ACOUSTIC EMISSION GENERATED DURING DRYING

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Acoustic emission (AE) are the transient elastic waves generated by the release of mechanical energy. AE is generated as a result of fractures that occur when a material is stressed beyond some critical limit. AE is typically measured by attaching or embedding piezoelectric transducers to or in the material. With regard to lumber drying, AE is generated during the initiation and propagation of defects, such as surface and internal checking (honeycomb), and collapse.

Most AE applications use characteristics of AE "events" to quantify the state of a process. A diagram of such an event is shown in Figure 1. AE measurements used to characterize a process include the rate at which these events occur, and certain characteristics of the event envelope itself. As shown in Figure 1, characteristics of the event envelope include ring-down counts (the number of threshold crossings for a given event), peak amplitude (given in volts (v) or dB), rise time (the time from the first threshold crossing to the peak, given in μs), duration (μs), slope (mv/μs), and a measure of energy. A select number of these characteristics, or all of them, could be used for a given application. The threshold level is adjustable, and is set so that background noise is eliminated. In the case of lumber drying, the threshold level would be set such that noise associated with the operation of the fans, and the heat, steam, and venting systems were ignored.

The ultimate goal of AE research is to incorporate AE technology into a reactive control system. In such a system the severity of drying conditions in the kiln would be controlled based on measurements related to the stress development in wood. This would optimize the drying. Currently, commercial process control systems are based on technology that measures some parameter or property that provide an estimate of moisture content or drying rate, and some inference is consequently made regarding the lumber (e.g., its moisture content or state of stress). Most of the currently available systems are used to determine end-point, and are therefore not useful in minimizing non-warp related defects. The potential advantage of AE is that it would be able to provide a measure of the condition of the lumber with regard to defect susceptibility in the early stages of drying.

A REVIEW AND SOME POTENTIAL PROBLEMS
OF AE-BASED CONTROL SYSTEMS

AE research related directly to wood drying began in earnest in about 1980, and since that time there have been many publications on the subject. Most of the drying related AE research has been conducted in Japan, the United States, and West Germany. Since a detailed literature review is beyond the scope of this paper, discussion will be limited to those publications directly pertaining to process control systems and issues.

In 1980 Skaar, *et al.* reported on the potential use of AE to control the drying process. In 1985 Honeycutt, *et al.* reported on experiments designed to test the concept described by Skaar in 1980. The drying rate of red oak was controlled by adjusting conditions in the kiln such that a ring-down count rate of
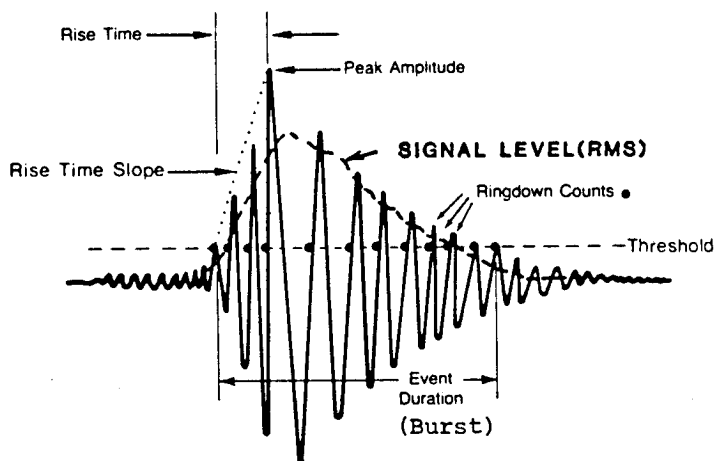
Figure 1.   Diagram of an acoustic emission event showing time domain characteristics that are often measured.

1000 per minute was maintained. They were successful in controlling the kiln conditions using this algorithm. Note that the count rate was somewhat arbitrary, in the sense that it did not try to optimize the process by maximizing drying rate or minimizing defects, and therefore this system was not reactive.

Noguchi, *et al.* (1987) and Kitayama, *et al.* (1985) reported on aspects of an AE-based reactive control system which they developed. Their findings are based on research using *Zelkova serrata* cross-sections, and consequently relate specifically to end-checking. They reported that AE event ring-down count rates were greatest in wood where checking occurred. Therefore, their control system is based on a preset value for the ring-down count rate, and on the rate of increase of this value over sequential time intervals. When the rate of increase reaches a given critical value the relative humidity in the kiln is increased, thereby reducing the severity of the kiln conditions. As a result, the ring-down count rate also decreases.

It has been shown that the AE generated by hardwoods during drying is greater than that generated by softwoods (Noguchi, *et al.* 1985), and that softwood sapwood generated more AE activity than the heartwood (Becker 1982). These findings indicate that an appropriate controlling algorithm may be a function of species.

Other issues preventing immediate application include the need for a more thorough understanding of the effect of physical and anatomical properties of wood on the attenuation of the acoustic signal in wood. Attenuation issues are particularly important because actual lumber sizes are quite variable, and because the source of a given acoustic emission is unknown. For successful implementation, it will be essential to understand how the propagating acoustic wave changes as a function of factors such as distance and propagating direction, between the acoustic source and the receiving transducer. Some research in this area has been reported (Quarles 1988). Finally, since the transducer must be in contact with the lumber, sample boards would have to be selected. This is a key factor, and an important potential disadvantage to consider.

OBJECTIVES

The remaining portion of this paper will discuss a portion of the on going research being conducted at this laboratory pertaining to AE generated during drying. The principal objective of this research is to characterize the acoustic signal associated with the initiation and propagation of surface checks.

Recent experiments have been conducted using California black oak (*Quercus kelloggii*) for specimen material. Experiments have been conducted at elevated temperatures (180/110°F). Not surprisingly, severe internal checking has been observed at the conclusion of each run. In order to determine exactly where the internal checking was occurring, a short experiment was conducted. In this paper, AE activity generated during drying will be discussed in conjunction with the results of that experiment.

MATERIALS AND METHODS

The oak specimens were flatsawn, 10 cm in the tangential direction by 14 cm along the grain. Nominal 4/4 (1-inch) and 8/4 (2-inch) end-matched samples were used. The 4/4 and 8/4 samples were obtained from separate boards. Drying conditions were maintained at 180°F dry bulb and 110°F wet bulb temperature. The severe conditions were used to help ensure that surface checking would occur.

The specimens used in these tests were free of visible knots. To minimize edge and end drying, all samples were sealed on each narrow edge with silicon caulk and a layer of aluminum foil.

Separate runs were conducted for the 4/4 samples for the 8/4 samples. Four specimens from each thickness group were dried during each run. One of the four samples in each thickness group was mounted on a load cell so that mass loss could be monitored. The specimen which was mounted on the load cell sample also had two AE transducers attached to its surface. A hot melt was used as the couplant to ensure adequate contact between the transducer and the wood surface and a metal clamp and constant force spring was used to hold the transducer in place. Although all specimens were rough sawn, a one-inch end mill was used to prepare a smooth surface where the transducers were to be placed. All specimens were positioned vertically in the experimental micro-kiln.

The run was interrupted at fixed intervals during the drying of the 4/4 and 8/4 specimens so that specimens could be pulled and evaluated for the appearance of internal checking. The evaluation consisted of cross-cutting each sample into thirds, making visual observations concerning the presence and extent of internal checking, and then oven-drying the sections in order to determine the moisture content. Shell and core moisture sections were cut from one of the three sections from each sample. For the 4/4 run, samples were pulled at 14, 22, 30, and 38 hours into the run. For the 8/4 run, samples were pulled at 24, 34, 44, and 54 hours into the run. The specimens mounted on the load cell were the last samples pulled.

An AET 5500 general purpose acoustic emission monitoring system was used to monitor AE activity. The transducers were both 175 kHz resonant frequency piezoelectric-type sensors. Other set-up parameters included a 1.0 V floating threshold, 80 dB total gain (60 dB preamp), and a 125-250 kHz filter. The AE data was analyzed using software developed and written at the UC FPL.

RESULTS AND DISCUSSION

4/4 Drying Run

The moisture content and AE event data for the 4/4 run (sample number S1644) is given in Figure 2. Although data from both transducers was collected, discussion will be limited to data from one transducer since the trends from each were similar. The AE event data were accumulated over 10 minute intervals, thereby giving an event rate per 10 minutes. The 10 minute interval is a convenient size for observing AE activity over an extended period, but is probably too large for any control algorithm. Note that the events have been segregated into four peak amplitude groups, including 40-49 dB, 50-59 dB, 60-69 dB, and 70-79 dB. Higher energy events are normally associated with higher peak amplitudes. Approximately 98% of the events fell into the 40-59 dB peak amplitude groups. An initial peak occurred at 0.5 hours (designated point A in Fig.2), with a subsequent larger peaks occurring at approximately 3 hours (point B) and 9 hours (point C) into the run. These peaks are most evident with the low peak amplitude events (40-49 dB), and become less distinct at higher peak amplitudes. It is conjectured that the peak at point A is caused by events related to cavitation of water in the cell lumens located near the specimen surface. Experiments conducted at this laboratory have shown that similar peaks occur even at relatively mild drying conditions. AE associated with cavitation has been documented (Tyree and Dixon, 1983).

It was not possible to view the specimens which had the surface mounted AE transducers during this run since the other specimens blocked the view.
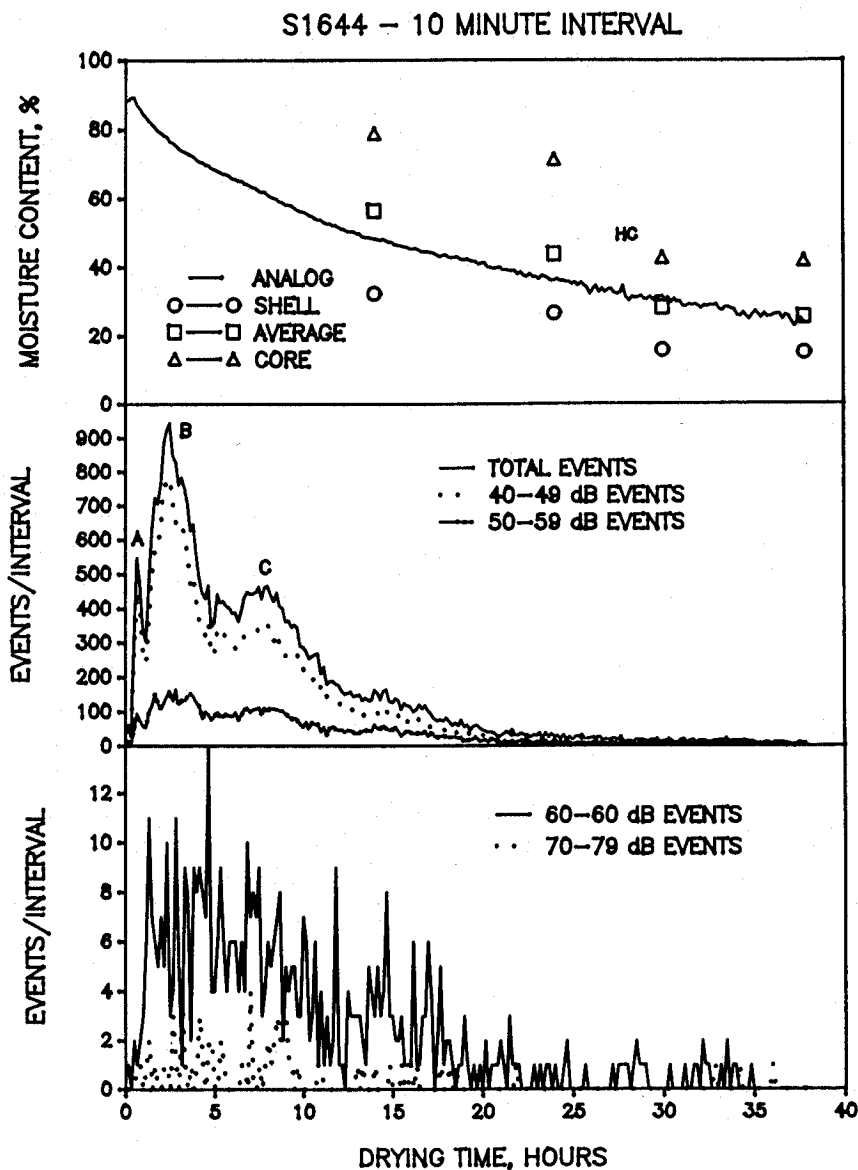
S1644 — 10 MINUTE INTERVAL

Figure 2.   Moisture content and event rate data for the 4/4 specimen. The drying time was approximately 38 hours and the kiln conditions were 180°/110° F. The approximate time associated with the initiation of internal checking (honeycombing) is indicated on the moisture content plot by "HC".

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However, in past runs at these conditions, visible surface checking occurred after about 3 hours of drying, and check propagation continued through the 10th hour. Check closure was always completed by hour 12. Consequently the peaks at points B and C were probably associated with check propagation. AE activity decreased dramatically in all peak amplitude groups after 12 hours of drying, or about the time check closure was completed. At this point the average moisture content was approximately 50%.

Other event characteristics from the 4/4 sample are shown in Figure 3. These include ring-down counts, event duration, and a measure of energy, again accumulated over 10 minute intervals. Note that the trends exhibited by these plots were very similar to the total event curve shown in Figure 2. This indicates that monitoring other time-domain parameters in addition to events may be unnecessary.

Internal checking began in the 4/4 specimens after about 30 hours of drying. The average moisture content at this time was 30%, with the core being 40% and the shell 15%. The AE activity during the period of time when internal checking was occurring was minimal. This indicates that embedded probes, or the use of wave guides, would be necessary to detect the occurrence of internal checking.

8/4 Drying Run

The moisture content and AE data for the 8/4 run (sample number S0784) is given in Figure 4. The initial event peak occurred after 1 hour of drying (designated point A in Figure 4), with a subsequent peak after 10 hours of drying (point B). Note that the actual values of the event rate for the 8/4 specimen was somewhat less than that measured with the 4/4 specimen. Although both 4/4 and 8/4 specimens were free of surface knots, this indicated that thickness alone will not cause an increase in activity. The 4/4 and 8/4 AE data were obtained with the same transducer.

As was the case with the 4/4 run, it was not possible to observe the specimen with the AE transducers. However, surface check initiation and propagation was typically visible in the 8/4 specimens after approximately 6 hours of drying. Therefore it is again likely that the initial peak (A) was associated with cavitation, with the subsequent peak (B) being associated with check initiation and propagation. The 40-49 and 50-59 dB events decreased steadily after the second peak was reached (point B), whereas the 60-69 dB events maintained a minimal, but relatively constant, level throughout the run. Observations on other 8/4 specimens dried at these conditions indicated that check closure began after approximately 25 hours of drying. Observations on these specimens showed that internal checking began developing after 44 hours of drying. As was the case with the 4/4 samples, AE activity during this time was relatively low.

Other event characteristics from the 8/4 sample are shown in Figure 5. As was the case with the 4/4 specimen, the trends exhibited by these plots were very similar to the total event plot shown in Figure 4. This reinforces the previous statement indicating that monitoring other time-domain parameters in addition to events may be unnecessary.

SUMMARY

The trends observed in the AE data were very similar for both the 4/4 and 8/4 specimens. An initial event rate peak occurred at approximately 0.5 to 1.0 hours into the run, and was thought to be caused by the cavitation of water in the
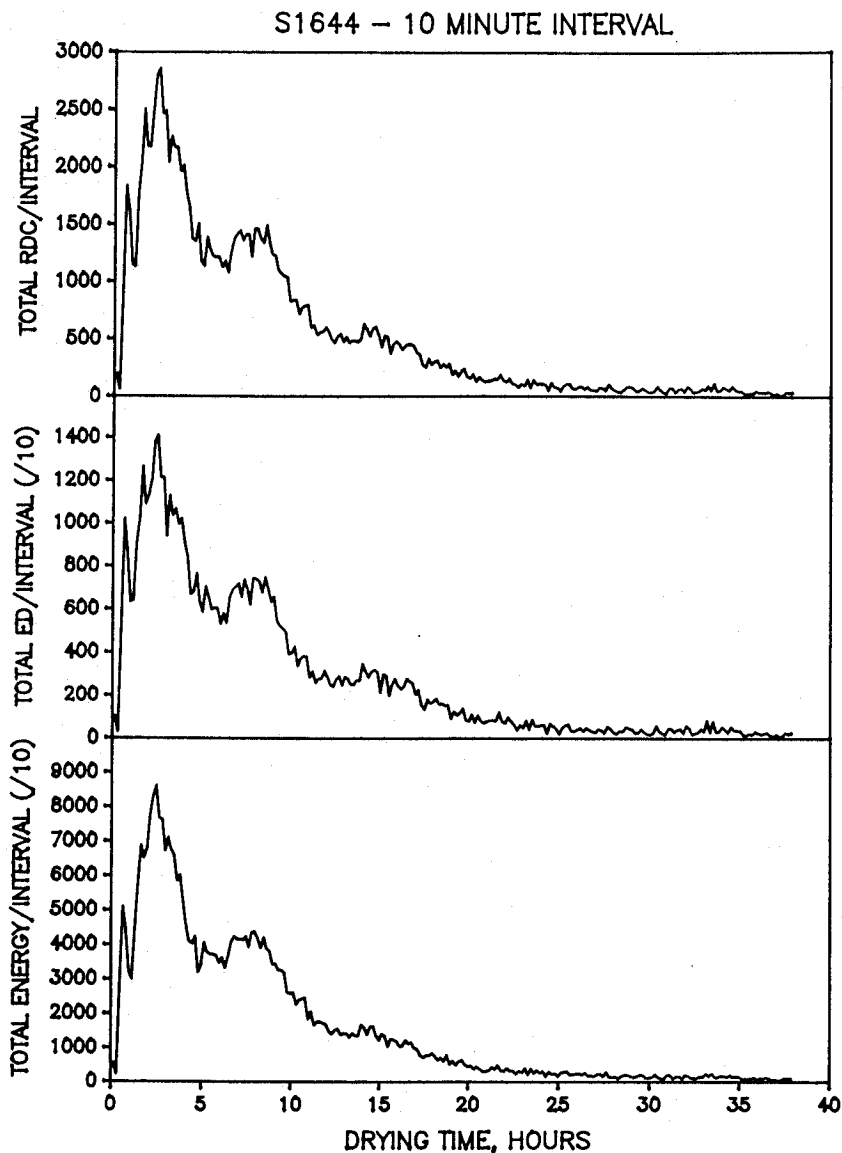
Figure 3.   Ring-down count, event duration, and energy data for the 4/4 specimen. The drying time was approximately 38 hours and the kiln conditions were $180°/110°$ F.
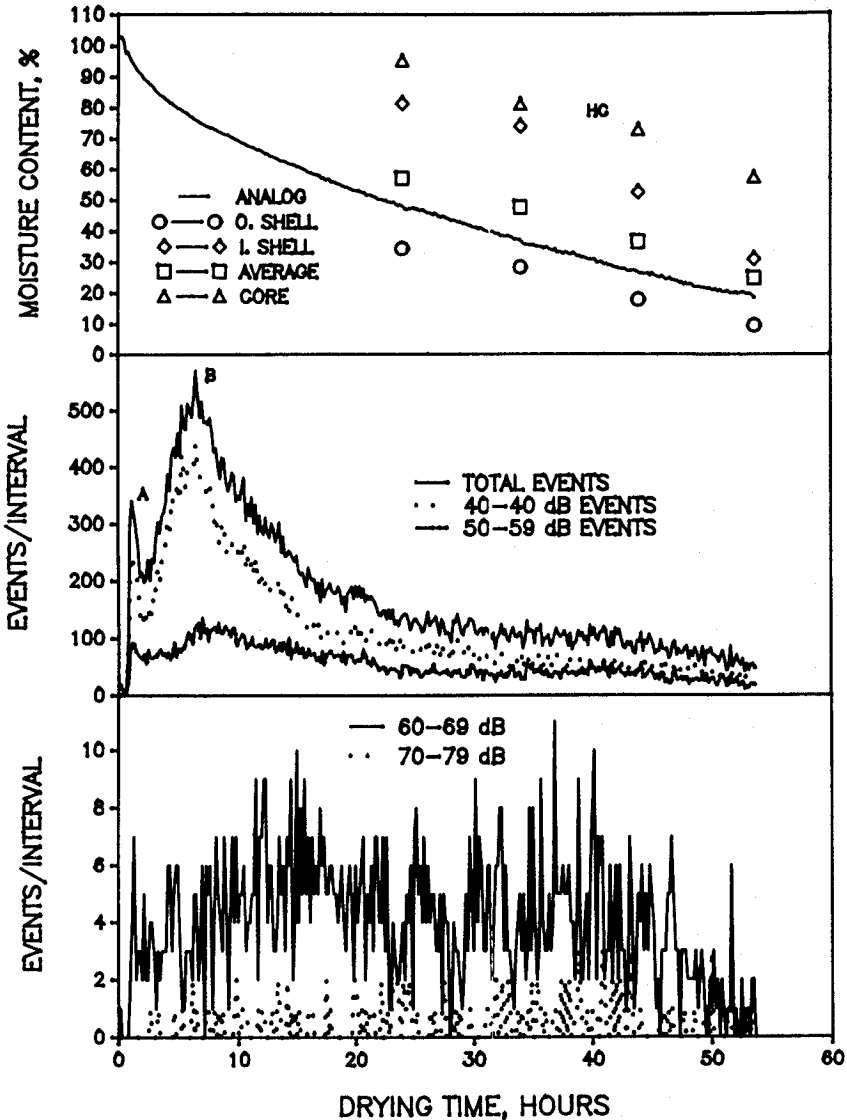
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Figure 4. Moisture content and event rate data for the 8/4 specimen. The drying time was approximately 54 hours and the kiln conditions were 180°/110°F. The approximate time associated with the initiation of internal checking (honeycombing) is indicated on the moisture content plot by "HC".
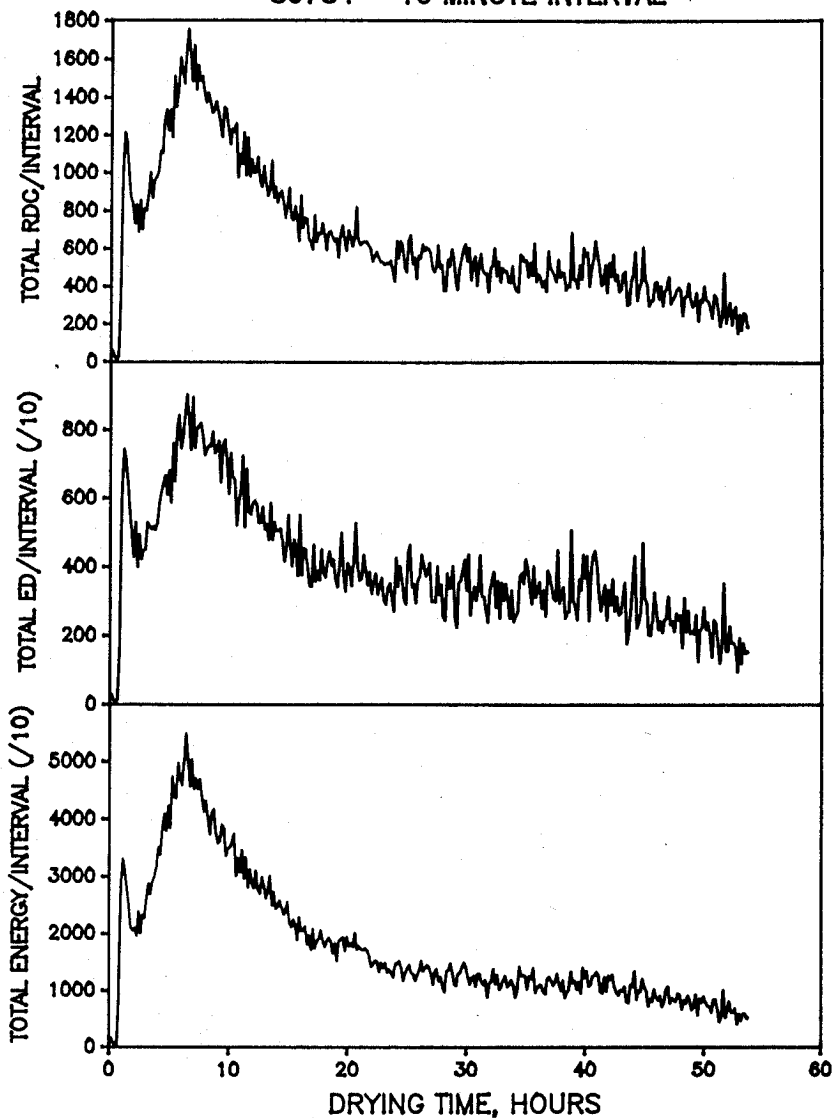
Figure 5.   Ring-down count, event duration, and energy data for the 8/4 specimen. The drying time was approximately 54 hours and the kiln conditions were 180° /110° F.

surface region. Subsequent increases in event rate are probably related to the initiation and propagation of surface checks, although a consistent and repeatable pattern has thus far been elusive. Information contained in other time-domain AE measures (e.g., ring-down counts and event duration) are similar to that contained in the event rate data, and therefore does not provide additional useful information.

Surface mounted transducers did not detect the AE activity associated with the internal checking that occurred relatively late in the drying run.

In time AE should become a viable alternative as a process control technique. This author believes that certain issues must still be resolved before an AE-based system can be successfully implemented.

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