THE POST IRRADIATION EXAMINATION OF FUEL IN SUPPORT OF BRUCE A NUCLEAR DIVISION FUELING WITH FLOW PROGRAM

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ABSTRACT

Bruce A Nuclear Division (BAND) units are operating at ~ 75% of full power, because of the potential of a power pulse in the event of an inlet header break. As a result, BAND is converting to fueling with flow, to eliminate the potential of a power pulse and to allow for full-power operation. Concerns regarding the integrity of the end-of-life (EOL) bundles interacting with the latch at the downstream end of the fuel channel were raised. BAND carried out a test program in which EOL bundles in the upstream position 13 of Unit 2 were cascaded into the downstream latch position 1 of another channel. Six of twelve cascaded bundles and two typical EOL position 13 (benchmark) bundles were selected for post-irradiation examination (PIE). Incipient cracks were found in the assembly welds (endplate-to-endcap welds) of all six cascaded bundles. No incipient cracks were found in the benchmark bundles. Metallographic and fractographic examination, along with crack dating, and hydrogen and deuterium analyses, indicated that the incipient cracks were the result of delayed-hydride assisted cracking at the EOL. Consequently, Ontario Hydro changed the design of the outlet shield plug to support all three rings of the fuel bundle, to minimize stress and prevent endplate cracking. Also, an ultrasonic endplate inspection tool (UT) was developed and located in the fuel bay, to inspect fuel-bundle endplates for cracks. A second test was done involving a series of four bundle cascades in BAND Unit 4 channels that had new outlet shield plugs. The latch bundles were discharged after a hot shutdown. The cascaded Unit 2 and Unit 4 latch bundles were checked for cracks using the UT. The PIE found incipient cracks or less-than-ideal welds in the assembly welds of fuel elements from Unit 2 (latch-supported fuel bundles) that had been identified by the UT as having incipient cracks. No incipient cracks were found in the assembly welds of fuel elements from Unit 4 (new outlet shield-supported fuel bundles) confirming the UT results.

INTRODUCTION

Bruce A Nuclear Division (BAND) units are operating at ~ 75% of full power, because of the potential of a power pulse in the event of an inlet header failure (i.e., flow reversal resulting in an axial shift of the fuel string). As a result, BAND is converting to fueling with flow (FWF), to eliminate the potential of a power pulse and to allow for full-power operation. The present fueling method is to fuel against the flow (FAF); in this method a power pulse could occur, because "fresh" fuel could shift toward the center of the reactor core as a result of flow direction reversal, in the unlikely event of an inlet header failure. In the case of FWF, "older" fuel would shift toward the center of the reactor core, which results in a negative reactivity pulse.

Typically, new (unirradiated) bundles reside in the downstream latch position (axial position 1) in a FAF scheme. In the FWF scheme, fully irradiated end-of-life (EOL) bundles would reside in the downstream latch position. Concerns were raised regarding the integrity of these EOL bundles interacting with the latch at the downstream end of the fuel channel. BAND carried out a test program in which 12 EOL bundles in the upstream position 13 of Unit 2 were cascaded into the adjacent channel's downstream position 1. This test was not a perfect simulation of the FWF concept. Typically, the downstream endplate of a FAF bundle becomes domed, as Figure 1 shows. The endplate distortion (doming or dishing) results from the force of the coolant acting on the elements that are not directly supported by the latch mechanism. In this test, the cascaded bundle was inserted into position 1 of the adjacent channel, with its domed endplate against the domed endplate of the position 2 bundle, as shown in Figure 1. This "reverse-dome" situation represents a worst-case scenario with respect to endplate loads. The bundles were discharged after a period of seven weeks, during a pressure-tube delayed-hydride cracking (DHC) avoidance maneuver, as shown in Figure 2.

Six cascaded bundles and two benchmark bundles were selected for post-irradiation examination at Chalk River Laboratories (CRL) and Whiteshell Laboratories (WL). Incipient cracks were found in the assembly welds of the cascaded EOL bundles. The incipient cracks were the result of delayed-hydride assisted cracking.

Consequently, the design of the outlet shield plug was changed to support all three rings of the fuel bundle, to minimize stress and prevent endplate cracking. Also, an ultrasonic endplate inspection tool (UT) was developed and located in the fuel bay, to inspect fuel-bundle endplates for cracks. A second test was done, involving a series of four bundle cascades, from positions 10 to 13 into positions 4 to 1 of BAND Unit 4 channels, that had a redesigned outlet shield plug. The four bundle cascades also reduced the stress on the position 1 bundle associated with the dome-on-dome endplate situation. The position 1 bundles were discharged after a pressure-tube DHC avoidance maneuver, and checked using the UT. No through-wall cracks were observed, and the UT did not detect any incipient cracks. Twenty-two Unit 4 elements were selected for PIE at CRL to qualify the performance of the new UT and the new outlet shield plug design. The Unit 4 elements came from locations at or adjacent to radial web junctions that are more susceptible to cracking. Three bundles from the Unit 2 test were also examined using the UT, and incipient cracks were detected. Eight elements were selected for PIE, to qualify the performance of the new UT.

FUEL IRRADIATION HISTORIES

An approximate equal number of bundles and elements manufactured by Zircatec Precision Industries (ZPI) and General Electric Canada (GEC) were examined.

Bundle-average burnups calculated using the simulation-of-reactor-operation code (SORO) ranged from 170 to 349 MWh/kg U. The bundle powers ranged from 500 to 800 kW.

EXAMINATION RESULTS

The examination for each bundle comprised:

1. A visual examination of the endplates for distortion and cracking.
2. Bundle length and endplate distortion measurements for the benchmark bundles only.
3. A visual examination of the elements for obvious defects.
4. Bundle disassembly.
5. Metallographic examination of ten assembly welds from each bundle.
6. Peel testing of all remaining assembly welds, to facilitate examination of the welds for incipient cracks.
7. Hydrogen and deuterium analysis of the endplate-weld material.
8. Crack dating based on the measured oxide thickness, using a fourier transform infrared (FTIR) spectrometer.
9. Scanning electron microscope (SEM) examination of selected incipient cracks.

Peel testing and H/D analysis were done on the individual elements examined in the second campaign.

Visual Examination

No through-wall cracks were detected in any of the bundle or element endplates. The bundles' endplate doming and dishing, and bundle-length measurements, were comparable to bundles previously examined from the Bruce and Darlington nuclear generating stations.

Metallographic Examination

Incipient cracks were detected metallographically in all six Unit 2 cascaded EOL bundles. The incipient cracks were at critical welds. Critical welds are welds at radial web junctions. These locations are typically under higher stresses, because the coolant drag load across the endplate and elements is shed from the inner elements to the outer elements, which are in direct support with the latch fingers via the endplate radial webs.

Incipient cracks propagating into or along the heat-affected zone (HAZ) were observed. The microstructures for all the cascaded and benchmark EOL bundles were comparable and no anomalies were detected. Figures 4 and 5 show typical micrographs of the microstructure and the hydride distribution of an assembly weld with an incipient crack. Less-than-ideal welds (Figure 6) were also found in the cascaded bundles from both manufacturers. Less-than-ideal weld micrographs show weld expulsion at the notches, and incomplete bonding along the weld line.

Endplate-To-Endcap Peel Test

Peel tests were performed on all the assembly welds, except for the elements that were selected for metallographic examination. Incipient cracks were detected in all six Unit 2 cascaded EOL bundles using the peel test. The peel test consists of inserting the tip of a screwdriver between the top of the endcap and the endplate, and prying upwards until the endplate peels off the endcap. The prying is done on both sides of the weld in several small steps, and the endplate generally peels off in one or two pieces. The endplate will peel off at an incipient crack if one is present. The fracture face created by peeling, on the bottom of the endplate and on the endcap, was examined using a stereomicroscope. The fracture face is generally shiny and rough in appearance when it has been created in-cell. Dark patches on the fracture faces are indicative of an in-reactor incipient crack. The dark patches are oxide, which forms on the incipient crack faces as a result of exposure to the primary-heat-transport-system coolant.

Figures 7 and 8 show a typical example of an incipient crack detected using the peel test that had dark patches of oxide exhibiting two zones with different colours. The two colour zones are the result of different oxide thicknesses on the fracture face, and indicate that the cracks grew in two discrete steps, likely associated with the two cool-down steps experienced by these bundles.

Incipient cracks were detected in the majority of the elements that the UT had identified as having incipient cracks. Some elements were identified as having small incipient cracks by the UT. No cracks were detected in these elements using the peel test, but the fracture faces of the assembly weld of these elements had dark-grey, mottled areas around the circumference of the weld. The mottled grey surface (oxide layer) areas are quite flat, and the depth could not be measured. The welds for these elements were less than ideal, and contained areas of incomplete weld bonding, weld expulsion or weld upset that could crack before or during irradiation.

No incipient cracks were found for the two benchmark bundles or for the individual elements from BAND Unit 4 using the peel test.

Crack Depth

The peel test crack depth was measured from the endcap side profile photographs, and is defined as the depth to which the crack penetrated vertically into the endplate. Metallographic crack depths were measured from either the as-polished or the etched micrographs at 50 or 150X. Bundles that experienced two cool-downs had crack depths ranging from 0.3 to 1.0 mm. Bundles experiencing one cool-down exhibited crack depths in the range of 0.1 to 0.5 mm.

Hydrogen And Deuterium Results

Assembly weld material was analyzed for hydrogen and deuterium. The equivalent hydrogen concentration ranged from 35 to 74 µg/g and 41 to 111 µg/g for the BAND Unit 2 benchmark and the cascaded bundles, respectively. The equivalent hydrogen concentrations ranged from 27 to 66 µg/g for the BAND Unit 4 fuel elements. Equivalent hydrogen is defined as follows:

$$[\text{Equivalent Hydrogen}] = [\text{Hydrogen}] + \frac{[\text{Deuterium}]}{2}$$

The hydrogen terminal solid solubility limit for dissolution (TSSD) at the zero-power-hot (ZPH) shutdown temperature (~250°C) is approximately 30 μg/g of equivalent hydrogen. The assembly weld equivalent hydrogen concentration exceeded the TSSD value in most cases.

Crack Dating

The age of the crack was estimated by comparing the predicted oxide thickness to the measured oxide thickness on the peeled endplate and endcap incipient crack faces. The oxide thickness was measured using an FTIR spectrometer. The predicted oxide thickness was calculated based on the power history of BAND-2, and the oxidation kinetics determined for the Darlington Nuclear Generating Station (DNGS) N12 Program [1].

The FTIR equipment used to measure the oxide thickness has a detection limit of 0.2 μm, and all the fracture faces examined had an oxide thickness less than the detection limit. The fractures are estimated to have occurred within the last three days of residence in the cascaded channel, and are likely associated with the pressure-tube DHC-avoidance maneuver prior to discharge.

SEM Examination

Two fracture faces were examined using the SEM. Figure 3 shows a SEM photograph that contained areas of ductility (pulled-out features) and crystallographic facets. The fracture faces from these two elements do not resemble the river- and beach-mark patterns observed for the beginning-of-life fatigue cracks from the DNGS N12 investigation [2]. These cracks are not fatigue cracks.

CRACK MECHANISM

SEM examinations of the endplate cracks found in the Unit 2 cascaded bundles did not resemble the beginning-of-life DNGS N12 fatigue cracks [2]. An extensive fractographic and metallographic examination of the cracks was performed to identify the mechanism of cracking. DHC was considered as the most likely cause of cracking, because of the presence of high stresses and sufficiently high equivalent hydrogen concentration. DHC has been previously identified as the most likely and widely observed cracking mechanism in pressure tubes made of Zircaloy and Zr-2.5Nb materials [3]. Fatigue cracking has been observed in assembly welds [2]. Generally, stress-corrosion cracking (SCC) is more common in Zircaloy fuel sheathing and endcaps. Recent work at AECL indicates that SCC remains the most probable mechanism for the Bruce-type end-cap defects, as several methods used to initiate and promote DHC (adding hydrogen and temperature cycling) failed to produce defects similar to those observed in the Bruce defects. DHC has been observed in endcap welds of Zr-2.5Nb fuel sheathing [4], and recently DHC-assisted SCC has been observed in the endcap-to-sheath welds of Zr-4. After the preliminary examination showed that the cracks were not caused by fatigue, emphasis shifted to determining whether the cracks were caused by DHC.

DHC is a time-dependent process, the rate of which is controlled by diffusion of hydrogen to the crack (flaw) tip. To initiate and grow a DHC crack, the following conditions must be met:

1. A sufficient concentration of hydrogen must be available in the bulk of the material, to result in the diffusional buildup of hydrogen at the flaw tip to a level equal to the terminal solid solubility limit for hydride precipitation at a given temperature.
2. There must be a sufficiently high, normal tensile stress (or, equivalently, for sharp cracks, stress-intensity factor) acting on the crack-tip hydride to cause it to fracture (i.e., the applied $K_I > K_{IH}$, the threshold stress-intensity factor).

Evidence for DHC in the Endplate Cracks

The following evidence indicates that DHC was the crack mechanism:

1. The majority of the assembly welds' equivalent hydrogen concentration exceeded the TSSD concentration at 250°C of ~ 30 μg/g.
2. The cascaded bundles were in a high-stress situation.
3. Evidence of DHC arises from the metallographic and fractographic examinations. Features typical of DHC, such as the accumulation of hydrides at the crack tip and around the crack, and brittle features on the fracture surface corresponding to fractured hydrides, were observed.
4. Crack dating indicated that the cracks occurred during the bundles' last three days of residence. The amount of crack growth during the reactor pressure-tube DHC-avoidance maneuver was calculated using the available DHC data on Zircaloy [5]. The calculated crack growth for the two cool-down steps was 1.2 and 0.5 mm, respectively, which is in good agreement with the observed crack depths, based on the uncertainties on the DHC velocity for Zircaloy and the affect of crystallographic texture [5]. The amount of crack growth at the ZPH hold was calculated to be 7.4 mm, which would lead to through-wall cracks, which were not found during the examination, and supports the fact that the cracking occurred only during the two cool-down steps.

CONCLUSIONS

This campaign shows the importance of PIE in checking operational concerns and qualifying non-destructive techniques.

The Unit 2 cascaded bundles had incipient cracks at the endplate-to-endcap welds, while the benchmark bundles did not have any incipient cracks. The incipient cracks (thirty in total) were equally divided between the two manufacturers. The cascaded and benchmark bundles had comparable equivalent hydrogen concentrations and irradiation histories. The cascaded and benchmark bundles were subjected to the same pressure tube DHC-avoidance maneuver. The cascaded bundles were placed in a high-stress situation at the EOL, when they were cascaded into an adjacent channel in position 1. In this position, they were placed against the channel end latch fingers, and the bundle endplate orientation was reversed to the normal situation (Figure 1).

The incipient cracks found in the assembly welds of the cascaded bundles were the result of DHC.

No incipient cracks were found in the elements from BAND Unit 4, which had comparable equivalent hydrogen concentrations, burnups, and power histories. The PIE results confirm the UT results, and indicate that the redesigned outlet shield plug prevented DHC cracks in the assembly welds. The UT performance was also verified by the PIE results from the Unit 2 elements that were tested using the UT.

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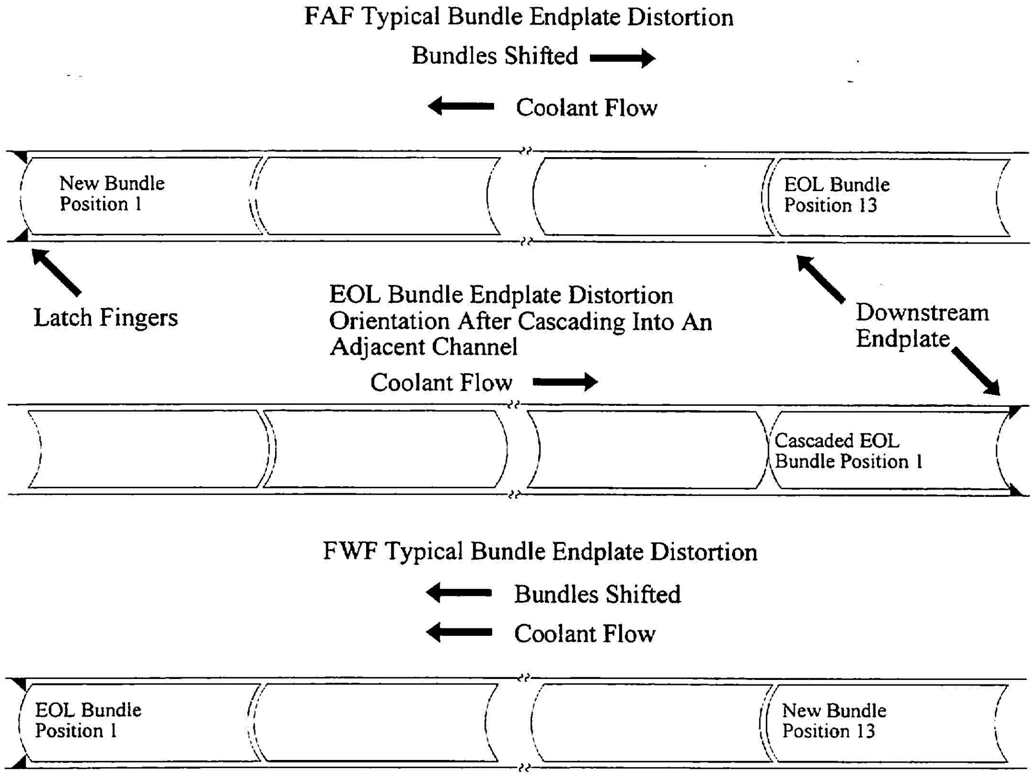

FIGURE 1: Endplate Distortion For FAF and FWF

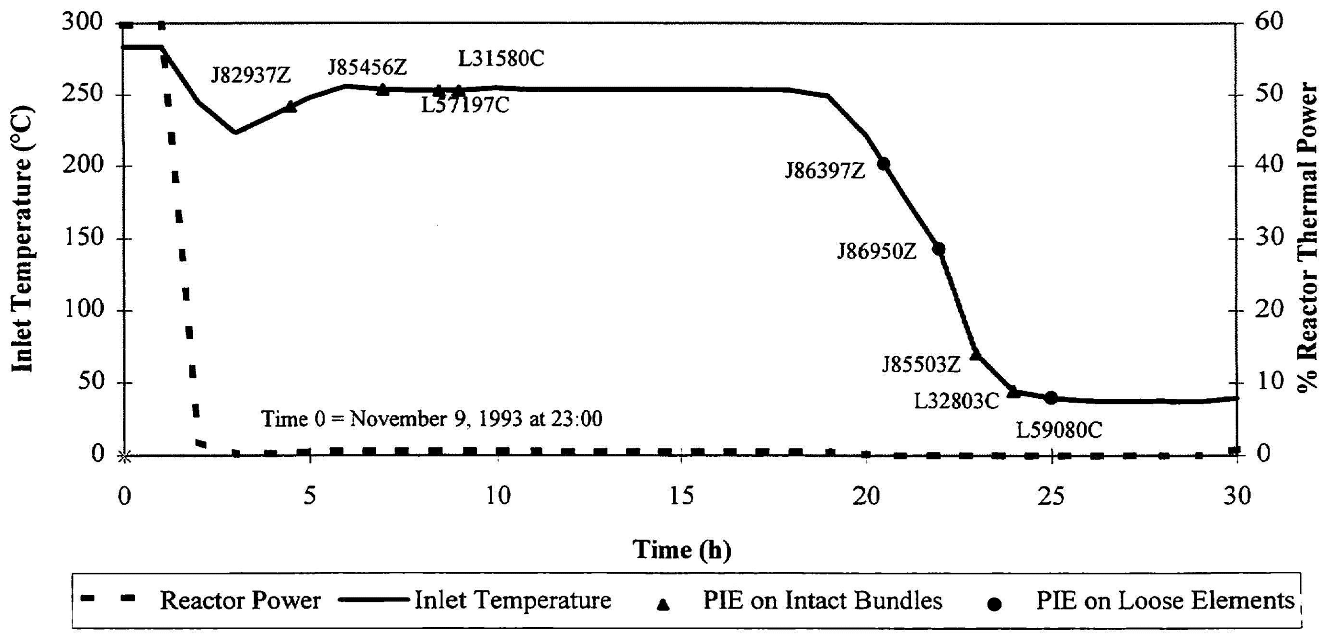

FIGURE 2: Cascaded Bundle Discharge History During the 1993 November 10 Pressure-Tube DHC-Avoidance Maneuver

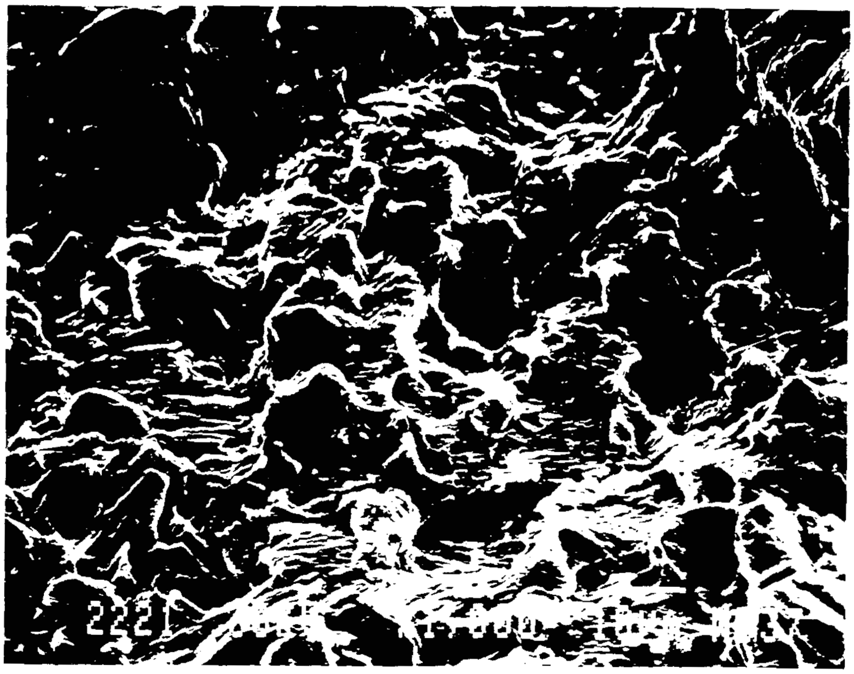

FIGURE 3: Fracture Face at High Magnification (L32803C -3 Non-Monogrammed Endplate, 1000X, 2221)

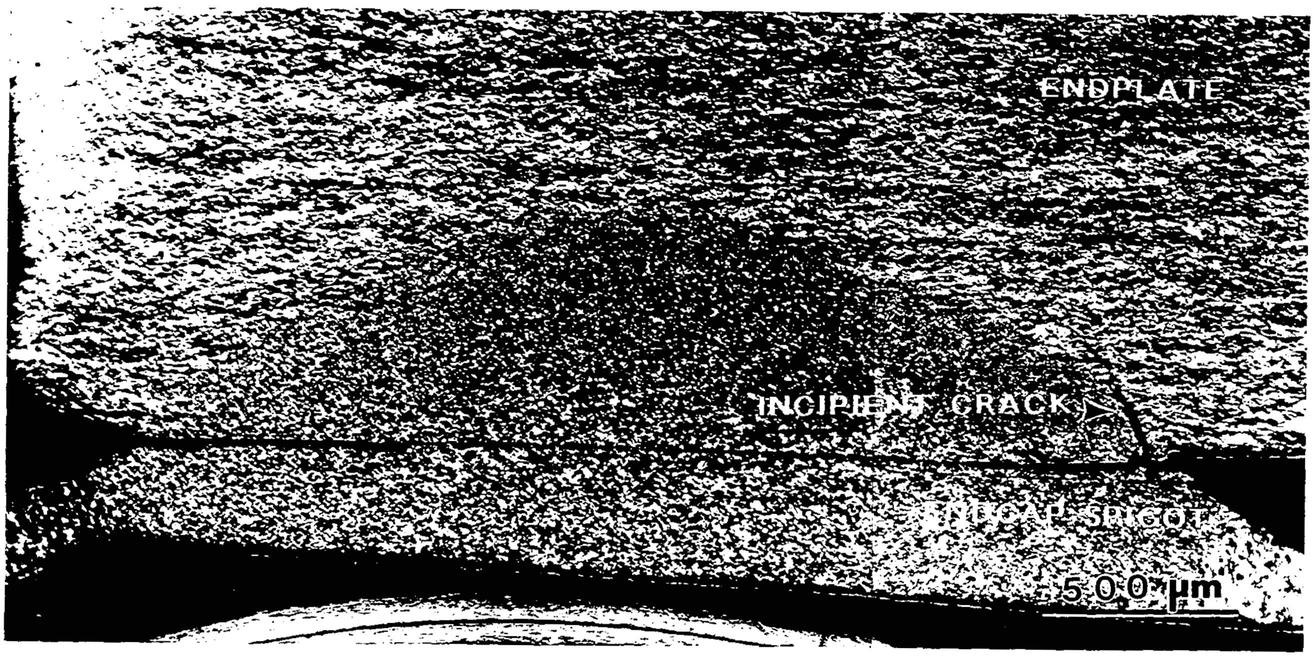

FIGURE 4: L32803C-18 Non-Monogrammed Endplate Weld Microstructure with an Incipient Crack (50X, GG30G8-G9)

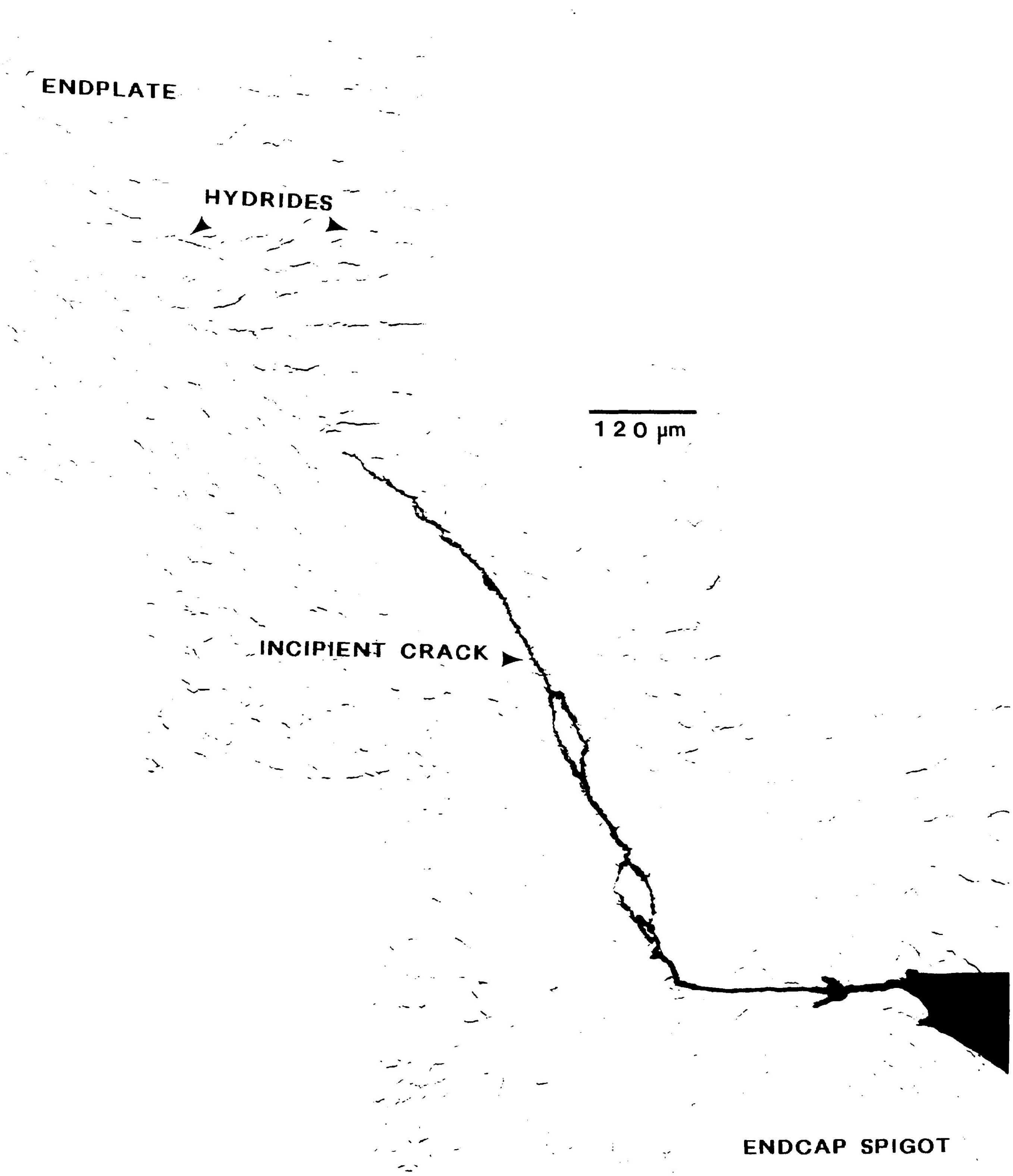

FIGURE 5: L32803C-18 Non-Monogrammed Endplate Hydride Distribution Around the Incipient Crack and in the Bulk of the Weld (150X, GG30G13-G14, G20)

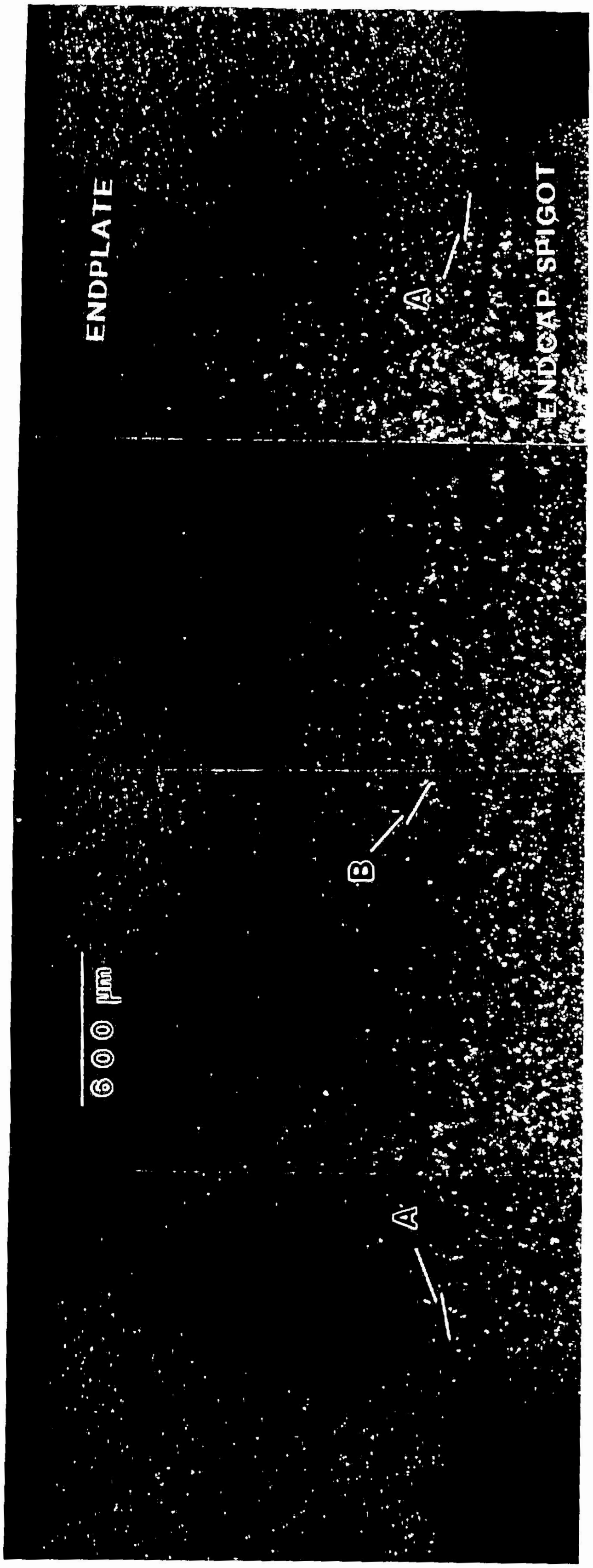

FIGURE 6: A Typical Less-Than-Ideal Assembly Weld (A. Weld Expulsion, B. Incomplete Weld), (L58277C-5 Non-Monogrammed Endplate, 50X, HH2K3-K6)

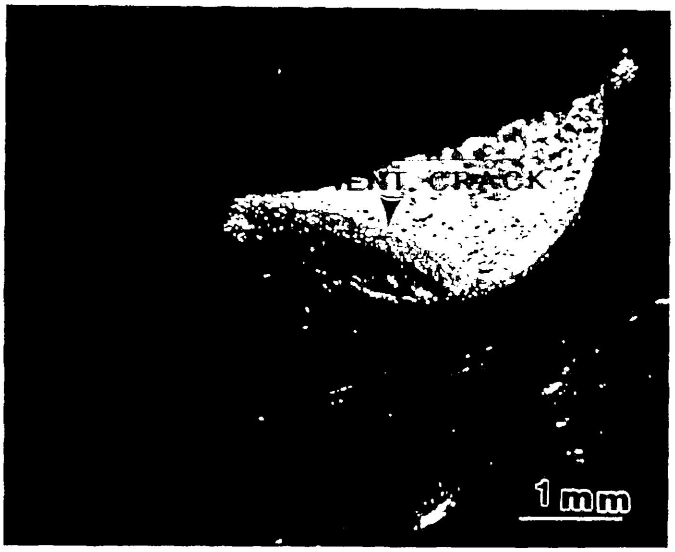

FIGURE 7: Typical Incipient Crack Detected Using the Peel Test Showing a Two-Colour Zone Dark Patch on the Endplate (J85503Z-23 Monogrammed Endplate, 13.6X, 910A-21)

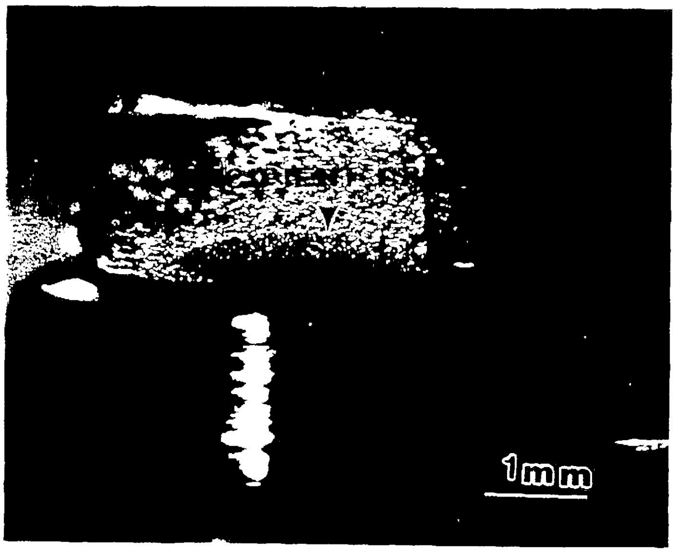

FIGURE 8: Mating Two-Colour Zone Dark Patch on the Endcap (J85503Z-23 Monogrammed Endplate, 13.6X, 910A-22)