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L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

APPLICATION OF ACOUSTIC EMISSION TO HYDRIDE CRACKING

Application de l'émission acoustique pour l'étude de la fissuration de l'hydrure

S. SAGAT, J.F.R. AMBLER and C.E. COLEMAN

Presented at 29th Acoustic Emission Working Group Meeting
The Royal Military College of Canada, 1986 June 23-26

Chalk River Nuclear Laboratories

Laboratoires nucléaires de Chalk River

Chalk River, Ontario

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APPLICATION DE L'ÉMISSION ACOUSTIQUE POUR L'ÉTUDE DE LA FISSURATION DE L'HYDRURE

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RÉSUMÉ

On applique l'émission acoustique depuis plus d'une décennie pour étudier la fissuration retardée de l'hydrure (DHC) dans les alliages de zirconium.

On s'est d'abord servi principalement de l'émission acoustique pour détecter le début de la fissuration retardée de l'hydrure. Il a été possible de le faire étant donné que la fissuration retardée de l'hydrure était accompagnée d'une très faible déformation plastique du matériau et, en outre, l'amplitude des impulsions acoustiques produites lors de la fissuration en phase fragile de l'hydrure était beaucoup plus forte que celle produite par le mouvement de dislocation et le macalge.

On s'est également servi de l'émission acoustique pour mesurer la propagation des fissures lorsqu'on a constaté que, pour un seuil d'amplitude convenable, le total des coups d'émission acoustique était en relation linéaire avec la surface fissurée. Une fois qu'on avait déterminé la constante de proportionalité, on pouvait convertir les coups d'émission acoustique en longueur de fissuration.

On se sert maintenant de la proportionalité entre le taux de comptage et la vitesse de propagation des fissures en plus de la technologie informatique pour obtenir la réaction entre la longueur de fissuration et la charge appliquée. Dans un système de ce genre, on peut maintenir constante la contrainte à l'extrémité de la fissure lors de l'essai en règlant la charge appliquée à mesure que la fissure évolue-ou on peut la modifier d'une façon déterminée d'avance, par exemple pour mesurer la contrainte de seuil de fissuration.

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ABSTRACT

Acoustic emission has been used for over a decade to study delayed hydride cracking (DHC) in zirconium alloys.

At first acoustic emission was used primarily to detect the onset of DHC. This was possible because DHC was accompanied by very little plastic deformation of the material and furthermore the amplitudes of the acoustic pulses produced during cracking of the brittle hydride phase were much larger than those from dislocation motion and twinning.

Acoustic emission was also used for measuring crack growth when it was found that for a suitable amplitude threshold, the total number of acoustic emission counts was linearly related to the cracked area. Once the proportionality constant was established, the acoustic counts could be converted to the crack length.

Now the proportionality between the count rate and the crack growth rate is used to provide feedback between the crack length and the applied load, using computer technology. In such a system, the stress at the crack tip can be maintained constant during the test by adjusting the applied load as the crack progresses, or it can be changed in a predetermined manner, for example, to measure the threshold stress for cracking.

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APPLICATION OF ACOUSTIC EMISSION TO HYDRIDE CRACKING

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1. INTRODUCTION

The fuel channels in Canadian power reactors are made of Zr-2.5 Nb alloy. Zirconium alloys dissolve hydrogen in large quantities but they form zirconium hydrides if the solubility limit is exceeded. The hydride phase has very low ductility and under some conditions can embrittle the components made of zirconium alloys. Two types of embrittlement have been recognized. The first is a reduction in ductility and fracture toughness below 520 K if sufficient hydride phase is present while in the second, cracking progresses stably under static load conditions; this latter is called "Delayed Hydride Cracking", (DHC). It has been postulated that DHC occurs by repetition of the following processes (1):

- stress-induced migration of hydrogen and precipitation of the hydride at a flaw tip
- growth of the hydride phase, and
- fracture of the hydride after reaching a critical state.

Our objective is to understand DHC in zirconium alloys and to investigate different methods that would reduce the susceptibility of these alloys to this type of embrittlement.

2. ACOUSTIC EMISSION FROM HYDRIDE CRACKING

Acoustic emission (AE) has been used successfully (2) to measure the following parameters:

- time from the start of the test until the onset of cracking (incubation time),
- relative crack growth rates, and
- the minimum load necessary for crack growth.

DHC is studied using notched single and double cantilever beam specimens machined from Zr-2.5 Nb pressure tubes. Hydrogen is added gaseously to the specimens up to a concentration of 1 at% (100 ppm). The specimens are tested in test rigs shown schematically in Figure 1. The cantilever beam specimen is held by two grips while the double cantilever beam specimen is attached to pull rods using pins. The stress conditions at the specimen notch are described in terms of elastic fracture mechanics as "stress intensity factor", K_I (Appendix I). The transducer is fastened to the grips or the pull rods. The signal from the transducer is preamplified and fed into an analyzer providing additional gain, filtering and counting.

3. MEASUREMENT OF CRACK GROWTH

Crack growth was estimated by measuring the number of acoustic emission events produced by a unit area of cracking. A series of crack growth tests under nominally identical conditions (temperature of 475 K and load of 1070 N) were performed on a double cantilever beam specimen. After AE indicated a sufficient amount of cracking, the specimen was broken open (Figure 2), and the cracked areas were measured and the calibration constants determined (Table 1 and Figure 3). The calibration held reasonably constant for all tests but the last two, in which the fracture was accompanied by an increased amount of plastic deformation.

Tests performed at different temperatures showed that the calibration constant was insensitive to temperature and K_I (Table 2). The calibration constant, however, was different in different tubes and in different alloys (Table 2).

The calibration may vary between different AE set-ups and hence, the calibration constant must always be established for the particular apparatus.

In DHC of Zr-2.5 Nb alloys, the total AE count, N, is proportional to the cracked area A

$$N = C.A = C.W.L$$

where C is the calibration constant, W is the thickness of the specimen and L is the crack depth.

Assuming a plane crack front, the crack depth, L, is given by

$$L = N/(C.W)$$

AE emission generated from the fracture of metals is dependent on the fracture mechanics parameters such as K_I (3). The independence of AE on K_I in these experiments is unique to DHC process in which the crack growth rate is insensitive to K_I in the steady-state crack growth regime.

4. FEEDBACK BETWEEN AE COUNTS AND THE APPLIED LOAD

The linear relationship between the total number of acoustic counts and the cracked area, led to the use of a computer to provide a feedback between the measured crack length and the applied load.

Figure 4 shows a schematic diagram of the experiment with computer control for cantilever beam specimens. The load was applied via a slotted nut driven by a stepping motor. The nut screwed onto a fine thread screw rising from the load cell through a clearance hole in the arm. By rotating the nut clockwise, the arm was pushed down, applying a bending moment on the specimen while the load cell measured the applied load. During the test, the current crack length was calculated from the acoustic emission using an appropriate calibration constant. The K_I was calculated from the measured load, crack length, and the specimen cross-sectional area. Since the computer kept track of all these variables, an appropriate action such as changing the load or switching the furnace off could be taken anytime during the test. This allowed tests to be performed at a constant or reducing K_I and the test could be terminated automatically.

As a crack grows in a cantilever beam specimen, K_I increases unless the load is reduced. (This load reduction is not necessary in the double cantilever beam specimen which compensates for the increase in crack length by an increase in cross-sectional area through its tapered shape.) Figure 5 (a) shows the results from a crack growth test on a cantilever beam specimen in which K_I was maintained constant by computer control. The test temperature was 475 K and the initial K_I was 17.5 $MPa\sqrt{m}$. After an incubation time of 0.3 h, the crack started to grow and continued to grow at a constant rate of 4.5 mm/day. The crack length did not increase with time in a continuous manner but in a step-wise fashion, indicating the intermittent nature of the cracking process. The distribution of acoustic emission bursts converted into crack length increments is shown in Figure 5 (b). It ranges from 0.15 μm (about 100 counts) to 4 μm (about 2800 counts). A calibration constant of 2.46×10^{11} counts/m^2 was used in this test. The actual calibration constant was obtained after the specimen was broken open and the DHC fracture area measured. Dividing the total number of counts by the fracture area gave a value of 2.77×10^{11} counts/m^2, which is about 13% different from the calibration constant used in the test. This error in the calibration constant meant that K_I was not maintained perfectly constant during the test but changed from the initial value of 17.5 $MPa\sqrt{m}$ to 16.8 $MPa\sqrt{m}$ (4% difference). Without the computer control, the final K_I would have been 26 $MPa\sqrt{m}$ (49% difference).

To measure the minimum load for crack growth (or the threshold K_I value denoted as K_{IH}), a specimen was heated to 473 K and initially loaded to a K_I of 17.5 $MPa\sqrt{m}$ and every time the crack grew 5 μm, K_I was reduced by 2%. The crack stopped growing at K_I of 5.7 $MPa\sqrt{m}$ and no cracking was observed for the next 114 h (Figure 6).

5. CONCLUSIONS

Acoustic emission has been successfully used not only to detect the onset of hydride cracking but also to measured crack growth in Zr-2.5 Nb alloys.

Total AE count during DHC is proportional to the area of cracking.

The variability of the calibration constant in nominally identical tests is about 16%.

The calibration constant has a weak dependence on temperature and K_I.

The calibration constant is different in each experimental set-up and also varies from material to material.

Proportionality between the AE count and the cracked area allows use of a computer to control K_I during DHC tests.

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(2) C.E. Coleman and J.F.R. Ambler, "Susceptibility of Zirconium Alloys to Delayed Hydrogen Cracking", Zirconium in the Nuclear Industry, ASTM STP 633, A.L. Lowe, Jr. and G.E. Parry, Eds., American Society for Testing and Materials, 1977, pp. 589-607, also as AECL Report-5942, Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, 1977.

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APPENDIX

Expressions used for Calculating the Stress Intensity Factors K_I (MPa m)

<u>Cantilever beam specimen:</u>

$$K_I = \frac{4.12\ M\ (X^{-3}\ \mathrm{x}\ X^3)^{\frac{1}{2}}}{B\ D^{3/2}} \cdot (B/B_n)^{\frac{1}{2}}$$

where M = net bending moment at the notch,
B = specimen breadth,
D = specimen depth,
A = depth of notch plus crack,
B_n = specimen breadth at side grooves,
X = 1 - A/D

<u>Double Cantilever Beam Specimen:</u>

$$K_I = P\sqrt{\frac{E}{2B}\left(\frac{dC}{dA}\right)}$$

where P = load,
E = Young's modulus,
B = specimen breadth,
$\frac{dC}{dA}$ is obtained from calibration where compliance C is measured as a function of crack length A.

Table 1: Variability in the Calibration Constant in Double Cantilever Beam Specimen Tested at 475 K and K_I of 15 MPa$\sqrt{m}$. Total gain on AE apparatus was 75 db.

Band*	AE Counts	AE Counts Cumulative	AE/Area Counts/m^2
1	268 710	268 710	7.53×10^{10}
2	215 870	484 580	6.81×10^{10}
3	303 890	788 470	6.37×10^{10}
4	243 800	1 032 270	6.53×10^{10}
5	284 700	1 316 970	7.17×10^{10}
6	289 900	1 606 870	6.25×10^{10}
7	187 800	1 794 670	2.92×10^{10}
8	130 100	1 924 770	1.41×10^{10}

The mean calibration constant in bands 1 to 6 is 6.78×10^{10} counts/m^2 with 95% confidence limits of the mean $\pm 5.2 \times 10^9$ counts/m^2 or $\pm$7.7% from the mean.

* See Figure 2

Table 2: The Effect of Temperature, K_I, and Material on the Calibration Constant. The Results were Obtained on Cantilever Beam Specimens.

Effect of Temperature

Gain = 90 db
K_I = 17.5 MPa$\sqrt{m}$
Temperature = 423 K and 523 K
Single Zr-2.5 Nb Specimen.

Temperature K	Calibration Constant counts/m^2
423	4.626×10^{11}
523	4.533×10^{11}

Effect of K_I

Gain = 95 db
Temperature = 523 K
Material: Zr-2.5 Nb, single specimen

K_I, MPa$\sqrt{m}$	Calibration Constant counts/m^2
12	7.56×10^{11}
15.5	7.85×10^{11}
20	6.91×10^{11}

Effect of Tube

Gain = 90 db
K_I = 17.5 MPa$\sqrt{m}$
Temperature = 523 K
Material: Zr-2.5 Nb

Tube	Calibration constant counts/m^2
X	$(4.498 \pm 0.36) \times 10^{11}$
349	$(3.305 \mp 0.44) \times 10^{11}$

Effect of Alloy

Gain = 90 db
K_I = 17.5 MPa$\sqrt{m}$
Temperature = 523 K

Material	Calibration Constant counts/m^2
Zr-2.5 Nb	$(3.852 \pm 0.42) \times 10^{11}$
XL	$(6.184 \mp 1.60) \times 10^{10}$

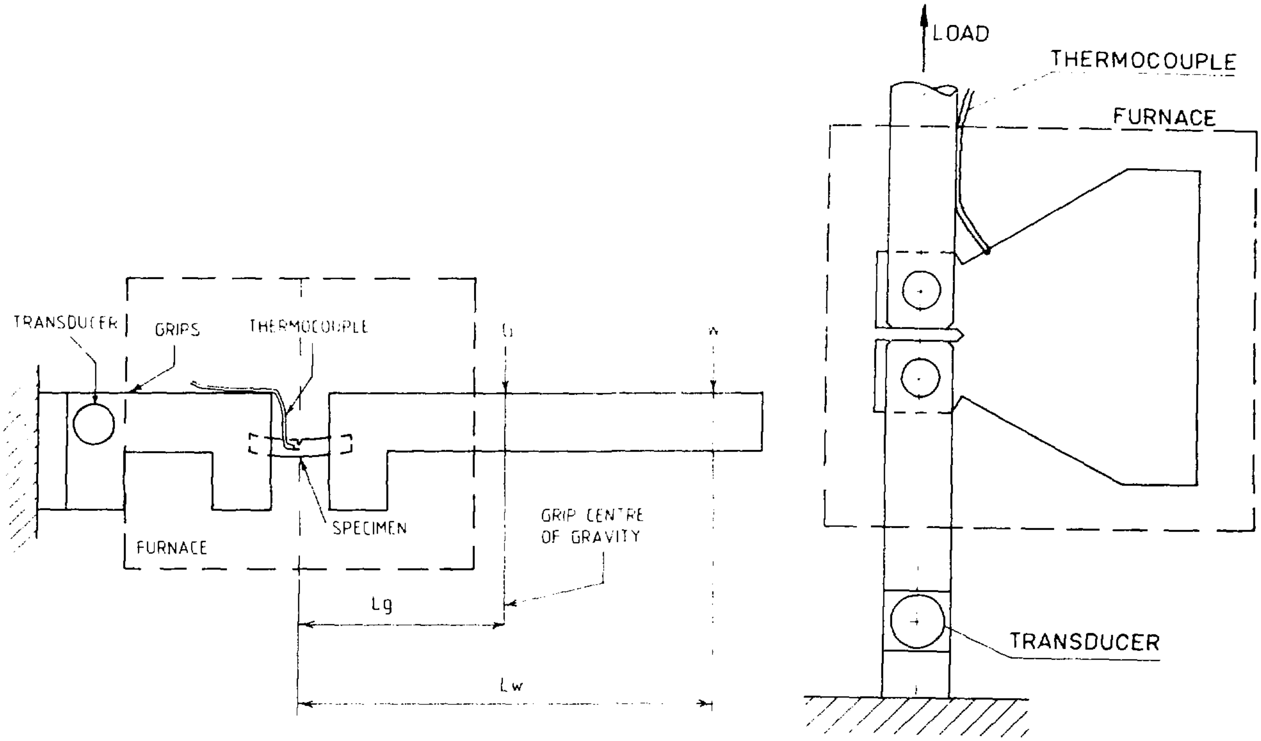


Figure 1: Schematic diagram of test set-ups in DHC testing using cantilever beam (left) and double cantilever beam specimens (right).

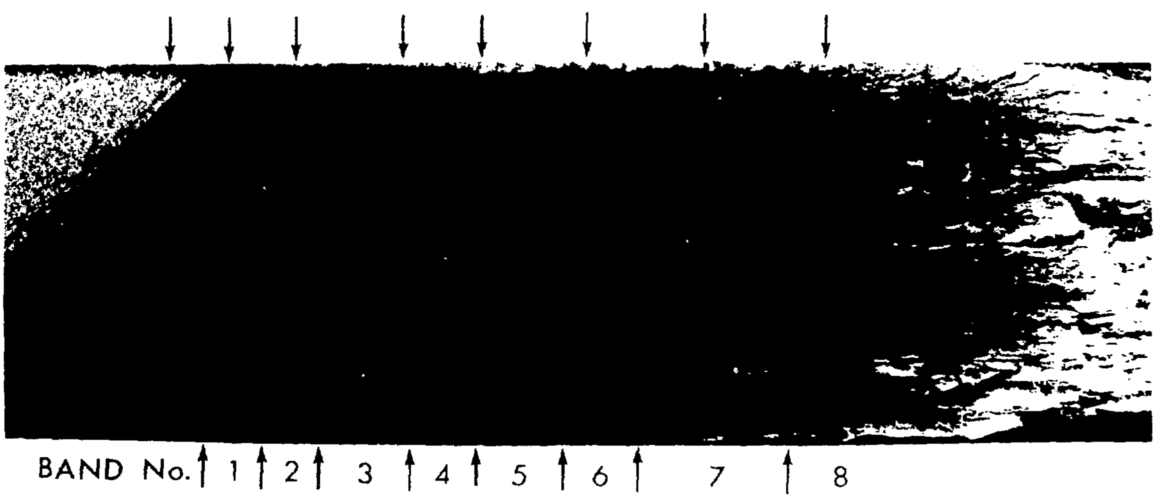


Figure 2: Fracture surface of a Zr-2.5 Nb double cantilever beam specimen after a series of eight, nominally identical crack velocity tests at 475 K and K_I of 15 MPa$\sqrt{m}$.

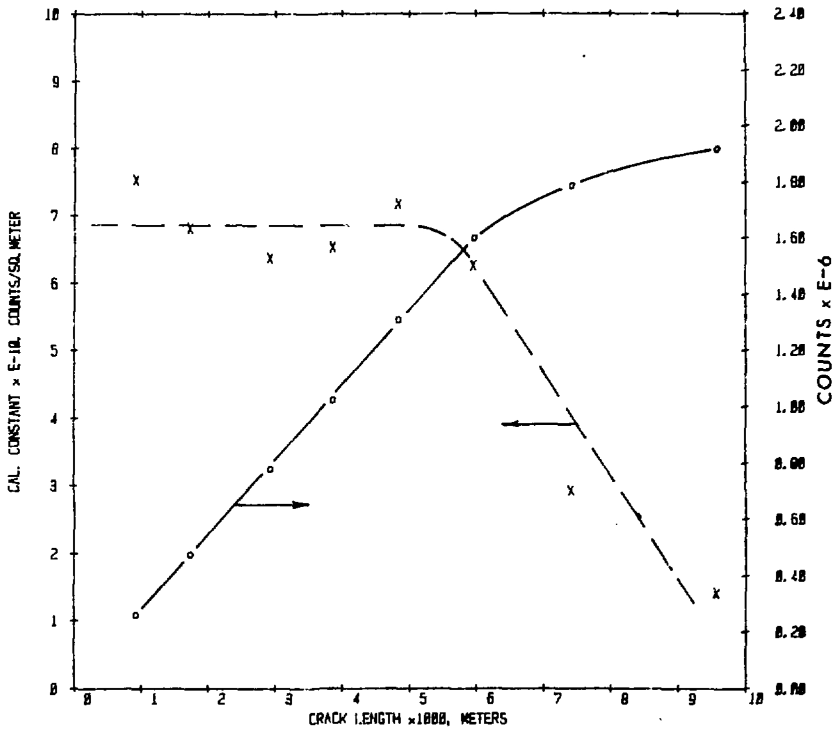


Figure 3: Calibration constant and cumulative counts as a function of crack length from Table 1.

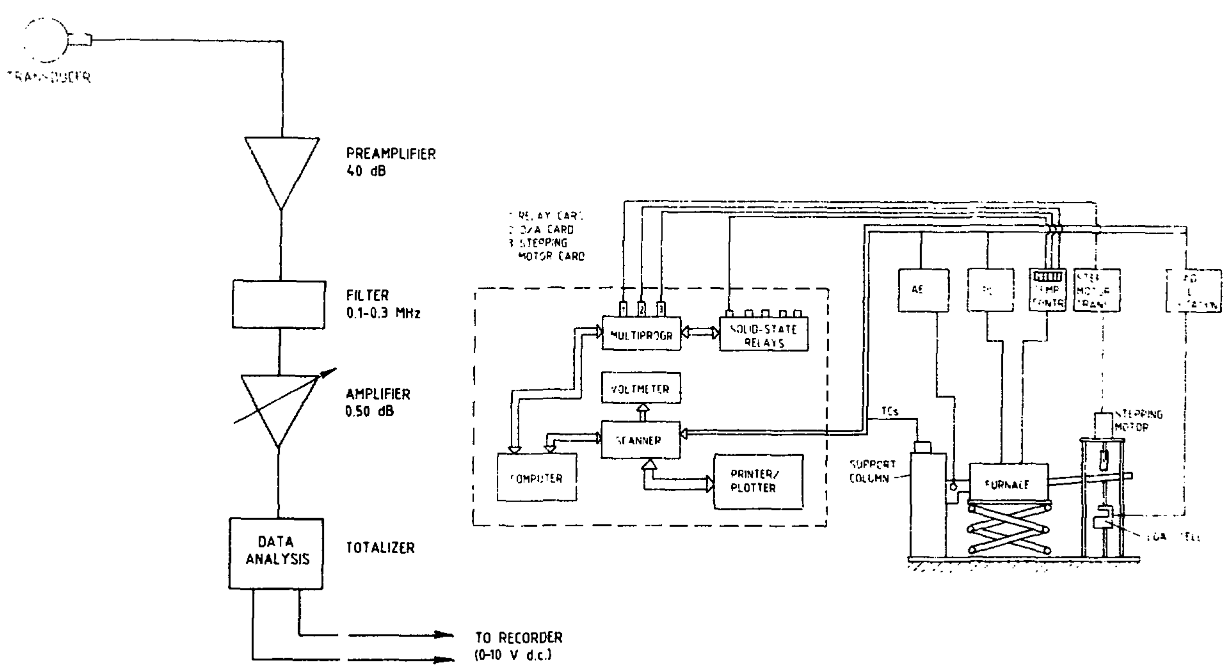
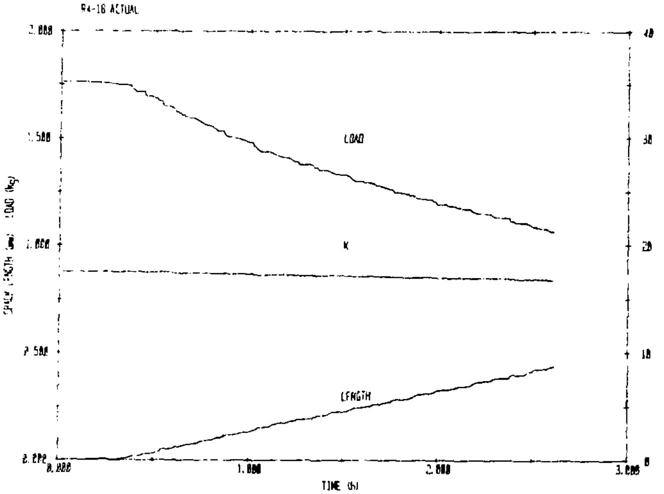
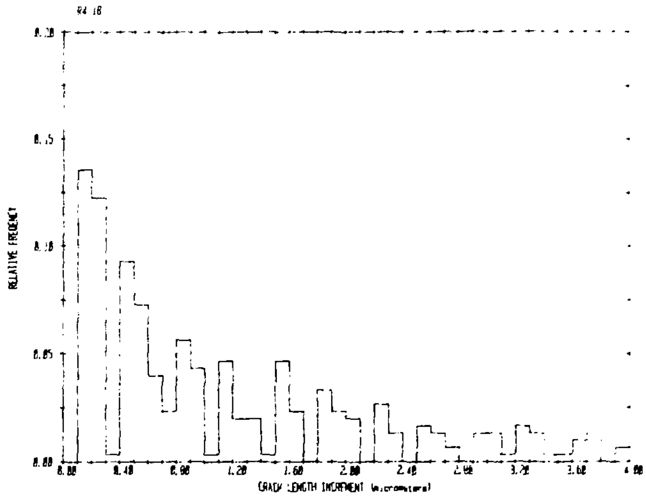


Figure 4: Schematic Diagram of the AE apparatus and the computerized DHC Rig.



a)



b)

Figure 5: DHC results on Zr-2.5 Nb cantilever beam specimen tested at nominal K_I = 17.5 MPa$\sqrt{m}$ and 523 K:

a) crack length and the load versus time
b) crack increment (AE bursts) distribution.

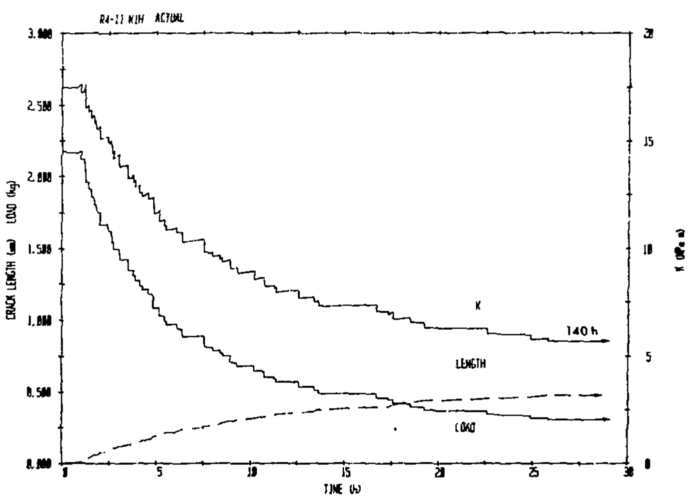


Figure 6: Measurement of the threshold stress intensity factor using AE to control the applied load. Every time the crack extended 0.005 mm, the load was reduced by 2% until cracking stopped. The corresponding K_I of 5.7 MPa$\sqrt{m}$ is the threshold stress intensity factor.

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