# An Overview of the Metallurgical Investigations into the Failure of Darlington NGS Unit 2 Fuel Bundle End Plates

E.G. Price
AECL CANDU
2251 Speakman Drive
Mississauga, Ontario L5K 1B2
Canada

## 1.0 INTRODUCTION

In November 1990, difficulty was experienced in refuelling channel N12 of DNGS Unit 2. The carrier tube containing replacement fuel (from another channel) could only be inserted into the outlet end fitting with difficulty but fuelling could not be performed. The carrier tube was removed from the end fitting but in turn difficulties with the fuelling machine operation indicated fuel debris was trapped in the fuelling machine. When the carrier tube was fully removed from the fuelling machine at a later dat and the fuel from the carrier tube examined in the fuel bay, pieces of fuel elements were found among the intact replacement fuel. This finding led to the formation of an investigation team to determine the cause of the problem. The team which subsequently recommended an examination by television of the downstream end plates on outlet bundles of a number of channels. This inspection revealed other channels in columns 12 and 13 (either side of the midline of the reactor) in which the outlet bundle had cracked end plates. A typical diagram of cracking sketched from the video of the inspection is shown in Figure 1.

Following the detection of cracking a metallurgical committee was set up to support the activities of the N12 team. The nominal objectives of the committee were to determine:

- the mode of failure of the end plates
- when failure had occurred
- the type of stressing or metallurgical conditions that caused failure
- the heat transport conditions under which the cracks were formed

This overview describes the examination and test effort into damage cause. It involved the efforts of inspection teams at Darlington site, support fuel engineering at Ontario Hydro NOCSD, examination teams of AECL Chalk River and Whiteshell and test efforts at OHRD, and AECL-CANDU.

It should be noted that initially the investigation had been concerned with end plate cracking. However as more information on fuel bundle condition was obtained it was apparent that other types of fuel damage existed as follows:

- end plate deformation (doming, dishing or distortion)
- end plate fretting wear
- spacer pad wear
- bearing pad wear (which could indicate pressure tube wear).

Of these end plate doming and dishing had been observed in fuel exposed in Bruce reactors; spacer pad wear and bearing pad wear had been seen but not of the same magnitude; and end plate fretting wear was just detectable on Bruce bundles following further close examination.

## 2. THE FUEL BUNDLE AND THE FUEL STRING ENVIRONMENT

A typical Darlington fuel bundle is shown in Figure 2. This bundle design flat shoulders on the end caps to accommodate the outlet end holding latch and a staggered bearing pad arrangement on alternate outer elements. The element end caps are welded to the end plate in a slightly non-symmetrical pattern which differs from manufacturer to manufacturer.

The weld between the end plate and end cap is really a high temperature differsion bond induced by resistance heating under pressure. The weld region is slightly stronger than the parent metal. It consists of a core of recrystallized grains that have been heated into and cooled rapidly from the beta grain region and transformed to alpha. From the core region the prior beta grain size gradually decreases to a zone of recrystallized alpha grains which effectively outline the weld zone (Figure 3).

The Darlington Channel is similar to Bruce B and contains 13 bundles (Figure 4). These bundles are supported by a 4-piece latch which bears on the shoulders of the end caps of the outlet end bundle. Depending on the orientation of the bundle two or four elements will not be supported directly by the latch. The outboard bearing pad of the inlet end bundle is supported on a spacer ring between the pressure tube and the liner tube.

The axial load on the fuel imparted by the flow is carried by the latch. The inner element loads are transmitted through the end plates to the outer elements which will carry a load which increases from inlet to outlet end. With high temperature operation, creep deflection of the end plates can lead to contact between the central regions of the adjacent end plates and this will increase the load on the central region of the downstream end plates (load "shedding").

It is obvious that the latch loading of the outer elements and the dished geometry of the bundles allows the inner elements to move axially with respect to the outer from axially varying forces restrained by the end plates.

## 3. PRELIMINARY INVESTIGATIONS

Due to fuelling machine problems, the observed damaged fuel could not be examined for some time and the videos of outlet end plates were the only inspection information available. An initial series of programs were started that investigated the potential for failure from one or more of the following causes or mechanisms:

- cracking due to initial (manual) fuel loading procedures
- cracking due to zirconium hydride phenomena (delayed hydride cracking)
- manufacturing problems
- accelerated corrosion in the crevice of the end cap to end plate weld
- embrittlement due to hydrogen or nitrogen or other elements
- fatigue due to end plate cyclic deflection from load cycles induced by start-up and shut-down flow cycles

3.1 Manual Fuel Loading Practice

First charge fuel bundles are inserted through the inlet end and slide along the pressure tube on a stainless steel shim until they contact the latch or the preceding bundle. It was surmised that the #1 fuel bundle may at times have hit the latch with sufficient force that the inertia of the inner elements may not have been absorbed by elastic deformation of the end plates and cracking resulted. Attempts to produce such cracking in test channels at site and in channels at Sheridan Park Engineering Laboratories did not reproduce the cracking. Specimen tests on end plate to end cap welds showed that at impact energies greater than could be experienced on impacting the latch, cracking that could be produced was in the form of shallow ductile tears without the characteristics of the end plate cracking.

3.2 Delayed Hydride Cracking

Delayed hydride cracking (dhc) is a phenomena seen in Zr-2.5% Nb pressure tubes but only rarely in the more ductile Zircaloys used for fuel components. In Zircaloy, d.h.c. can be produced in the laboratory but not as easily as with the higher strength Zr-2.5% Nb alloy. The conditions to cause it are a hydrogen concentration in the metal in excess of the terminal solid solubility; a stress intensity in excess of a threshold value, and an incubation time. Although the fuel had been fabricated about three years before use, an evaluation of the potential for d.h.c. concluded that the conditions were unlikely to have caused cracking and any cracking at room temperature, due to the low velocity of d.h.c. at room temperature, would progress extremely slowly. On heating, the available hydrogen would go into solution and cracking would stop for this reason.

No d.h.c. testing program was initiated because of this conclusion.

### 3.3 Embrittlement

The video indicated low ductility cracking had developed in the end plates close to weld positions. The possibility of hydrogen, nitrogen and oxygen causing such embrittlement was investigated by chemical analyses and microstructural examination of fuel fabricated over the same time period as the failed fuel. No out-of-specification analyses were observed and metallographic examination failed to show any evidence of hydride or other element segregation. Oxidation in the weld notch was not great enough to cause embrittlement. Subsequently specimens of end cap to end plate welds were hydrided to confirm that the pattern of hydride precipitation was not such as to produce a zone of weakness either side of the weld in the end plate which may have been produced by residual stresses from welding.

### 3.4 Manufacturing

The fabrication process at the manufacturer of the majority of the failed fuel, G.E. Canada, was reviewed in detail without finding any aspects of the weld procedure that could lead to cracking. The assembly procedure met the requirements of the drawing, specification and approved procedures. However, it was subsequently established that within the drawing tolerances, the amount of dishing of the end plate was greater in one manufacturer than the others, and these differences affect the crept dimensions of end plate in service and likely the vibration characteristics of the fuel string.

### 3.5 Fatigue

A fatigue program was started to evaluate the effect of a significant number of start-up and shut-down cycles incurred during commissioning of Unit 2. The pattern of cracking seen in K12 suggested that the location of the latch could have an influence on the stressing pattern on the outlet end plate.

The initial program was performed at OHRD and evaluated the fatigue properties of the welds. It was initially to show that the number of shut-down/start-up cycles needed to cause failure by low cycle fatigue was much greater than those experienced. Loop tests simulating the startup/shutdown cycles produced the same result. This program then went on to develop the design criteria for fatigue failure of the end cap to end plate welds.

## 4. FRACTURE CHARACTERIZATION

Examinations of outlet end bundles at CRL, starting with pieces of the end plate of the N12 channel and continuing with failed bundles from the Q12 and K12 channels, showed that failure had occurred by fatigue. The fracture surfaces were generally characterized by a region of relatively featureless crack propagation (called a "black eye" from the SEM photographic image) followed by a region which contained "beachmarks" where the texture of the surface differed but the main crack propagation features were continuous through to adjacent bands (Figure 4). Over this region of surface, fatigue striations 0.5 - 2.0 microns were present. On some surfaces, particularly those of Q12, up to three crack arrest marks were seen indicating the driving force decreased below the fatigue threshold for a period at that stage of cracking.

The cracks mostly originated in the crevice formed between the end cap and the end plate by the welding. Crack initiation occurred slightly away from the trip of the crevice at the edge of the altered metal structure and progressed through the heat affected and weld region to the parent metal and through the plate.

The crack surfaces were relatively undamaged by post fracture rubbing and were covered with a thin oxide (< 2 microns).

Four main types of cracks were detected (Figure 6):

- those starting from the fissure of the weld close to the intersection of the radial arm and the intermediate ring. These generally produced an "anvil" type crack predominantly through the radial arm. Fracture surface oxide thicknesses were greater on these cracks than on others.

- those from a similar position but where the crack mostly progressed through the circumferential ring giving a "clamshell" appearance to the fracture surface.

- those originating from welds on the circumferential rings which tended to propagate in a radial direction.

- those which did not originate from a weld but from the outside surface and occurred on the radial arms or between pencils on the circumferential rings.

Overall the crack pattern analysis led to the following conclusions:

- practically all the cracks are consistent with stress patterns developed by axial oscillation of the inner pencils with respect to the outer pencils.

- failure occurred first in the region of end plate adjacent to the intersection of the radial and circumferential rings.

- the channels could be divided into two types - heavily damaged channels such as K12 and K13, and lightly damaged channels such as Q12 and N12. In the heavily damaged channels cracks occurred in nearly all areas of the end plate. With bundles from Q12 and N12 failure was predominantly near the intersection of the radial arm and the intermediate circumferential ring on the downstream end plate and on the inner ring of the upstream and plate.

- generally failure occurred as a continuous event.

- the absence of deformation even in the region of the final ligament indicated a high cyclic stress was not present. The flat fracture surfaces and absence of secondary cracking indicated cyclic stresses were just sufficient to cause cracking.

# 5. SUPPORTING TESTING PROGRAMS

## 5.1 Fatigue Design Data

As described in another session paper[1], the test program at OHRD was successful in establishing:

- the fatigue strength of the end cap to end plate welds subjected axial loadings. This showed that a fatigue notch reduction factor of 4 was produced by the geometry of the weld, from that produced in unnotched Zircaloy.

- the similarity in features of the fatigue failures indicated that the cyclic stress amplitude was just above the fatigue threshold amplitude. This would imply cyclic life between $4 \times 10^5$ and $10^7$ cycles.

- because of the notch, cracking started early in the cyclic life when the fatigue threshold amplitude was exceeded. At least 90% of the cyclic life was expended in growing a crack to the width of the circumferential ring.

- beachmarks were most easily produced by tests at 310°C in which the cyclic amplitude was slightly changed about a level just above the threshold value.

- the higher the cyclic amplitude the rougher the fracture surface and the greater the amount of associated deformation. Alternatively the closer the cyclic amplitude to the threshold level the flatter the surface.

- fatigue striations became finer than the resolution of the SEM when fatigue life exceeded $\sim 4 \times 10^5$ cycles.

- it was not possible to detect the effect of frequency on crack propagation characteristics above 1 Hz.

- the fatigue properties were similar at RT and 310°C and from manufacturer to manufacturer.

## 5.2 Other Fatigue Tests

Fatigue tests were carried out on complete fuel bundles on which cyclic axial loads were applied to a bundle loaded against a simulated latch.[2] These tests did not reproduce the cracking in the same location as field failures but the features of crack propagation were similar. They showed that the fatigue life was predictable from specimen tests. It also confirmed the crack growth-cyclic life predictions.

Fuel element transverse vibration was also investigated as a cause of failure by a series of fuel element deflection tests.[2] At lower amplitudes of vibration the fracture appearance was similar to that produced by simulated end plate bending. The fatigue transverse threshold and amplitude was just above the maximum possible amplitude of transverse vibration available to the fuel elements.

5.3 Dating of Fractures

The availability of infra-red spectral reflectance techniques allowed the oxide thicknesses to be measured at thicknesses too small to obtain accurate thicknesses metallographically (< 1.5 microns). By standardizing each fracture face oxide thickness measurement against the thickness on the adjacent region of the end plate, the time since cracking was estimated for the out-of-flux end plates of bundles #1 and #13. Although considerable difficulty was experienced in obtaining reliable data, the ultimate conclusion was that failure occurred after the reactor had reached full power and individual cracks on end plates occurred at intervals after the first crack.

5.4 Fretting Wear

In a number of Darlington channels fretting wear occurred between spacers, between end plates of adjacent bundles and between the bearing pads and the pressure tube. This fretting was undoubtedly the source of zirconium in the circuit as detected by gamma flux monitors.

Although no test programs were carried out that were initiated as a result of the Darlington problem, the data produced in CRL test programs studying bearing pad to pressure tube wear was made use of to interpret the Darlington fuel and pressure tube damage.

Zirconium fretting wear has the following characteristics when tested in low oxygen water:

(a) large variation in fretting rate under seemingly identical conditions. For example bearing pad to pressure tube wear ratios can vary from 1 to 3 to as high as 3 to 1.

(b) A variable effect of oxide. An initial layer of oxide reduces fretting wear at lower temperatures. The effect was small at higher temperatures (~ 300°C).

(c) A strong dependence of fretting rate on vibration amplitude with amplitudes in excess of 200 microns causing wear rates an order of magnitude higher than amplitudes below 200 microns.

(d) An increase in fretting damage with temperature to about 225°C to 285°C but above 285°C decrease with temperature. About 310°C the rate is about the same as at room temperature.

(e) An effect of water chemistry and the chemicals used to control pH and oxygen content on fretting rate. Using hydrogen as a control chemical produced more fretting wear than LIOH at room temperature.

Fretting wear is dependent on a number of parameters such as wear surface area, A; sliding distances, S; contact force, $F_n$; wear coefficient, $K_{FW}$; and frequency of motion, F.

The time $t_w$ to wear to a depth $D_w$ is

$$t_w = \frac{A}{2K_{FW}.F_N.f.s}.D_w$$

The time is inversely proportional to contact force, frequency and sliding distance. Thus higher frequencies, longer sliding distances and higher contact forces reduce the time to produce damage. For the same sliding distance frequencies of 150 Hz for example, reduce wear times by a factor of 10 compared to 15 Hz.

The above relationships and use of estimated values for the unknown parameters such as wear coefficient provides an estimate of time for observed bearing pad damage to take weeks rather than hours.

For end plate wear the duration of fretting was also estimated to be about 1 month for the worst damage seen.

These estimated suggested that the fretting wear phenomena was likely on-going.

Scanning electron microsopy of fretted surfaces showed wear patterns in the form of elliptical marks (dimples) or scratches. The longest dimension indicated the predominant direction of relative motion.

Examination of spacer pads showed that the direction of relative motion depended on spacer location. Spacers separating rings of elements fretted from relative axial motion. Spacers between elements within a ring fretted from relative transverse motion.

Bearing pad wear at the inlet end was predominantly due to relative axial motion to the pressure tube.

End plate wear resulted from small relative radial motions of contracting end plates.

### 5.5 Support to Loop Test Work

Examinations of end plates failed in out-reactor loop tests contributed to the understanding of the fracture process. For instance, correspondence of some of the features of the fractures confirmed the failure temperature as occurring during hot conditions. Generally the loop tests produced failures similar to those seen on the heavily damaged channels in Darlington Unit 2..

## 6.0 CONCLUSION

The metallurgical investigations showed that:

(a) Fatigue was the cause of failure.

(b) The cyclic stress amplitude just exceeded the fatigue threshold.

(c) Failure occurred at temperatures at or above 265°C.

(d) Axial cyclic loading of the bundles was the predominant cause of failure. However transverse vibration of the fuel elements may have contributed to the failure process.

(e) Failure predominantly occurred after the reactor had reached fuel power and was not associated with one event, but a series of events in one channel and in different channels.

(f) The uniform oxidation on the surface of field failures indicated crack progression times were not greater than a few days. Correspondence of failures between in-reactor and out-reactor loop tests indicated 150 $H_z$ oscillations s the prime mechanism of failure.

(g) Fretting damage was more likely the result of high frequency vibrations than low frequency.

## 7.0 REFERENCES

(1) E.T.C. HO, G.K. SHEK, M.L. VANDERGLAS and M. LEGER, "Development of Fatigue Failure Criteria for Darlington Fuel Bundle End Plates", CNA/CNS Annual Conference, Saint John, N.B., June 1992.

(2) M. GABBANI, T. RICHARDS, A. BABAYAN and E.G. PRICE, "Mechanical Fatigue Simulation Testing of Fuel Bundles and Specimens for End Plate Failure", CNA/CNS Annual Conference, Saint John, N.B., June 1992.

(3) V.F. URBANIC, M.A. MAGUIRE and N. RAMASURBRAMANIAN, "Dating the Fractures in Darlington End Plates from Oxide Thickness Measurements", CNA/CNS Annual Conference, Saint John, N.B., June 1992.

(4) N.J. FISHER, C.E. TAYLOR, M.J. PETTIGREW, "Fuel Element Vibration and Bearing Pad to Pressure Tube Fretting", AECL Report 10164, August 1990.

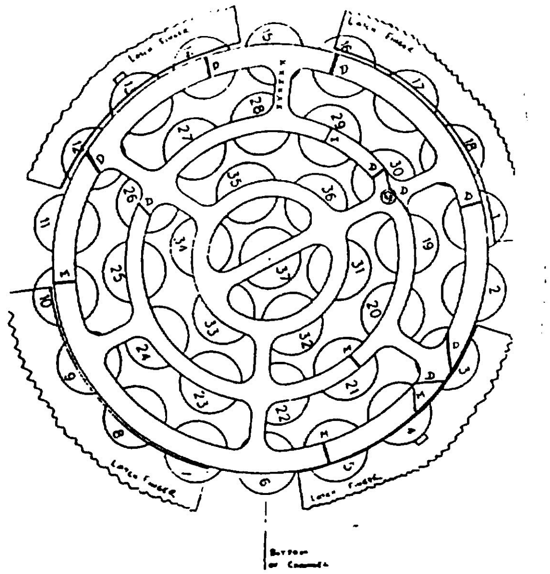

Figure 1: Diagram of a Cracked Outlet Bundle End Plate (Channel K12) Obtained from an In-Situ Television Inspection

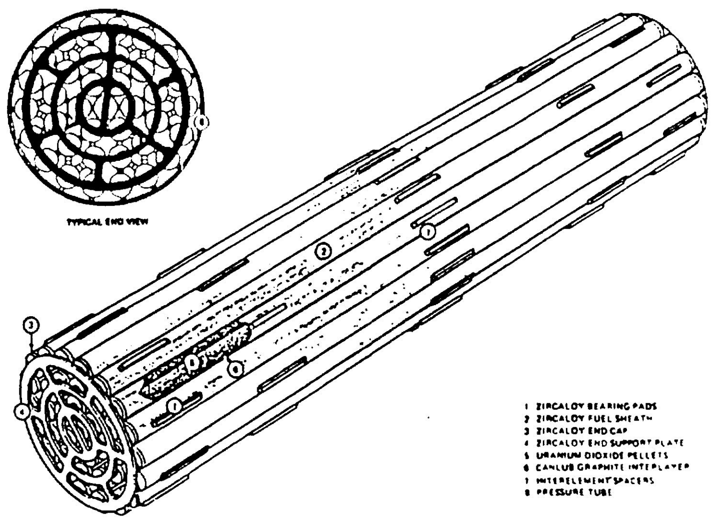

Figure 2: Darlington Fuel Bundle

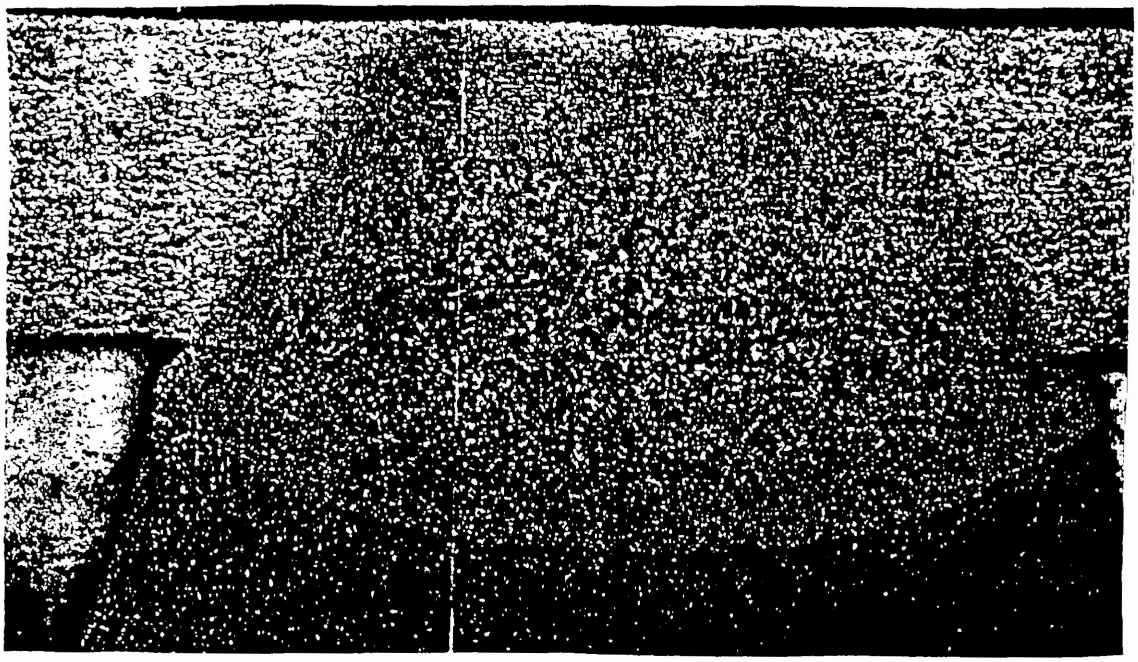

Figure 3: The Weld Microstructural Characteristics of an End Plate to End Cap Weld

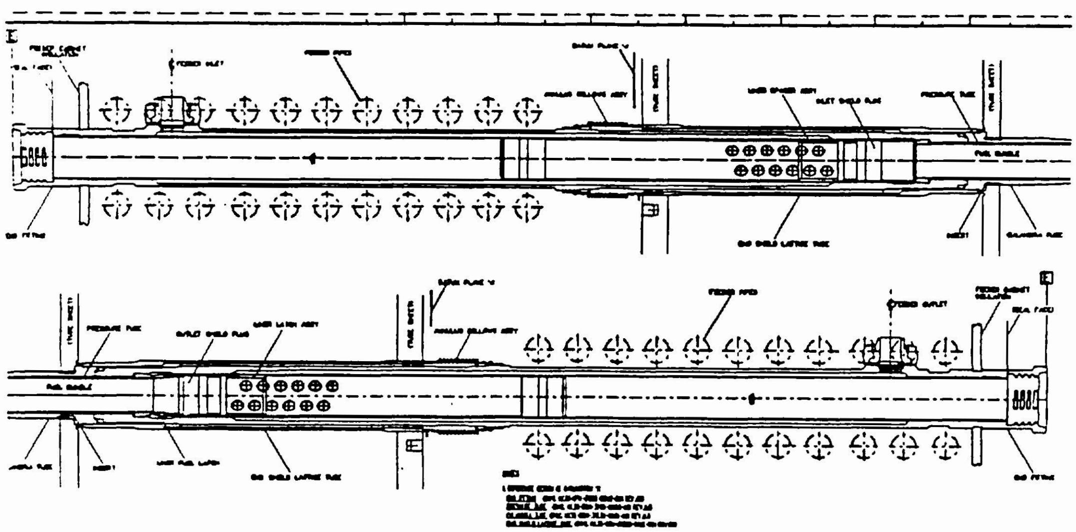

Figure 4: Illustration of Fuel String Positioning in a Darlington Channel

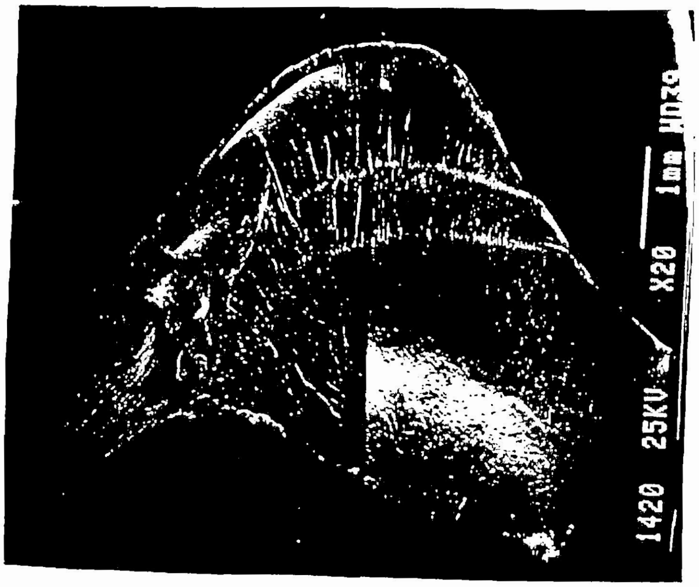


Figure 5: Typical Fracture Surface Formed in the End Plate

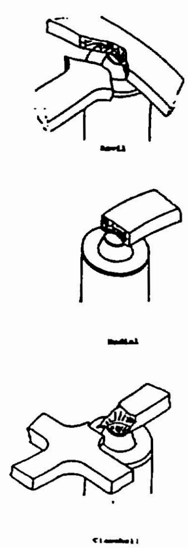

Figure 6: Types of Cracks Observed on the End Plates