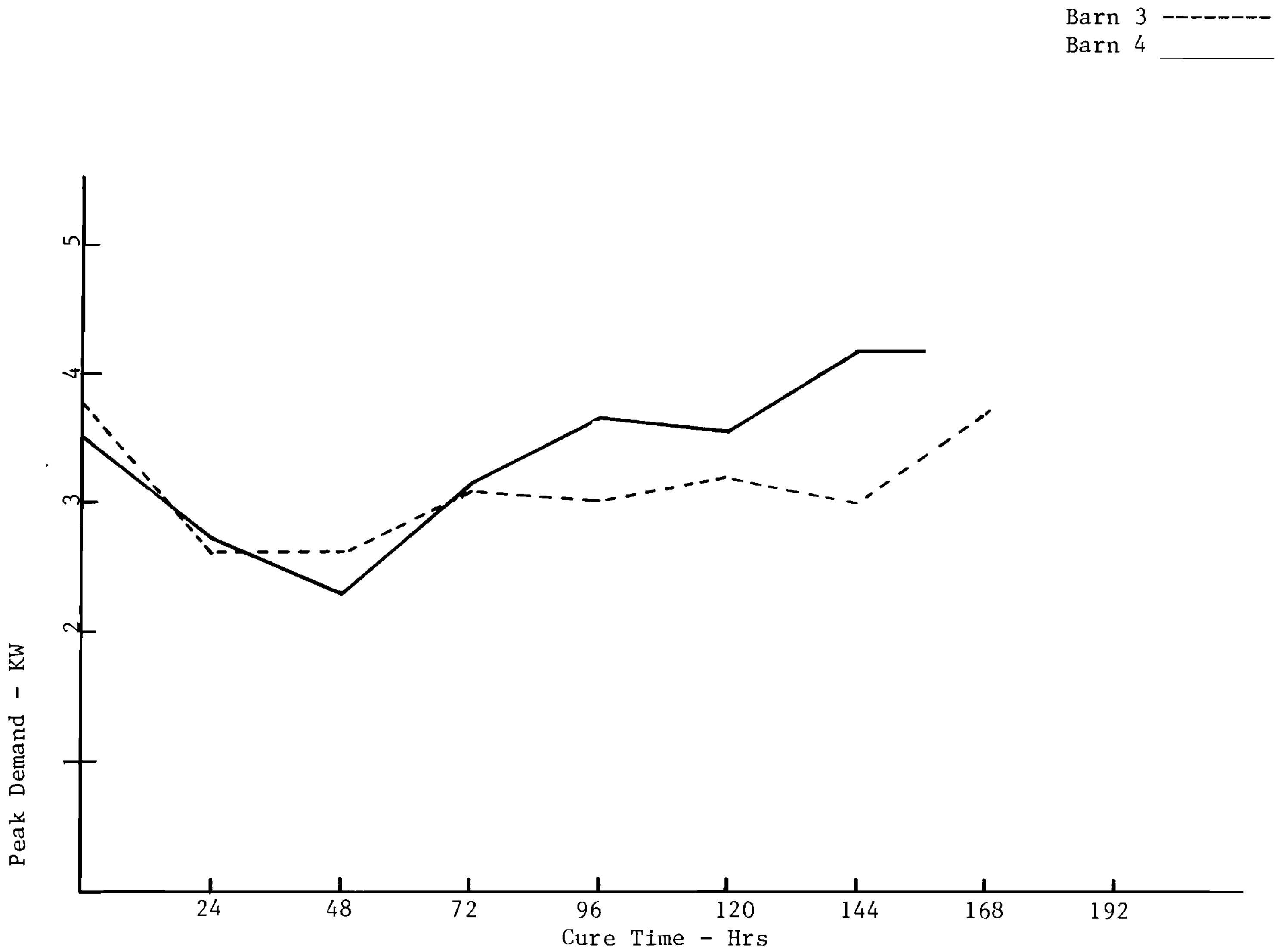

Figure 6. Peak Demand, (KW) for Barns 3 and 4, Cure 4.

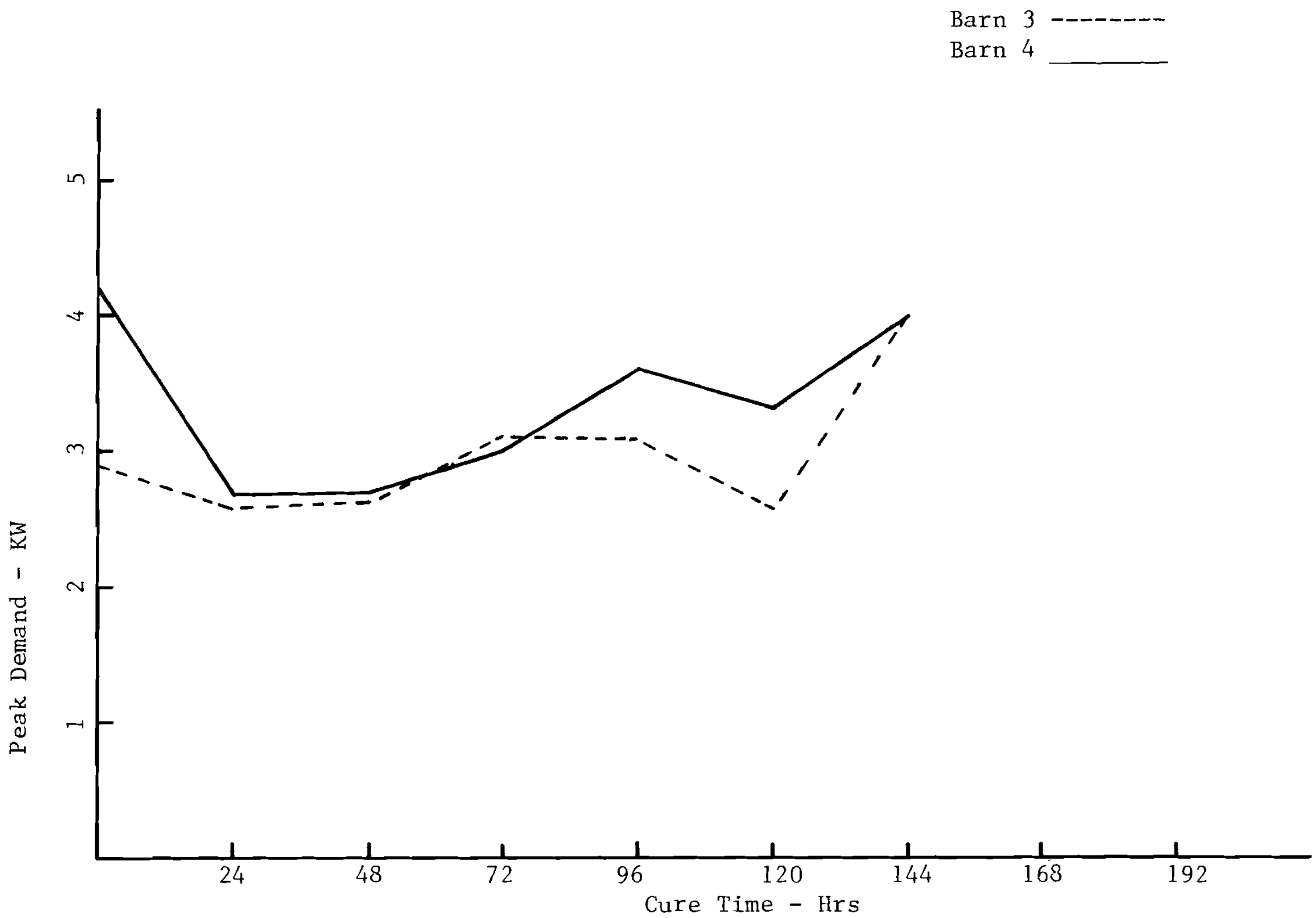

Figure 7. Peak Demand, (KW), for Barns 3 and 4, Cure 5.

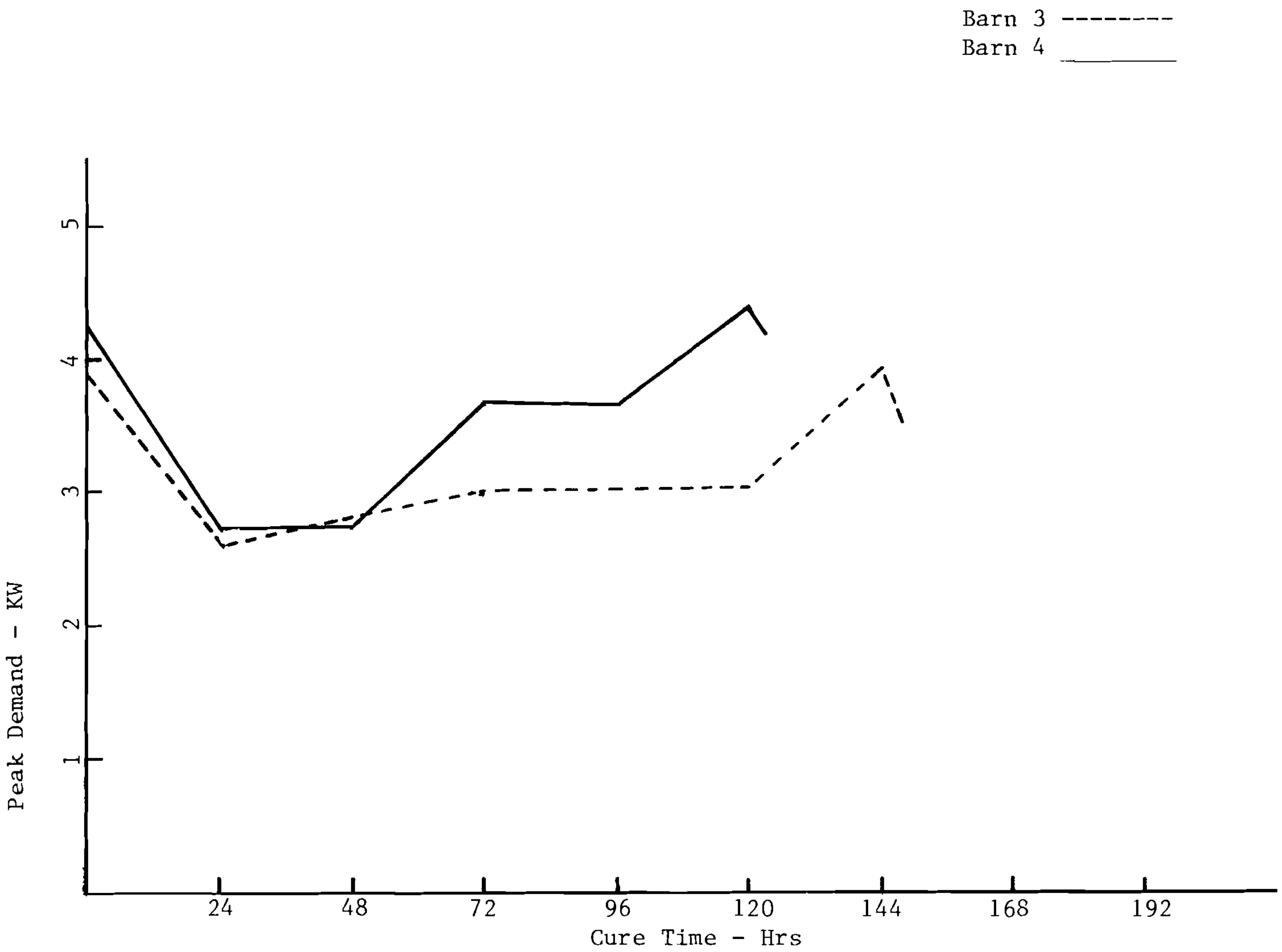

Figure 8. Peak Demand, (KW), for Barns 3 and 4, Cure 6.

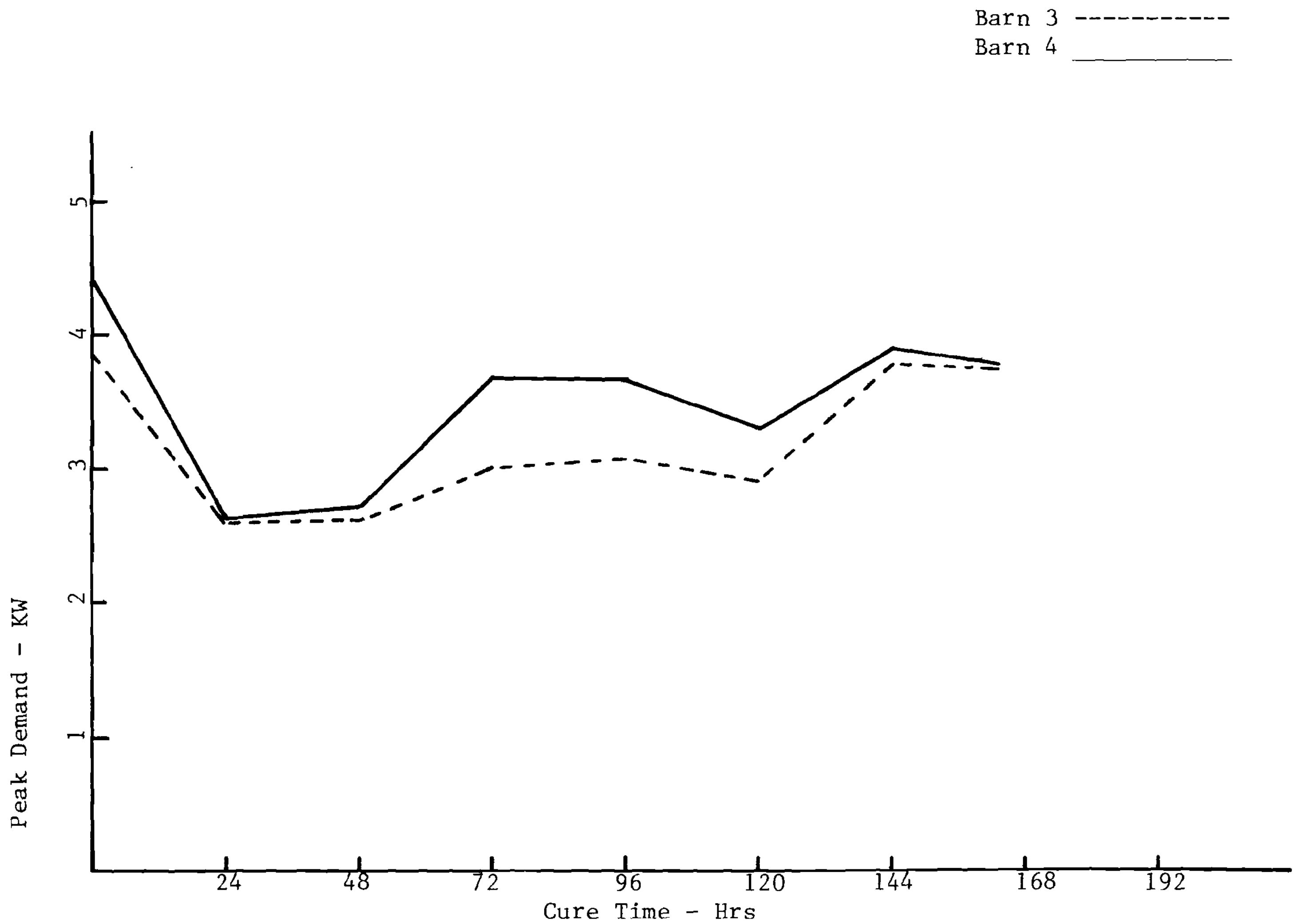

Figure 9. Peak Demand, (KW), for Barns 3 and 4, Cure 7.

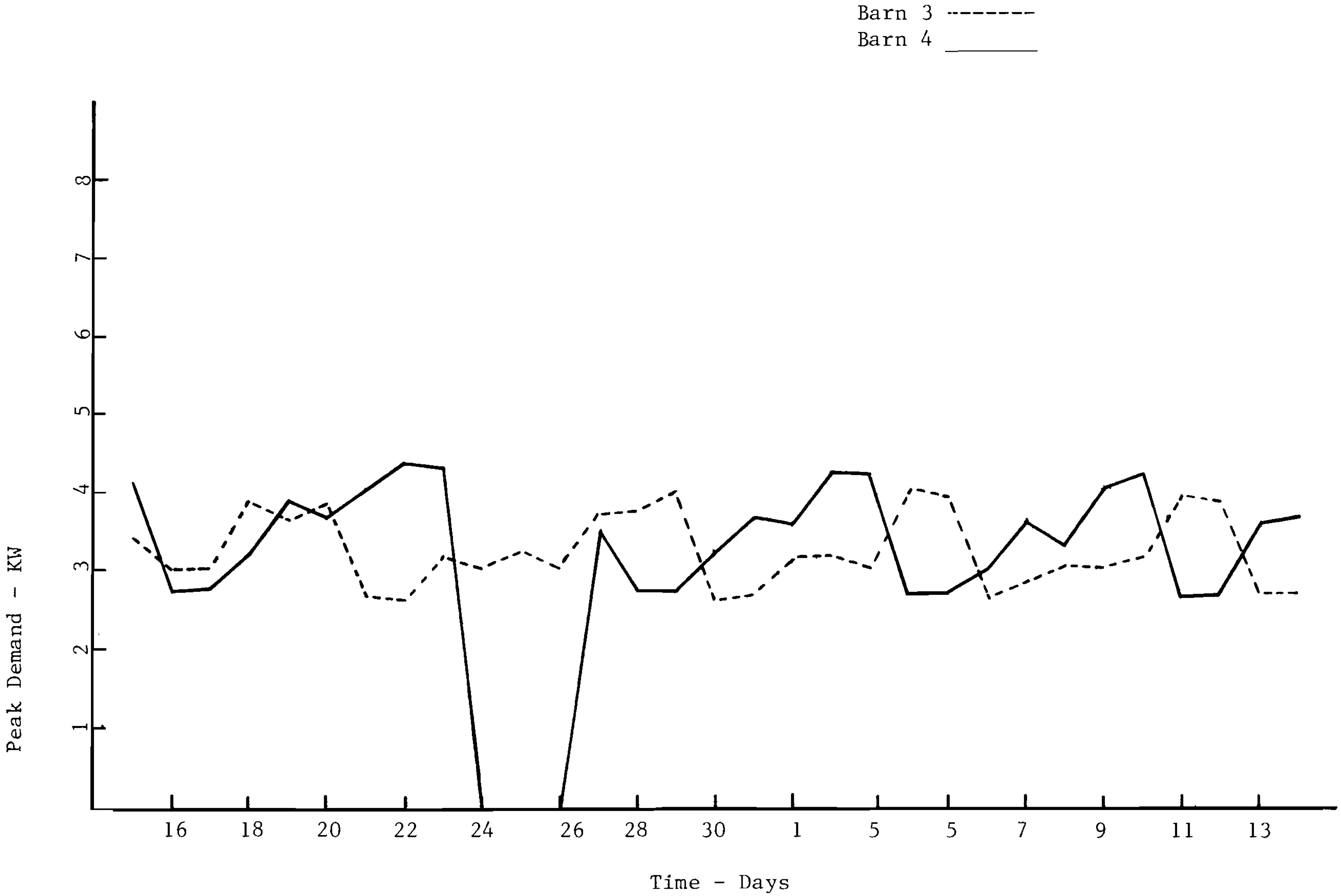

Figure 10. Peak Demand, (KW), for Barns 3 and 4, for one month.

Table 1. Thermal resistance of curing compartment surfaces, Barns 1-4.

Thermal Resistance, $\frac{^{o}C}{J/hr\text{-}m^2}$ x10^{-5}

Variable	Barn 1	Barn 2	Barn 3	Barn 4
R_r	99.99	99.99	7.49	27.52
R_e	17.82	17.82	17.82	30.46
R_ℓ	2.66	2.66	2.66	2.66
R_{su}	17.82	17.82	17.82	30.46
R_s	38.12	8.12	17.82	30.46
R_d	38.12	38.12	17.82	30.46
R_{rw}	7.49	7.49	7.49	36.43
R_{ff}	6.27	6.27	6.27	21.54
R_{cf}	3.82	3.82	3.82	19.10
R_{fs}	3.82	3.82	3.82	19.10
R_{fb}	19.10	19.10	19.10	19.10
$R_{s\ell c}$	8.28	8.28	8.28	26.78
$R_{s\ell u}$	2.66	2.66	2.66	19.10

Variable Description:

R_r - roof

R_e - gable end

R_ℓ - front exhaust louver

R_{su} - side of return duct to furnace

R_s - side wall of curing compartment

R_d - loading end doors

R_{rw} - rear wall of curing compartment

R_{ff} - furnace room floor

R_{cf} - furnace room ceiling

R_{fs} - furnace sides

R_{fb} - furnace front and back

$R_{s\ell c}$ - lower plenum side wall covered

$R_{s\ell u}$ - lower plenum side wall uncovered

Table 2. Cure hours in various cure phases in Barns 1-4, Cures 2-7.

Cure No.	Leaf Coloring Phase		Leaf Drying Phase		Stem Drying Phase	
	Hrs	$t_{\ell c}$	Hrs	$t_{\ell d}$	Hrs	t_n
			Barn 1			
2	60	60	40	100	80	180
3	66	66	36	102	58	160
4	76	76	20	96	52	148
5	74	74	22	96	52	148
6	74	74	22	96	26	122
7	74	74	14	88	48	136
			Barn 2			
2	72	72	26	98	58	156
3	54	54	38	92	68	160
4	66	66	22	88	48	136
5	74	74	14	88	50	138
6	66	66	18	84	50	134
7	82	82	16	98	40	138
			Barn 3			
2	72	72	24	96	70	166
3	64	64	32	96	60	156
4	68	68	24	92	76	168
5	70	70	30	100	44	144
6	70	70	26	96	48	144
7	74	74	22	96	48	144
			Barn 4			
2	74	74	28	102	38	140
3	76	76	32	108	42	150
4	74	74	26	100	44	144
5	72	72	26	98	40	138
6	68	68	22	90	30	120
7	68	68	18	86	46	132

Table 3. Total mass green leaf, W_g, cured leaf (oven dry), W_{co}, and water removed, W, for Barns 1-4, Cures 2-7.

Cure No.	W_g (kg)	W_{co}(kg)	W(kg)
	Barn 1		
2	5144	591	4522
3	4091	649	3408
4	4632	889	3696
5	2535	662	1838
6	4676	880	3750
7	5730	855	4830
	Barn 2		
2	5988	734	5216
3	5469	644	4791
4	4852	862	3945
5	3388	853	2490
6	5400	939	4412
7	5935	1071	4807
	Barn 3		
2	4653	650	3969
3	5050	705	4308
4	6547	790	5715
5	4593	838	3711
6	6205	772	5392
7	5133	883	4204
	Barn 4		
2	4589	658	3896
3	4861	744	4079
4	4777	867	3865
5	3251	747	2464
6	4934	900	3987
7	5535	894	4594

Table 4. Comparison of fuel energy, e_{fw}, (MJ/kg water removed) in Barns 1-4, Cures 2-7.

Cure No.	Barn 1	Barn 2	Barn 3	Barn 4
2	3.89	3.23	4.72	3.23
3	4.50	3.64	3.64	3.59
4	3.70	3.71	3.04	3.34
5	7.32	6.01	3.98	5.08
6	2.83	3.02	2.45	2.63
7	2.49	2.85	2.98	2.74
Mean	4.12	3.74	3.47	3.43
Mean Cures 2-3	4.19	3.44	4.18	3.41
Mean Cures 4-5	5.51	4.86	3.51	4.21
Mean Cures 6-7	2.66	2.94	2.72	2.68

Table 5. Comparison of fuel energy, e_{fo}, [MJ/kg cured leaf (oven dried)] used in Barns 1-4, Cures 2-7.

Cure No.	Barn 1	Barn 2	Barn 3	Barn 4
2	29.8	22.9	28.8	19.1
3	23.6	27.0	22.2	19.7
4	15.4	17.0	22.0	14.9
5	20.3	17.5	17.6	16.7
6	12.1	14.2	17.1	11.6
7	14.1	12.8	14.2	14.1
Mean	19.2	18.6	20.2	16.0
Mean Cures 2-3	26.7	25.0	25.0	19.4
Mean Cures 4-5	17.8	17.3	19.8	15.8
Mean Cures 6-7	13.1	13.5	15.6	12.8

Table 6. Comparison of fuel energy (%) and water removed (%) for Barns 1-4, mean Cures 2-7.

Barn No.	Leaf Coloring		Leaf Drying		Stem Drying	
	Water Removal	Fuel Energy	Water Removal	Fuel Energy	Water Removal	Fuel Energy
1	21	23	39	32	40	45
2	20	23	33	26	47	51
3	19	19	36	29	45	52
4	17	19	53	44	30	37

Table 7. Comparison of exhaust and structural heat loss energy, mean Cures 2-7.

Barn	Exhaust Energy (%)	Heat Loss Energy (%)
1	64	36
2	58	42
3	61	39
4	77	23

Table 8. Total electrical energy consumption (kw-hrs) estimated from daily peak demand, Barns 3 and 4, Cures 4-7.

Cure No.	Barn 3	Barn 4
4	596	565
5	495	426
6	457	451
7	357	566
Mean	476	502

Table 9. Chemical analysis of cured leaf, mean Cures 2-7, Barns 1-4.

Constituent, %	Barn 1	Barn 2	Barn 3	Barn 4
Total Nitrogen	2.23	2.07	1.83	2.16
Total Alkaloids	3.21	3.23	3.14	3.11
Starch	3.2	3.3	3.6	3.4
Reducing Sugars	6.3	9.7	9.8	8.3

Table 10. Ratios of constituents in tobacco from Cures 2-7, Barns 1-4.

Cure No.	Barn 1	Barn 2	Barn 3	Barn 4
	Total Nitrogen/Total Alkaloids			
2	0.84	0.75	0.71	0.73
3	0.64	0.62	0.60	0.59
4	0.50	0.61	0.64	0.54
5	0.71	0.62	0.51	0.80
6	0.84	0.64	0.54	0.80
7	0.76	0.64	0.59	0.78
Mean	0.72	0.65	0.60	0.71
	Reducing Sugars/Total Alkaloids			
2	2.8	3.7	3.3	3.2
3	2.7	4.3	3.5	2.9
4	1.2	3.2	3.1	2.0
5	2.0	2.4	2.9	1.8
6	1.3	2.6	2.7	3.6
7	2.4	2.8	3.4	3.0
Mean	2.1	3.2	3.2	2.8

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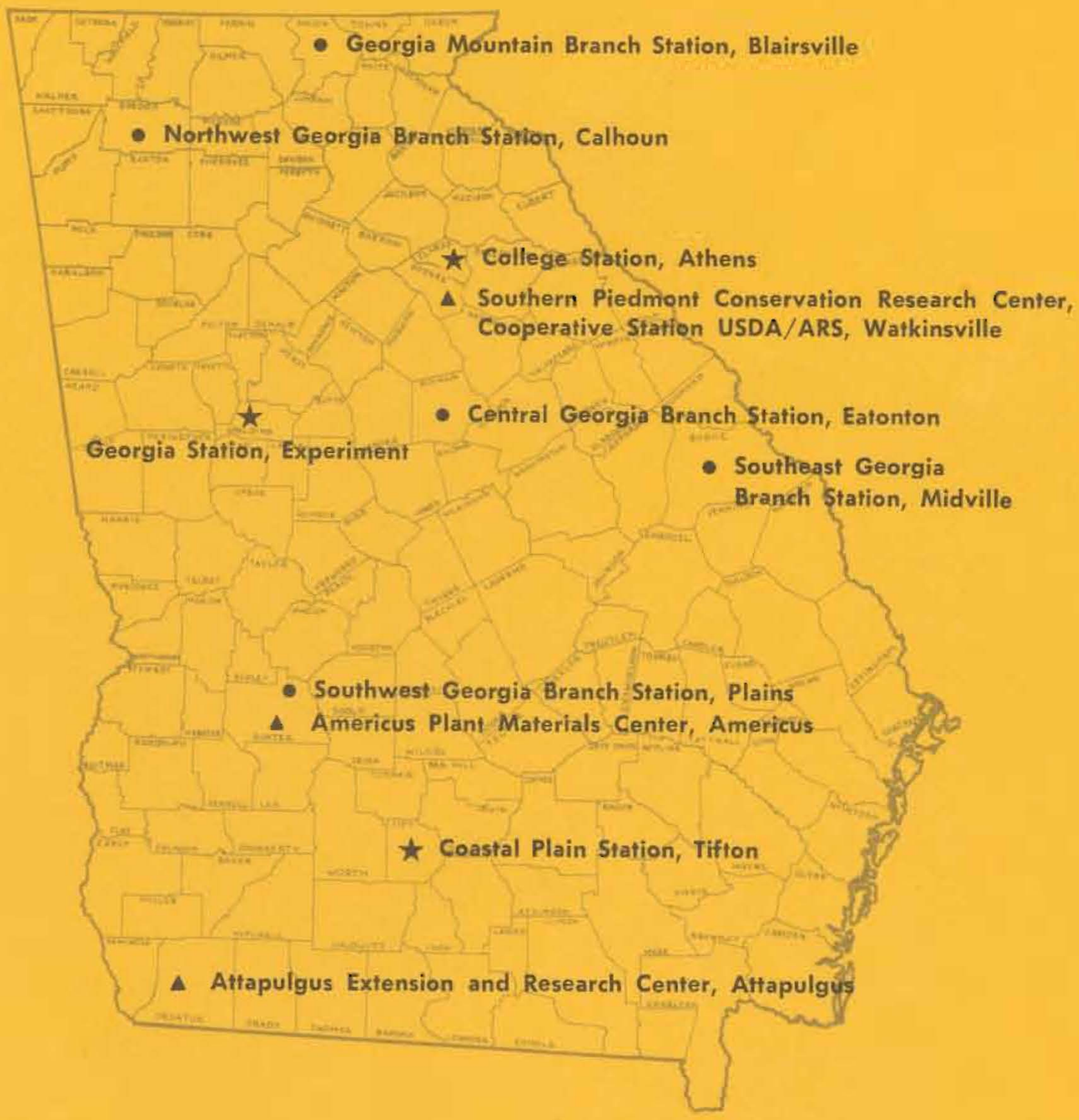

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