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DELAMINATION AND TRANSVERSE CRACKING IN  
GRAPHITE/EPOXY LAMINATES BY ACOUSTIC  
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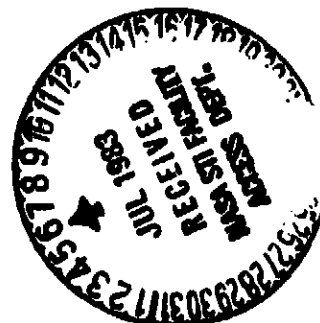
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May 1983



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# CHARACTERIZATION OF DELAMINATION AND TRANSVERSE CRACKING

## IN GRAPHITE/EPOXY LAMINATES BY ACOUSTIC EMISSION

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### ABSTRACT

A study has been made to characterize and differentiate between two major failure processes in graphite/epoxy composites - transverse cracking and Mode I delamination. Representative laminates were tested in uniaxial tension and flexure. The failure processes were monitored and identified by acoustic emission (AE). The effect of moisture on AE was also investigated. Each damage process was found to have a distinctive AE output that is significantly affected by moisture conditions. It is concluded that AE can serve as a useful tool for detecting and identifying failure modes in composite structures in laboratory and in service environments.

### INTRODUCTION

One of the major complications in the study of the mechanics of composite materials is the multiphase failure behavior. Generally, four failure modes can act separately or simultaneously, namely, fiber failure, matrix failure, fiber-matrix interfacial debonding, and interply delamination. The main problems from an analytical and experimental point of view are: (1) how to distinguish between the different failure modes, and (2) how to assess the

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individual and combined contributions of the failure modes to the overall failure process.

In most laminates, initiation and ultimate failure will occur at a load level significantly below the fiber strength. On the other hand, matrix failure is frequently associated with shear stresses that control yielding and viscoelasticity of the ductile polymer. In general, most failures start as intraply cracking (transverse cracking) and/or interply delamination [1-8].

The main objective of this investigation is to develop the methodology for on-line characterization, detection, and follow-up of transverse cracking and delamination by the acoustic-emission (AE) method. In addition, the effect of a hygrothermal environment on these failure modes and AE response was also studied.

## TEST PROCEDURE

### Transverse Cracking

The test specimens were designed to have a 90° ply at the external surfaces so that transverse cracks can be easily identified. Tri-directional Laminate (90 / ±45 / 90)<sub>2s</sub> made of AS/3501 material was used and specimens were initially tested under uniaxial tensile and flexural loading. Based on these preliminary tests, it was determined that uniaxial tensile loading led to complex AE response because of the simultaneous cracking of all 90° layers. Hence, it was decided to use 4-point flexural loading, where only a single layer (at the external surface) along a relatively small gage length would be subjected to the maximum tensile stress. In this way the cracking process could be easily isolated and monitored by AE, at least during initial loading.

Specimens were vacuum dried at 70°C for several weeks. Then, some were immersed in 70°C water for a few weeks to develop a moisture content of about 1.0%. Tests were conducted at room temperature. During loading, the AE

response was recorded using a 175-kHz resonant sensor attached to the specimen. In addition, load versus strain or crosshead displacement was recorded. A constant displacement rate of 0.025 mm/sec was kept during the test. In several cases, the load was held constant at various stages of cracking to enable duplication of the cracking pattern using a replicating tape technique [2].

#### Mode I Delamination

To study Mode I delamination behavior, double-cantilever-beam (DCB) specimens were prepared from specially fabricated laminates of T300/934. A mylar tape was inserted into one end at the desired interface to help initiate delamination. Following cure, the specimens were vacuum dried at 70°C for several weeks. Tests were conducted on dry specimens, on specimens exposed to 70°C/95% relative humidity, and on specimens immersed in 70°C water for varying times. All tests were performed under displacement-controlled conditions. The crosshead speeds were initially 0.08 mm/sec for short cracks and increased to 0.25 mm/sec for long cracks (beyond 90 mm). The load was applied until some predetermined delamination growth had occurred and the specimen was unloaded. This process was repeated. During delamination growth, AE response was recorded using a resonant sensor attached to the specimen.

### RESULTS AND DISCUSSION

#### Transverse Cracking

Typical AE outputs for dry and wet specimens obtained during continuous-loading tests are shown in Fig. 1. A significant difference in AE response between dry and wet specimens is apparent. The typical crack density observed in the external 90° ply at various levels of flexural strain is shown in Fig. 2 for wet and dry specimens. The corresponding AE counts as a function

of flexural strain is shown in Fig. 3. As can be seen, crack initiation occurs earlier in dry specimens. Crack density increases almost linearly with strain in dry and wet specimens. However, at high crack densities, cracking appears to slow down and approach saturation. At the lower strain levels, total AE counts also increase linearly with strain, suggesting a direct relationship between AE and transverse cracking. Generally, lower rms peaks (Fig. 1), lower crack density (Fig. 2), and fewer AE counts (Fig. 3) are observed in the wet specimens, for a given strain level, as compared with their dry counterparts.

Using an analysis similar to the one presented by Harris et al. [9], the total number of AE counts,  $N$ , can be related to applied strain,  $\epsilon$ , as follows:

$$N = B\epsilon \ln(\epsilon/\epsilon_0) \quad (1)$$

where  $\epsilon_0$  is the threshold value of strain below which no counts are observed and  $B$  is a constant of proportionality. For dry and wet specimens,  $\epsilon_0$  was found to be 0.0045 and 0.0059, respectively, and  $B$  was found to be  $5 \times 10^6$  counts and  $2.56 \times 10^6$  counts, respectively. In Fig. 3, the number of counts as predicted analytically by Eq. 1 shows good agreement with experimental results, especially in the case of wet specimens.

#### Delamination

Typical AE response of dry and wet specimens during delamination growth is presented in Fig. 4. As can be seen, the rms peaks from the dry specimens were again higher than for wet specimens. Moreover, in the dry specimens the rise of the rms signal appears to be sudden near the maximum load, whereas in the wet specimens, the rms signal rises slowly as maximum load is approached. It is interesting to note that the number of AE counts varies linearly with delamination growth as seen in Fig. 5 (shown only for a few dry specimens).

The number of layers has no appreciable effect on AE response. The moisture was found to reduce the AE counts, as shown in Fig. 6.

#### CONCLUSIONS

From the foregoing studies it may be concluded that:

1. AE characteristics are different for transverse cracking and delamination. In delamination AE response is continuous with damage growth, whereas transverse cracking is characterized by a discontinuous AE response.
2. Total AE counts vary almost linearly with delamination growth and with the density of transverse cracks at low strain levels.
3. In both delamination and transverse cracking, moisture was found to reduce AE response per unit of damage growth (both total AE counts and rms peaks).
4. During delamination growth, the total number of AE counts is unaffected by specimen thickness.

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9. D. O. Harris et al., ASTM STP 505, 238 (1971).

Figure Titles

Fig. 1. Typical acoustic emission output for dry and wet graphite/epoxy specimens (AS/3501, 90/±45 ) loaded in flexure (indication of transverse cracking only).

Fig. 2. Transverse crack density versus flexural strain for dry and wet graphite/epoxy specimens (AS/3501, 90/±45 ) loaded in flexure.

Fig. 3. Total AE counts versus flexural strain for dry and wet graphite/epoxy specimens (AS/3501, 90/±45 ) loaded in flexure.

Fig. 4. Typical AE response for dry and wet specimens during delamination growth (T300/934, U.D.).

Fig. 5. AE counts versus delamination growth (T300/934, U.D.).

Fig. 6. AE counts versus moisture content of specimen during delamination (T300/934, U.D.).

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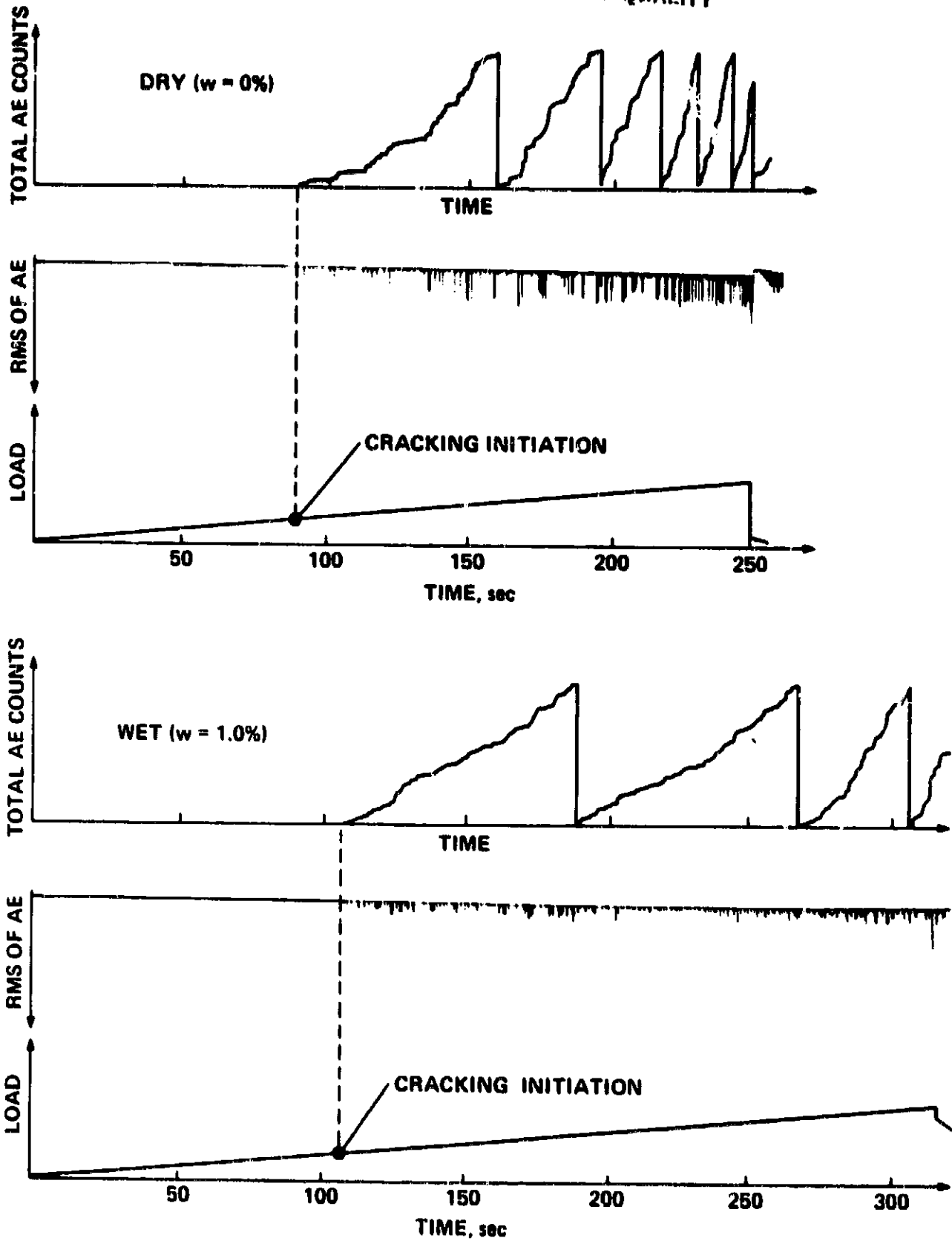


Fig. 1.

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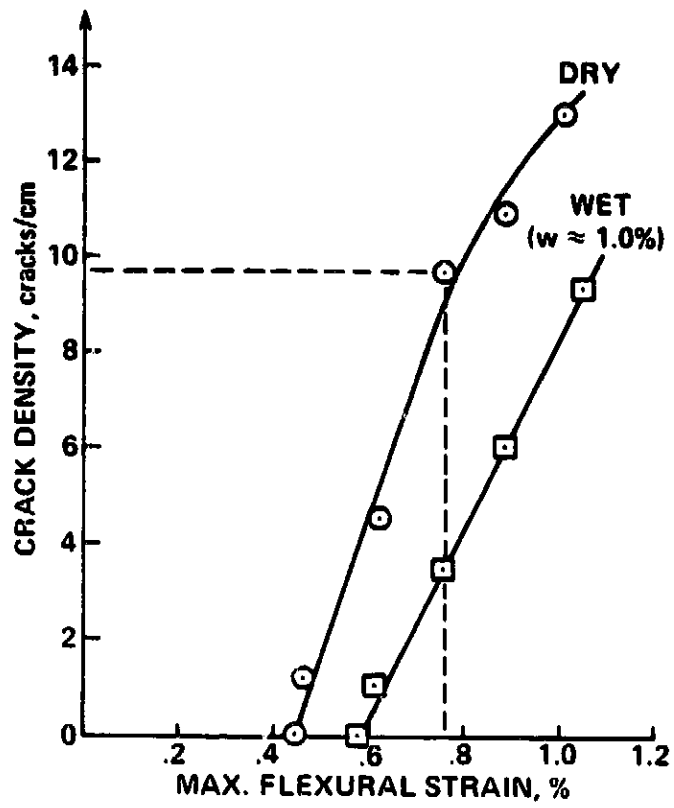


Fig. 2.

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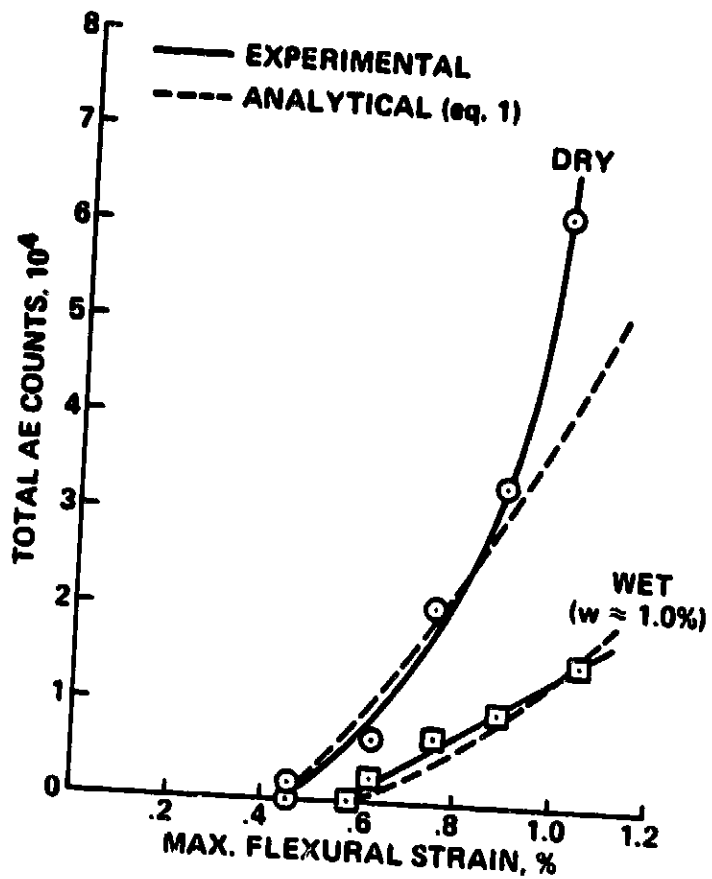


Fig. 3.

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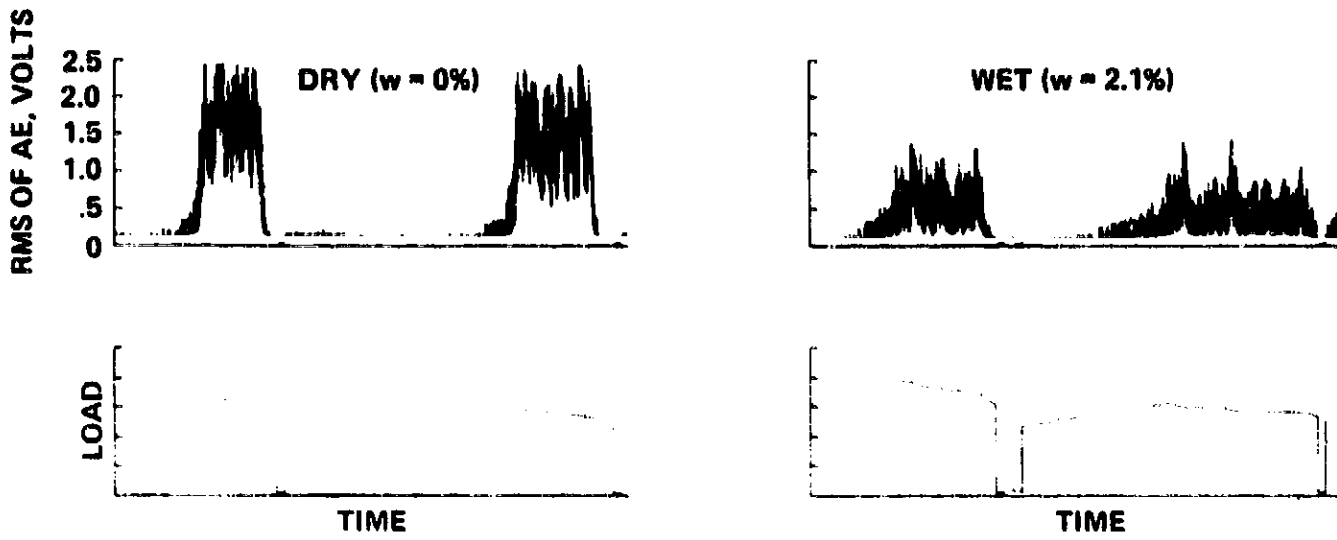


Fig. 4.

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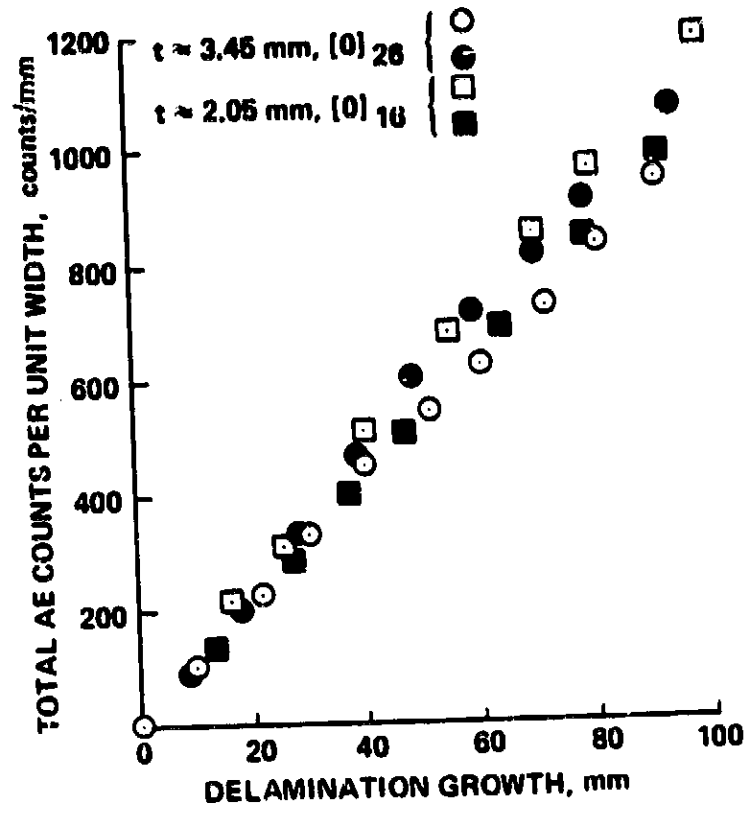


Fig. 5.

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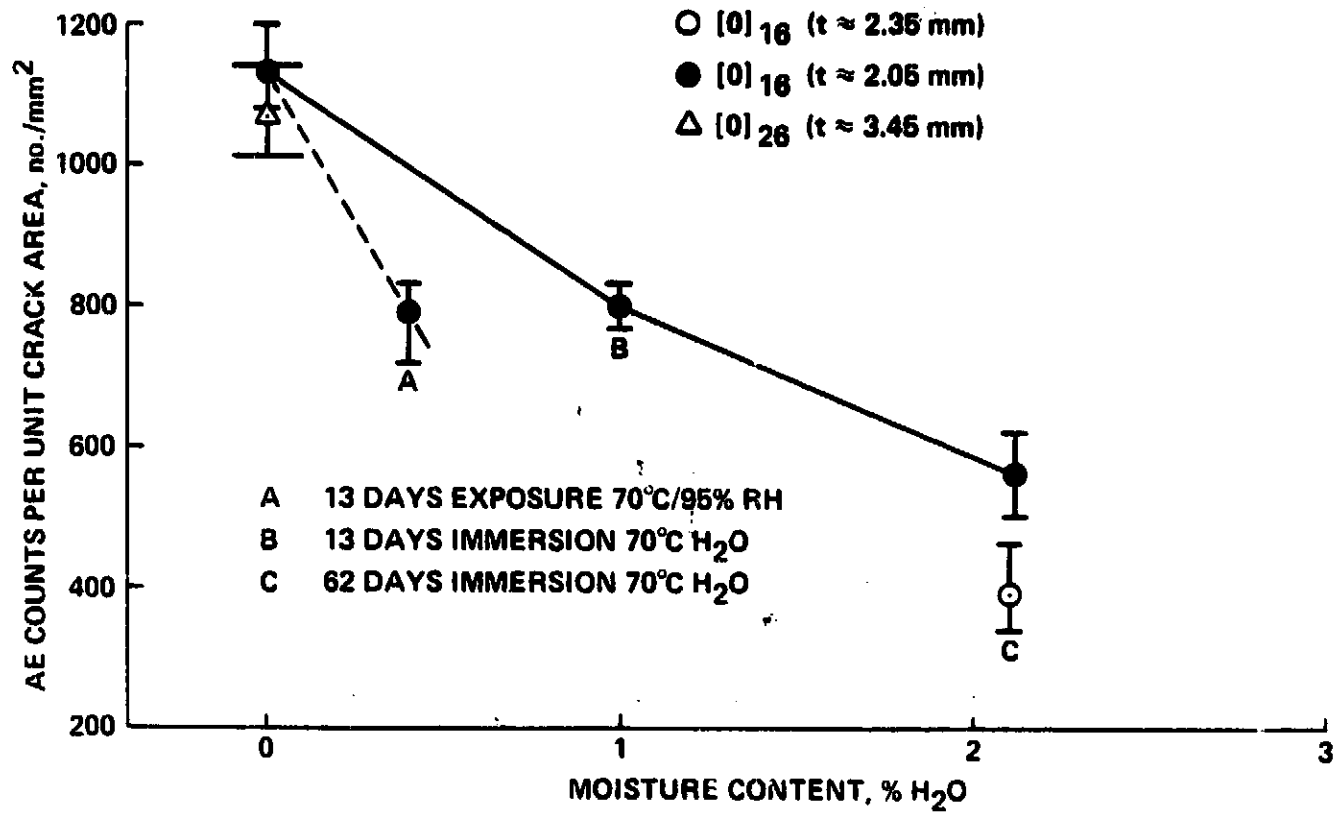


Fig. 6.