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Evaluation of Fuel Rod Leakage Mechanisms—Summary Report

Joint EPRI/ESEERCO/Westinghouse Studies

Prepared by
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Pittsburgh, Pennsylvania

Legacy - ND

REPORT SUMMARY

Evaluation of Fuel Rod Leakage Mechanisms—Summary Report

Joint EPRI/ESEERCO/Westinghouse Studies

To achieve a zero fuel defect goal, utilities have identified failed fuel rods and determined failure causes using a combination of poolside ultrasonic testing and visual inspection. Hot cell examinations, described in this report, have helped resolve the status of leaking rods for which there appeared to be no apparent cause of failure. Utilities can incorporate the findings of this project into their poolside fuel inspection planning and fuel quality requirements.

INTEREST CATEGORY

Light water reactor fuel

KEYWORDS

Fuel rods
Failure mechanisms
Ultrasonic testing
Corrosion
Integrated fuel burnable assembly performance

BACKGROUND Up to the early 1990s, utilities with PWRs relied on nondestructive evaluation (NDE), ultrasonic testing (UT), and visual inspection at the poolside to identify failed fuel rods and to determine the failure causes. Poolside UT combined with visual inspection has identified the failure mechanisms in approximately 70% of failed rods. However, UT sometimes misclassified failure status, leading to concern of UT miscalls. The remaining 30% of failed rods were classified as having "unknown" failure causes because the primary defects could not be identified. The inability to identify the failure causes makes it impossible to prescribe proper corrective actions and may result in either premature discharging of sound rods or reinsertion of failed rods.

OBJECTIVES To evaluate fuel rod leakage mechanisms, determine remedial actions, and evaluate the performance of Vantage-5 rods.

APPROACH The project team reviewed poolside NDE results obtained in 20 campaigns together with fabrication records and coolant chemistry data. The team next selected 16 rods for hot cell examinations, based on this broad database. Utility personnel at Byron, Callaway, and V. C. Summer plants helped retrieve and ship the 16 rods for detailed hot cell examination. Specifically, the team examined 12 rods to determine the causes of fuel leakage and UT miscalls as well as the degree of secondary degradation. They examined four Vantage-5 integrated fuel burnable assembly (IFBA) rods to identify the effect of crud deposition on cladding corrosion and to determine the performance of ZrB_2 coating on the fuel pellets.

RESULTS Poolside NDE previously identified the following four leakage mechanisms for which corrective actions have been implemented: debris-induced fretting, grid-rod fretting, fuel rod collapse at sections with missing fuel, and incomplete endplug girth welds. Current hot cell examination of failed rods having no apparent primary defects revealed endplug piping, random hydrogenous contamination, and a potential seal weld anomaly at the upper endplug as additional leakage mechanisms. These defects were manufacturing-related, and corrective actions have now been implemented. Various forms of hydride damage and accelerated corrosion of the cladding were also found.

UT overcalls were identified for five of the rods examined at the hot cell. The overcalls were related to bonding of fuel chips on the cladding, suggesting that hard contact or bonding of fuel pellets with the cladding may have contributed to distortion of the UT signals.

Significant localized corrosion acceleration and oxide spalling in the cladding were found on the V. C. Summer rods with heavy crud deposits. However, the ZrB_2 burnable poison coating on fuel pellets in the Vantage-5 IFBA rods performed satisfactorily.

UTILITY PERSPECTIVE A combination of poolside NDE and hot cell destructive examinations identified seven leakage mechanisms in Westinghouse PWR fuel. The vendor evaluated factors contributing to each failure mechanism and implemented corrective actions. This project moves utilities one step closer to achieving the industrywide goal of zero-defect fuel. Because UT overcalls may be associated with pellet-cladding bonding—which increases with burnup—utilities will need to select alternative nondestructive techniques for detecting high burnup failed fuel. Utilities will also need to take future actions to prevent the acceleration of corrosion due to crud deposits. Finally, information on the performance of the ZrB_2 fuel pellet coating will help utilities more accurately analyze the behavior of Vantage-5 IFBA rods.

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ABSTRACT

Poolside and hot cell examinations identified a number of leakage mechanisms. They are debris induced fretting, grid-to-rod fretting, rod collapse, incomplete weld, end plug piping, possible hydrogenous contamination, and potential seal weld anomaly. Corrective actions have been taken to address each of the leakage causes.

Hot cell examinations confirmed that UT inspection can mis-identify leaking rods. A possible cause of the miscall was determined to be pellet-cladding contact at the rod location where the UT was probed.

The examination of the V.C. Summer demonstration rods revealed potential performance concerns for high burnup fuel. The excessive flaking oxide and hydride localization associated with the cold spots could threaten fuel integrity.

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A number of leaking fuel inspection campaigns performed by Westinghouse and utilities from 1986 to 1989 identified several leakage mechanisms: debris induced fretting, grid-to-rod fretting, and rod collapse. These examinations also revealed some UT identified leaking rods with no apparent causes.

In order to resolve the status of theses rods, a hot cell examination was planned. Prior to the hot cell examination, additional examinations were performed at Callaway and Indian Point 3 under the funding of EPRI to resolve the status of some UT identified leaking rods. During this time period, additional rods became available for the hot cell examinations from other sites.

Selection of candidate rods for the hot cell examination was made following the completion of the on-site examinations. A total of 16 rods were selected from Callaway, Byron 1, Byron 2, and V.C. Summer. Ten of these rods came from a group where the leakage cause was not identified despite detailed on-site examinations. Two non-leaking rods were included in the hot cell examination to assist in the evaluation of any possible UT mis-classifications. Four VANTAGE 5 demonstration rods from V.C. Summer were selected although these were not leaking. The rods showed unusual crud deposits and higher than expected waterside corrosion.

The hot cell examination revealed that two rods from Byron 2 were leaking due to end plug piping. The leakage cause of one Byron 1 rod, and one V.C. Summer rod was determined to be possible hydrogenous contamination. Of the six UT identified leaking rods which showed no visible anomaly (from Callaway and Byron 2), only one Byron rod was determined to be leaking. The leakage cause of the rod was determined to be potential seal weld anomaly. The UT miscalls were determined to be caused by pellet-cladding contact. The V.C. Summer rods showed excessive flaking of waterside corrosion and hydride localization at the cold spots which could become potential leakage causes of high burnup fuel.

Corrective actions have been taken to eliminate each of seven leakage mechanisms (debris induced fretting, grid-to-rod fretting, rod collapse, incomplete weld, end plug piping, possible hydrogenous contamination, and potential seal weld anomaly). The confirmation of the UT miscalls and the identification of a possible cause will provide significant information for both the utilities and leak testing vendors to make decisions on inspection techniques and interpretation of UT data.

1.0 INTRODUCTION

One of the primary objectives in the nuclear industry over the past several years has been to reduce coolant activity resulting from leaking fuel rods to very low levels. In order to accomplish this objective, twenty on-site examinations were conducted as of mid-1989, often in conjunction with fuel assembly repair operations, to identify the leaking rods and determine the cause of leakage. From these examinations, three leakage mechanisms were confirmed: debris induced fretting, grid-rod fretting, and rod collapse. These mechanisms are well understood and have had a series of corrective actions implemented to prevent or reduce the probability of their occurrence in the future.

However, several rods identified as leaking by UT exhibited no defects in subsequent visual examinations and/or eddy current inspections. Therefore, it is not known whether the leakage detection of those rods was due to errors in the UT inspections (UT overcall) or that the rods were actually leaking due to certain microscopic mechanisms which can not be determined by visual inspection. It was concluded from the available data that these rods, if leaking, were not leaking due to any of the confirmed mechanisms described above. In addition, some other rods identified by UT as leaking were confirmed to be leaking during the poolside examination through the visual identification of defects, but the underlying leakage mechanism could not be identified.

As part of a joint program involving the Electric Power Research Institute (EPRI), the Empire State Electric Energy Research Corporation (ESEERCO), and Westinghouse, a program was developed to determine the status and leakage mechanisms of some of the unconfirmed rods and the rods with unknown causes. This program consisted of additional on-site examinations at two sites followed by detailed destructive examination of selected rods in the hot cells at Atomic Energy of Canada Limited, (AECL) - Chalk River, Canada.

2.0 PROGRAM OBJECTIVES AND WORKSCOPE

2.1 PROGRAM OBJECTIVES

The objectives of the program addressed two outstanding questions remaining from the examinations previously performed. The first objective was to determine the leakage cause for several rods which had been identified as leaking by UT but were either not examined at that time or had an unidentified leakage cause. The second objective was to resolve the status of the rods for which detailed examination had not confirmed that the rods were leaking despite the fact that they were identified as leaking by UT. In order to achieve the defect-free core goal, it was necessary to resolve the status of these rods so that, if the rods are leaking, the appropriate corrective actions can be identified and implemented. If the rods are determined to be non-leaking and were misclassified by UT, further examination of the rods would also be beneficial to potentially identify factors which led to the UT misclassifying the rods as leaking. This information can then be used by the UT vendors to evaluate and refine their data acquisition and interpretation procedures.

2.2 PROGRAM WORKSCOPE

The overall program was divided into four separate tasks: Tasks A, B, C, and D. Tasks A and B involved on-site examination data from several sites which were used to assess the causes of leaking fuel and to identify the candidate rods for a hot cell examination. Task C involved the hot cell examination of sixteen fuel rods. Task D consisted of the determination of the program conclusions and the publication of the summary report. Tasks A and D were performed under the funding of Westinghouse. Task B was carried out through EPRI funding. Task C was principally funded by Westinghouse, and ESEERCO, with supplemental funding from EPRI. The detailed workscope for each of the individual tasks is summarized below:

Task A: On-site Examinations

This task involved inspections of UT identified leaking rods (found from 1986 to 1989) at nineteen Westinghouse plants. These rods are summarized in Table 2.1-1. A Westinghouse WCAP report which contains information such as fuel in core, coolant activity history, examination results, manufacturing traceability, and power history for these individual examination campaigns was issued under this task.[1]

Task B: Callaway and Indian Point 3 Exams

This task consisted of mobilization of repair equipment, on-site removal of selected UT identified leaking rods from assemblies, and an examination of individual rods at the Callaway and Indian Point 3 sites. Upon completion of Tasks A and B, all of the available rod data were reviewed and a selection of rods to be shipped to the hot cell was made. During the time frame between when the Callaway and Indian Point campaigns were conducted and the shipments were made to the hot cell, additional rods became available from Byron 1 and 2 and from V.C. Summer and were included in the hot cell examination. In addition, several VANTAGE 5 demonstration fuel rods from

TABLE 2.1-1

SUMMARY OF PIE

Plant	Defect Cause Identified			Cause Not Identified		
	Debris Fretting	Grid Fretting	Rod Collapse	Hydride Only	No Visual Anomaly	UT Exam Only
A	5					2
B	1					2
C	1	1			2	
D	1	7				
E	2					9
F	1					
G				3		
H	2					
I	3					1
J			1			
K		5		1		
L	3				4	10
M						2
N						6
O						4
P	4				2	
Q	2					3
C						2
R	1					
S			1	1		
Total	26	13	2	5	8	41

the V.C. Summer reactor were added to the hot cell examination. Although these rods were not leaking, they were considered to be good candidates for the hot cell examination due to the unusual crud and the high oxide levels. An EPRI report which summarized the results of the site examinations and the selection of the rods for the hot cell examination was issued under this task.[(2)] This report also included more recent fuel examination campaigns from Callaway, Byron 1, Byron 2, ad V.C. Summer as the background data. Several additional rods from these campaigns were incorporated into the hot cell program.

Task C: Hot Cell Examination

A total of sixteen rods selected from the candidate rods identified in Tasks A and B were shipped to the hot cell facilities operated by the Atomic Energy of Canada Limited (AECL) in Chalk River, Ontario. This task consisted of the rod shipment, hot cell examination, and reporting. The hot cell examination report is to be issued by ESEERCO.[(3)]

Task D: Final Report

The report herein, issued under this task, summarizes the final conclusions from the above three tasks concerning the rod leakage mechanisms, the impact of UT results, and the identification of any required corrective actions.

3.0 SUMMARY OF EXAMINATION RESULTS

3.1 TASK A: ON-SITE EXAMINATIONS

Program Background

Following the identification and elimination of some initial problems in the early 1970's, coolant activity remained relatively low and stable from the mid-1970's through the early 1980's. During this period, coolant activity levels were not a serious issue with the utilities. In the early 1980's coolant activity levels started to follow an increasing trend and became more of a concern to both the utilities and Westinghouse. Consequently, in 1981 Westinghouse initiated an effort to identify the causes of leaking fuel so that corrective actions could be identified and taken. This task was partly accomplished by a series of on-site examinations where leaking fuel assemblies were examined visually at the site. Since examination techniques were limited at that time, only leaking rods on the periphery of the assembly could be examined. This constraint was significant and limited the effectiveness of these campaigns.

The above examinations showed that the primary causes of the increased coolant activity in the early 1980's were baffle jetting and debris induced fretting. Corrective actions were implemented for both mechanisms. Baffle jetting has been virtually eliminated from Westinghouse plants with modification of reactor flow from downflow to upflow for the affected plants. Several improvements to prevent debris from being introduced into the reactor core made a significant reduction in the occurrence of debris fretting defects.

As can be seen in Figure 3.1-1, by 1986 the coolant activity levels had been substantially reduced from the levels of the early 1980's. However, the levels at that time (1986) were still higher than desired. One of the key unanswered questions concerning the cause of coolant activity at this point was whether the leakage mechanisms identified in the earlier examinations were continuing to be operative, but at reduced levels, or whether other mechanisms were not discovered in the previous efforts due to their relatively small number and the limited examination capabilities. Consequently, it was decided that further site examinations were needed to resolve this question. The probability of success of this effort was greatly enhanced over previous campaigns by improvements in on-site examination capabilities. The ability to routinely repair leaking fuel assemblies, by removing the leaking rods previously identified by ultrasonic examination (UT) from the assembly during the refueling outage, became available at about this time.

The availability of the above techniques made a detailed examination of each leaking rod outside of the assembly possible. Therefore, it was technically possible to obtain meaningful results at sites where only a few leaking rods were present (typically 1 to 5 rods, some of which would be internal to the assembly) that would not have been observable using previous techniques.

For the plants covered in this report, some level of examination had been performed during a total of twenty campaigns at nineteen plants. The initial examination in all except one of these campaigns was UT of the fuel assemblies to identify the leaking fuel rods. Further detailed rod examinations were conducted during fourteen of these campaigns. These generally consisted of reconstitution of the leaking assemblies where either the top or bottom nozzle was removed and

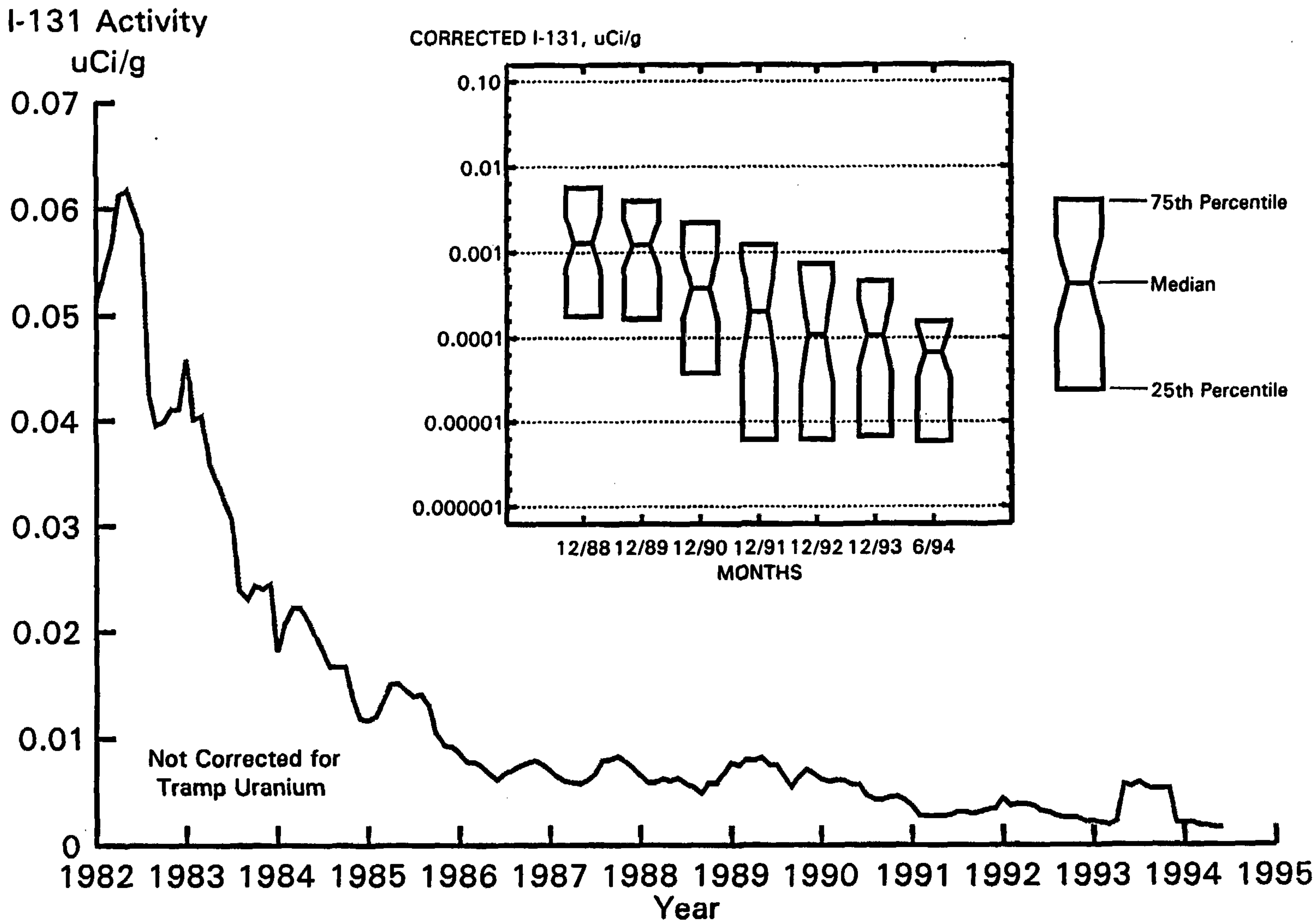


Figure 3.1-1. Plant Average Coolant Activity Levels Over Time for Westinghouse-Fueled Plants

the leaking rods were extracted from the assemblies. The leaking rods were then examined in detail at the site by TV, usually "Super Hi-Mag" TV (~25X). In a few cases, the removed rods were also examined by an eddy current (EC) technique. At six sites no reconstitution or single rod examination had been performed at the time this program was conducted.

General Fuel Description

The fuel examined in these inspections were of three configurations (14x14, 15x15, or 17x17) and two design types (OFA and standard). A brief description of the designs is given in the following paragraphs.

A standard 17x17 fuel assembly contains 264 fuel rods joined in a 17x17 array. The fuel rods are supported at eight locations along their lengths by Inconel grid assemblies which are mechanically fixed to Zircaloy thimble tubes attached to the top and bottom nozzles of the assembly. This arrangement of 25 thimble tubes, 8 grids, and a top and bottom nozzle make up the skeleton assembly which provides structural support for the fuel rods. The fuel rods consist of slightly enriched uranium dioxide ceramic, cyclindrical fuel pellets, encapsulated in the standard Westinghouse cold worked and stress relieved Zircaloy-4 tubes, which are plugged and seal welded at the ends. All fuel rods are prepressurized with helium.

A 17x17 optimized fuel assembly is the same as the 17x17 standard assembly with two exceptions: 1) an OFA assembly has only two Inconel grids - the top and bottom; the six middle grids are Zircaloy-4, and 2) the fuel rod diameter of an 17x17 OFA rod is smaller than the diameter of a 17x17 standard fuel rod.

VANTAGE 5 assemblies are similar to the optimized assemblies except for the incorporation of three intermediate flow mixer grids (IFMs), axial blankets, integral fuel burnable absorbers (IFBAs), removable top nozzles (RTNs), and high burnup capability.

A 15x15 standard assembly contains 204 fuel rods joined in a 15x15 array. The fuel rods are supported at seven locations along their lengths by Inconel grid assemblies which are mechanically fixed to Zircaloy thimble tubes attached to the top and bottom nozzles of the assembly. This arrangement of 21 thimble tubes, 7 grids, and a top and bottom nozzle make up the skeleton assembly which provides structural support for the fuel rods. All fuel rods are prepressurized with helium

A 15x15 optimized fuel assembly is the same as the 15x15 standard assembly with one exception: an OFA assembly uses only two Inconel grids - the top and bottom; the five 5 middle grids are Zircaloy-4.

A 14x14 standard fuel assembly contains 179 fuel rods joined in a 14x14 array. The fuel rods are supported at seven locations along their lengths by Inconel grid assemblies which are mechanically fixed to Zircaloy thimble tubes attached to the top and bottom nozzles of the assembly. This arrangement of 17 thimble tubes, 7 grids, and a top and bottom nozzle make up the skeleton assembly which provides structural support for the fuel rods. All fuel rods are prepressurized with helium.

Results of Completed Examinations

The results of the above examinations are summarized in Table 2.1-1. The data is broken into two major groups: 1) 54 rods- those where UT and detailed rod examination were performed, and 2) 41 rods- those where only UT was done. The rods which were examined in detail are further divided into two subgroups: 1) 41 rods- those where the defect cause was identified, and 2) 13 rods- those where the defect cause was not identified. Three mechanisms were confirmed: debris induced fretting, grid-to-rod fretting, and rod collapse. Twenty-six rods were confirmed to be leaking due to debris induced fretting, thirteen due to grid-rod fretting, and two due to rod collapse. The debris induced fretting cases were observed at twelve of the fourteen sites where detailed rod examinations were performed. Grid-rod fretting and rod collapse cases, on the other hand, were found on a less frequent basis, being seen at only three and two sites respectively.

The thirteen rods for which the underlying defect cause was not found despite visual and in some cases visual and eddy current examination have two subgroups: 1) those confirmed to be leaking and, 2) those which could not be confirmed to be leaking. There were five rods for which the leakage mechanism could not be identified even though the rods were confirmed to be leaking by visual examination. Hydride defects were observed on these rods, but could not be distinguished as being a primary or secondary defect. Three of these five rods (Plant G) are of little relevance to current vintage fuel since they were fabricated in the mid-1970's, prior to the introduction of many product and process improvements, and are considered as having limited relevance to today's product. Two other rods had suspicious areas at the bottom of the rod which could not be conclusively identified or confirmed as through wall. Detailed examination of the remaining eight rods (from 3 sites) showed no evidence of leakage or any evidence of the mechanism involved. Four of these rods were examined only by TV while the remaining four were examined by both TV and eddy current techniques. From these examinations it was not possible to identify the leakage mechanism or even confirm that the rods were, in fact, leaking. A significant fraction (2/3) of these rods were second cycle rods (intermediate burnup). In addition, several of these rods had UT signals which were on the boundary of what is normally judged to be leaking and required additional interpretation. The four rods at plant L and one of the two rods at plant P have stronger signals than the rods from the other two sites. In addition, confirmed leaking rods with comparable UT signals were observed in the same campaign at these two sites which tends to support the judgment made by the UT vendor. It can be concluded from the available inspection data that if these last eight rods are leaking, the defect mechanism is not one of the mechanisms confirmed at that time.

Leakage Mechanisms

The above examinations identified three leakage mechanisms to be operative in the time frame from mid-1986 to mid-1989, namely, debris induced fretting, grid-to-rod fretting, rod collapse, which are shown as the first group in Table 2.1-1. Steps were taken by the utilities and Westinghouse to address these potential leakage causes. These steps are summarized in Section 4.

3.2 TASK B: ADDITIONAL ON-SITE EXAMINATIONS AND RECOMMENDATION OF CANDIDATE RODS FOR HOT CELL EXAMINATION

3.2.1 BACKGROUND

Two issues remained from the above program under Task A.

A. A significant population of rods (41 rods in Table 2.1-1) were identified as leaking by UT but were not visually examined. Thus, it was not sure that all leakage mechanisms were identified.

B. Eight rods identified as leaking by UT were examined, but no detectable defect was found. It was not possible to either determine the leakage mechanism or verify if these rods were actually leaking. It could be concluded from the available data that, if the rods were leaking, it was not due to any of the observed leakage mechanisms.

The first issue was addressed by performing additional on-site examinations of rods identified as leaking by UT. These examinations were performed on a combination of rods which had not been examined and further examinations on rods previously examined to some extent. The second issue required a hot cell destructive examination to resolve the status of the rods. The additional site examinations under this task were performed at the following two plants for the reasons given below.

A. Indian Point 3

Both UT and gas sipping examinations were performed on the entire core following Cycle 5 of Indian Point 3. Four rods in four assemblies were identified as leaking by UT. The same four assemblies were identified as leaking by gas sipping. The coolant activity also showed an unusual behavior during the cycle, decreasing by more than an order of magnitude after the initial increase was observed. The examination scope consisted of removal of three leaking fuel rods from three leaking assemblies using a top nozzle repair technique. The rods were then examined using Super Hi-Mag TV. There were two reasons why determining the cause of these leaking rods was desirable. The unusual coolant activity suggested that the leakage cause might be a different mechanism than those previously identified. If it was not possible to identify a leakage site on these rods, they would be prime candidates for further examination since the assembly was confirmed to contain a leaking rod by sipping, which provided added confidence that the rods are, in fact, leaking. A secondary benefit in identifying the leakage mechanism was in understanding the cause of the unusual coolant activity behavior.

B. Callaway

The examination at the end of Cycle 2 identified ten Region 2 and 3 assemblies (inserted in the first cycle) and three Region 4 assemblies (introduced in Cycle 2) that contained leaking rods. The exams performed at the EOC-2 addressed the three Region 4 assemblies and two Region 3 assemblies (which contained five leaking rods). Of the five Region 3 leaking rods examined, only one was confirmed to be leaking (due to debris induced fretting). Since four of the five rods had an undefined leakage cause, it could not be stated with confidence that the dominant leakage mechanism in this fuel was understood. (These rods were eventually sent to the hot cell.) Therefore, the leaking rods from five of the remaining eight Region 2 and 3 assemblies were scheduled to be examined to obtain a better understanding of the operative mechanisms in these regions. The fact that these rods were in their second cycle of operation in Cycle 2 was of significance since it may have suggested a burnup dependent effect (either a leakage cause or an effect which impacts the UT inspection technique). The planned examination workscope included removal of six leaking rods from five assemblies using a top nozzle repair technique. These rods were then scheduled to be examined by Super Hi-Mag TV. Due to events that occurred during the on-site inspection, none of the rods originally scheduled for the examination was actually inspected.

Identification and selection of rods for the hot cell examination were made following the completion of the above site inspections. The Indian Point 3 rods were eliminated from the hot cell candidates since the leakage cause of the rods was found as described later. Four rods from Callaway (C12/K07, C12/M12, C04/J13, and C04/M13), one rod from Byron 2 (P05J/C01) and two other rods from Salem 2 were originally selected as candidates for the hot cell examination. All of these rods were identified to be leaking by UT, but showed no visible anomaly.

During the time frame between when the Callaway and Indian Point campaigns were conducted and shipments were made to the hot cell, additional rods not considered under Task B became available from Byron 1 and 2 and from V.C. Summer. Table 3.2-1 summarizes the onsite inspection results from these three plants. One rod from Byron 1 (D79F/H12), three rods from Byron 2 (T74J/I16, T77K/D02, and S22/C10) and one rod from V.C. Summer (G08/Q16) were finally selected for the hot cell examination program along with the previously mentioned Callaway and Byron 2 rods. All these newly added rods except for rod S22/C10 were confirmed to be leaking, but the leakage causes could not be identified despite the detailed onsite examinations. Rod S22/C10 was identified to be leaking by UT, but showed no visible anomaly. It was determined that the Salem rods would not be sent to the hot cell.

In addition to the examination summary of the additional Callaway and Indian Point 3 campaigns, a summary of the onsite examinations results for the additional leaking rods sent to the hot cell are summarized below even though they were not tasks originally identified under Task B.

3.2.2 INDIAN POINT 3, CYCLE 5 EXAMINATION

The Indian Point Unit 3 coolant activity increased significantly during Cycle 5. At the end of Cycle 5, an on-site investigation campaign was performed to determine the number and nature of the leaking fuel rods in the Cycle 5 core.

TABLE 3.2-1

SUMMARY OF ADDITIONAL PIE RESULTS

Plant	Cycle	Defect Cause Identified			Cause Not Identified		
		Debris Fretting	Grid Fretting	Rod Collapse	Hydride Only	No Visual Anomaly	UT Exam Only
Byron 1	3		4		1		1
V. C. Summer	5				1		2
Byron 2	2	3	1		2	1	
Total		3	5	0	4	1	3

The campaign was performed in two phases. The first phase, which was performed in May 1987 during the EOC-5 refueling outage, consisted of single rod UT testing and fuel assembly sipping examination. The characteristics of the coolant activity in Cycle 5, especially early in the cycle, indicated that the defects had extremely tortuous release paths and thus could have limited water present in the leaking rods. During the planning of the fuel inspection campaign to be performed at the EOC-5, it was suspected that the UT technique might have difficulty in detecting the leaking fuel rods. Because of this concern, it was decided to perform full core UT and sipping inspections and compare the results.

A total of four leaking rods contained in four assemblies were identified by UT. These rods are shown in Table 3.2-2. The gas sipping results revealed the same four assemblies to be leaking (sipping cannot identify individual leaking rods). Subsequent to the EOC-5 refueling outage, three of the four identified leaking rods were removed from the assemblies and visually examined. The fourth leaking rod was also scheduled for removal from its host fuel assembly, but a higher priority plant operation terminated the on-site inspection before the rod was removed.

The leaking rods were removed from the three assemblies (S28, S66, and T53). Visual inspection of all three identified leaking rods confirmed all to be leaking due to debris induced fretting. Since the leakage mechanism was identified, these rods were not included in the hot cell examination program.

3.2.3 CALLAWAY CYCLE 2/CYCLE 3 EXAMINATIONS

A single rod UT examination of all the assemblies from the Cycle 2 core found seventeen rods in fourteen assemblies to be leaking. In addition, four suspect leaking rods were found. These results are summarized in Table 3.2-3. The leakage cause of two of the three once burnt UT identified leaking rods was debris induced fretting. The single rod TV visual examination was also performed on five UT identified leaking rods from two twice burnt assemblies. Of all the twice burnt rods examined, only one rod was found to be leaking with a known cause: debris induced fretting. The remaining four twice burnt UT identified leaking rods showed no sign of defects. (These four rods were later sent to the hot cell.)

UT inspection identified one rod from the Cycle 3 core to be leaking. TV inspection revealed that the cause of the leakage was an incomplete weld.

The second phase campaign was scheduled to include rod removal and detailed visual examination of six identified leaking fuel rods from five assemblies. During the attempted removal of the first fuel rod, the rod was found to be severed and only a portion could be removed from the assembly. Once this portion of the rodlet had been placed in storage, the utility suspended all operations until the situation could be further evaluated. The resident NRC inspector expressed concern over the issue of the severed rod, even though this type of occurrence was not unprecedented. After several days of discussions among Westinghouse, Union Electric, and the NRC, Union Electric opted to terminate the remainder of the planned inspections, due to concerns expressed by the NRC and other schedule conflicts. TV inspections had been performed on the identified leaking fuel rods located on the periphery of the assemblies prior to the rod removal work. Therefore, there were limited TV visual results for the identified leaking rods located on the

TABLE 3.2-2

SUMMARY OF INDIAN POINT 3 EXAMINATION

Assembly	Rod	UT Result	Burnup (MWD/MTU)	Visual Result
R03	G12	Leaking	43,951	Not Examined
S28	I07	Leaking	31,555	Debris Fretting
S66	B14	Leaking	27,444	Debris Fretting
T53	H07	Leaking	15,356	Debris Fretting

TABLE 3.2-3

SUMMARY OF CALLAWAY EOC-2 EXAMINATION

Assembly	Rod	UT Result	Burnup (MWD/MTU)	Visual Result	Hot Cell Candidates
D12	D06	Leaking	22,235	Debris Fretting	
D23	M04	Leaking	22,815	Debris Fretting	
D45	O07	Leaking	18,945	Not Examined	
B01	K07	Leaking	33,957	Not Examined	
B02	F04	Leaking	33,581	Not Examined	
B04	K01	Leaking	33,581	Not Examined	
B34	I11	Leaking	34,217	Not Examined	
	I13	Leaking	34,346	Not Examined	
B48	G10	Leaking	33,660	Not Examined	
C04	J13	Leaking	32,140	No Anomaly	Yes
	M13	Leaking	32,485	No Anomaly	Yes
	A13	Suspect	---	No Anomaly	
	N13	Suspect	---	No Anomaly	
C12	K07	Leaking	31,655	No Anomaly	Yes
	L07	Leaking	32,588	Debris Fretting	
	M12	Leaking	30,948	No Anomaly	Yes
	G01	Suspect	---	No Anomaly	
C15	D17	Leaking	30,585	Not Examined	
C57	P13	Leaking	31,103	Not Examined	
C60	B16	Leaking	20,276	Not Examined	
C50	D10	Suspect	---	Not Examined	

periphery (or in the second row of rods) of the assemblies. The limited view of the periphery and second row rods identified hydride blisters on all the examined rods. However, the cause of the leakage could not be determined.

The four UT identified leaking rods that showed no evidence of visual leakage sites were identified for the subsequent hot cell examinations.

These four rods were also tested during the on-site examination with the eddy current system along the entire rod length except for the bottom 3 inches. No defect or anomaly was detected.

During the manufacturing record review, it was discovered that the four rods had a rework operation which corrected an outage on the minimum plenum length. The repair consisted of gently tamping the rod to close any inter-pellet gaps, thereby increasing the plenum length.

3.2.4 BYRON 1, CYCLE 3 EXAMINATION

The on-site examination workscope for the EOC-3 included ultrasonic testing, TV visuals, reconstitution, and detailed single rod TV visuals.

Ultrasonic testing was performed by Babcock & Wilcox (B&W) on the entire core of 193 fuel assemblies. Five assemblies with six fuel rods were identified as leaking, C22/A05, C40/A12, C40/O03, C48/O10, C56/A10, and D79F/H12. Four of the leaking fuel assemblies were from Region 3 (C22/A05, C40/A12, C40/O03, C48/O10, and C56/A10). One assembly from Region 4 was also identified as leaking (D79F/H12).

TV visuals were performed on individual removed leaking fuel rods. The removed fuel rods were visually examined as they were removed from the assemblies and as they were lowered into the fuel rod storage basket.

The leakage mechanism for the four removed fuel rods in Region 3 was found to be grid-to-rod fretting at the bottom Inconel grid location (Grid 1). A fifth rod from Region 3 was not removed and the leakage cause could not be determined. The leaking cause for the one rod from Region 4 (D79F/H12) could not be determined from the TV exam although the rod was confirmed to be leaking.

Rod D79F/H12 also showed substantial oxide spalling in the middle of the rod. The rod was selected for the hot cell examination.

3.2.5 BYRON 2, CYCLE 2 EXAMINATION

Ultrasonic testing (UT) was performed by Babcock & Wilcox (B&W) on all fuel assemblies from the Cycle 2 core. Six assemblies were identified to have a total of seven leaking fuel rods: T77K/D02, T21/P03, T21/P04, T70/F11, T74J/I16, S22/C10, and S23/B10.

The visual examination revealed that one of the seven fuel rods was leaking due to grid-to-rod fretting. Three of the fuel rods were leaking due to debris induced fretting. Two other once burnt rods (T77K/D02 and T74J/I16) were confirmed to be leaking. Open hydride blisters were observed on these rods. However, the primary cause of the leakage could not be determined from the visual examination. The one remaining twice burnt rod (S22/C10) showed no visual evidence of leakage sites. These latter three rods with unknown causes were selected for further examination in the hot cell.

3.2.6 V. C. SUMMER, CYCLE 5 EXAMINATION

The UT examination performed at the EOC-5 originally identified one fuel assembly with two leaking fuel rods. In addition, twenty-one assemblies were initially identified to have suspect leaking rods; all but two of these were cleared by rescan. One of these assemblies, originally identified as a suspect, was found to be leaking by visual inspections. This assembly (G08) was reconstituted through the top nozzle with the leaking rod replaced by a stainless steel rod.

Although hydriding was observed on the leaking fuel rod, the primary cause of the leakage could not be determined. The two UT identified leaking fuel rods were not visually examined due to their interior location in the fuel assembly. The rod with an unknown leakage cause (G08/Q16) was identified to be examined further in the hot cell.

3.2.7 V. C. SUMMER, VANTAGE 5 EXAMINATION

An on-site non-destructive inspection was performed on four VANTAGE 5 demonstration assemblies in November 1988. These assemblies completed three cycles of irradiation in V. C. Summer with an average burnup of 46,050 MWD/MTU.

Visual examinations indicated the performance and mechanical condition of the assemblies was good. Light to medium crud deposits were evident between grids 1 through 5. Heavy crud deposits were observed between grids 5 through 7, especially in the areas located below and above the IFM grids on several of the fuel rods. Also, there were isolated cases of spalling crud observed on several fuel rods. Contact marks were visible on the fuel rods at structural and IFM grid locations but no evidence of fretting was found.

Oxide thickness measurements of rods removed from the assemblies showed a maximum thickness of 93 microns. The maximum oxide thicknesses were observed between spans 5 through 7 and exceeded the values that would be expected at this burnup.

Removal and reinstallation of the reconstitutable top nozzle were performed successfully on two demonstration assemblies, VV-1 and VV-2. Twenty-three fuel rods were removed, examined, and seventeen fuel rods were reinserted back into these assemblies. Six fuel rods were left out of assembly VV-2 for possible future on-site or hot cell inspections. Four of the six fuel rods were selected for the hot cell examination.

3.2.8 ROD SELECTION AND SHIPMENT FOR HOT CELL EXAMINATION

Rod Selection Process

The results from the on-site examinations mentioned in Sections 3.1 and 3.2 can be categorized into two basic groups: The first group consisted of rods for which the leakage cause was identified by the on-site examinations. Corrective actions have been identified and implemented to address these mechanisms. There remained, however, a significant number of rods in the second group, rods for which a leakage mechanism could not be defined despite detailed on-site examination. Some could not even be confirmed to be leaking. The leakage cause for these rods needed to be resolved so that corrective actions can be defined and implemented to prevent future leaking rods from this cause(s).

The objectives of the hot cell examination, were therefore, 1) to confirm the leakage status of questionable leaking rods, 2) to determine the leakage mechanism for any confirmed leaking rods, and 3) to identify possible reasons for UT miscalls, if any. Proper selection of the rods to be sent to the hot cell was key for the above objectives to be accomplished.

A meeting was held with the program participants in September, 1989 to select the rods to be shipped to the hot cell. The original shipment was planned to be made in late 1989 and early 1990 to the hot cell facilities operated by the United Kingdom Atomic Energy Authority in Sellafield, United Kingdom. The shipment was delayed at that time due to problems encountered in shipping logistics and licensing problems with the shipping cask in the UK. Following this delay, the decision was made to perform the examination in the hot cell facilities operated by the Atomic Energy of Canada Limited (AECL) in Chalk River, Ontario. During this period, several additional fuel rods were incorporated into the program as mentioned earlier.

The final rod selection was based on the September 1989 review and subsequently available poolside data described in the above Section 3.2. A total of twelve rods were selected for the leaking mechanism investigation. These twelve rods consisted of two non-leaking rods from Callaway, four UT identified leaking rods from Callaway and two from Byron 2 which showed no visual evidence of leakage, and four confirmed leaking rods with an unknown cause from Byron 1, Byron 2, and V.C. Summer. The four UT identified leaking rods from Callaway and one from Byron 2 were part of rods identified in Table 2.1-1. The others were part of rods identified in Table 3.2 1 and selected as additional rods.

The VANTAGE 5 demonstration fuel rods from the V. C. Summer reactor were not originally considered for the program because they were not identified as leaking rods. The VANTAGE 5 fuel assemblies achieved an assembly average discharge burnup of 46,050 MWD/MTU. Nondestructive inspection after three cycles of irradiation revealed evidence of localized thick crud and high corrosion. Although these rods were not leaking, they were considered good candidates for a hot cell examination due to the unusual crud and the high oxide levels and were judged to merit detailed evaluation. The four VANTAGE 5 rods included one standard OFA and three IFBA rods.

Characteristics of the Selected Rods

The final inventory of rods selected for the hot cell examinations summarized in Table 3.2-4, included six rods from Callaway, five rods from Byron 1 and 2, and five rods from V.C. Summer. These sixteen rods fall into four different groups.

The first group consisted of two non-leaking rods which were included in the hot cell examination to assist in the evaluation of any possible UT mis-classifications. These rods, rod A10 of assembly B48 (rod B48/A10) and rod G01 of assembly C12 (rod C12/G01) from Callaway were to be examined in the bottom span and compared to characteristics observed on any of the UT identified leaking rods which may be found to be non-leaking. Rod B48/A10 is from the same manufacturing lot as rod B48/G10 which was found to be severed during the supplemental examinations at Callaway. Rod C12/G01was initially classified as a suspect leaker by the UT vendor, but later cleared. This rod also showed no visual or eddy current indications during the on-site examination.

The second group consisted of six rods which were identified as leaking by UT examination at the site, but showed no evidence of defects by visual and, in some cases, eddy current inspection. These include rods J13 and M13 of assembly C04 (rods C04/J13 and C04/M13) from Callaway; rods K07 and M12 of assembly C12 (rods C12/K07 and C12/M12) from Callaway; rod C01 of assembly P05 (rod P05J/C01) from Byron 2; and rod C10 of assemblyS22 (rod S22/C10) from Byron 2. The initial objective of the hot cell examination of these rods was to determine if they are leaking. For rods which are found to be leaking, the second objective was to determine the leakage cause. For rods which are found to be not leaking, the second objective was to characterize the lower elevation of the rod where the UT examination was performed so that the reason for the mis-classification can be investigated.

Four of the rods were confirmed to be leaking during visual inspection at the site, but did not have an identifiable root leakage cause. These included rod H12 of assembly D79F (rod D79F/H12) from Byron Unit 1, rod I16 of assembly T74J(rod T74J/I16) and rod D02 of assembly T77K (rod T77K/D02) from Byron Unit 2, and rod Q16 of assembly G08 (rod G08/Q16) from V.C. Summer. The observed leakage sites generally consisted of hydride blisters. Rod D79F/H1 2 also exhibited an unusual flaking surface appearance. This flaking condition has been observed on several leaking rods from other sites. The primary objective of the hot cell examination of these rods was to identify the root leakage cause. A summary of the visual observations on the rods is shown in Figures 3.2-1 through 3.2-4.

The four VANTAGE 5 demonstration rods from V.C. Summer - rods D07, J14, K14, and J05 of assembly VV2 (rods VV2/D07, VV2/J14, VV2/K14, and VV2/J05) - made up the fourth group of rods. These rods are non-leaking, but showed evidence of unusual crud deposits and higher than expected oxide film thicknesses, as mentioned earlier. Three of the rods contain ZrB_2 coated fuel pellets (IFBA fuel). The primary purposes of the hot cell examination of the rods were to understand the nature of the crud deposits, and to determine the effect of the crud on the oxide thicknesses and the hydrogen uptake in the cladding. The rod internal pressure measurements of the IFBA fuel rods were also considered to be valuable information. A summary of the visual observations of these rods is shown in Figures 3.2-5 through 3.2-8.

TABLE 3.2-4

CHARACTERISTICS OF LEAKING RODS SHIPPED TO HOT CELLS

Fuel Assembly/ Fuel Rod ID	Rod Type	Cycles of Operation	Rod Burnup (GWD/MTU)	UT Status	Visual Defects	Comments
Callaway Rods						
B48/A10	17 STD	2	33.8	Non-Leaking	N/A	Reference Rod
C12/G01	17 STD	2	29.6	Suspect/Non-Leaking	No	Reference Rod
C12/K07	17 STD	2	31.7	Leaking	No	No Eddy Current Indications
C12/M12	17 STD	2	31.0	Leaking	No	No Eddy Current Indications
C04/J13	17 STD	2	32.1	Leaking	No	No Eddy Current Indications
C04/M13	17 STD	2	32.5	Leaking	No	No Eddy Current Indications
Byron 1 Rod						
D79F/H12	17 OFA	2	38.1	Leaking	Yes	Flaking Surface
Bryon 2 Rods						
P05J/C01	17 OFA	1	17.7	Leaking	No	
S22/C10	17 OFA	2	31.9	Leaking	No	
T74J/I16	17 OFA	1	22.6	Leaking	Yes	
T77K/D02	17 OFA	1	22.9	Leaking	Yes	
V. C. Summer						
G08/Q16	17 OFA/V-5	1	19.2	Suspect/Non-Leaking	Yes	
VV2/J14	17 OFA/V-5	3	48.3	N/A	N/A	High Crud/Oxide
VV2/D07	17 OFA/V-5	3	46.1	N/A	N/A	High Crud/Oxide
VV2/K14	17 OFA/V-5	3	48.6	N/A	N/A	High Crud/Oxide
VV2/J05	17 OFA/V-5	3	47.5	N/A	N/A	High Crud/Oxide

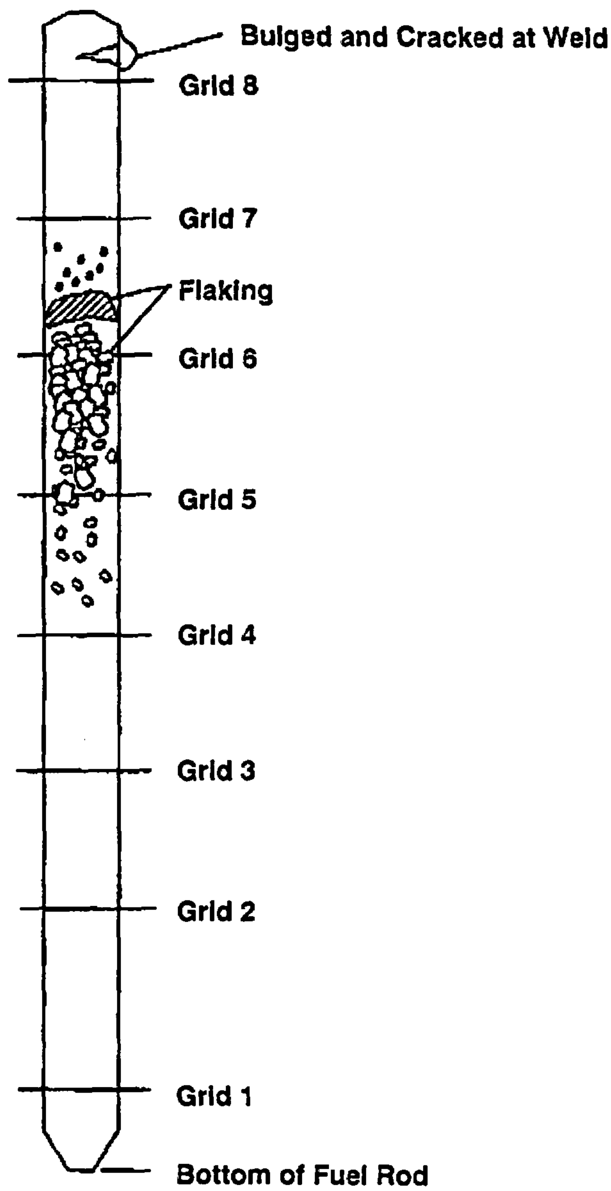


Figure 3.2-1. Byron 1 - Rod D79F/H12

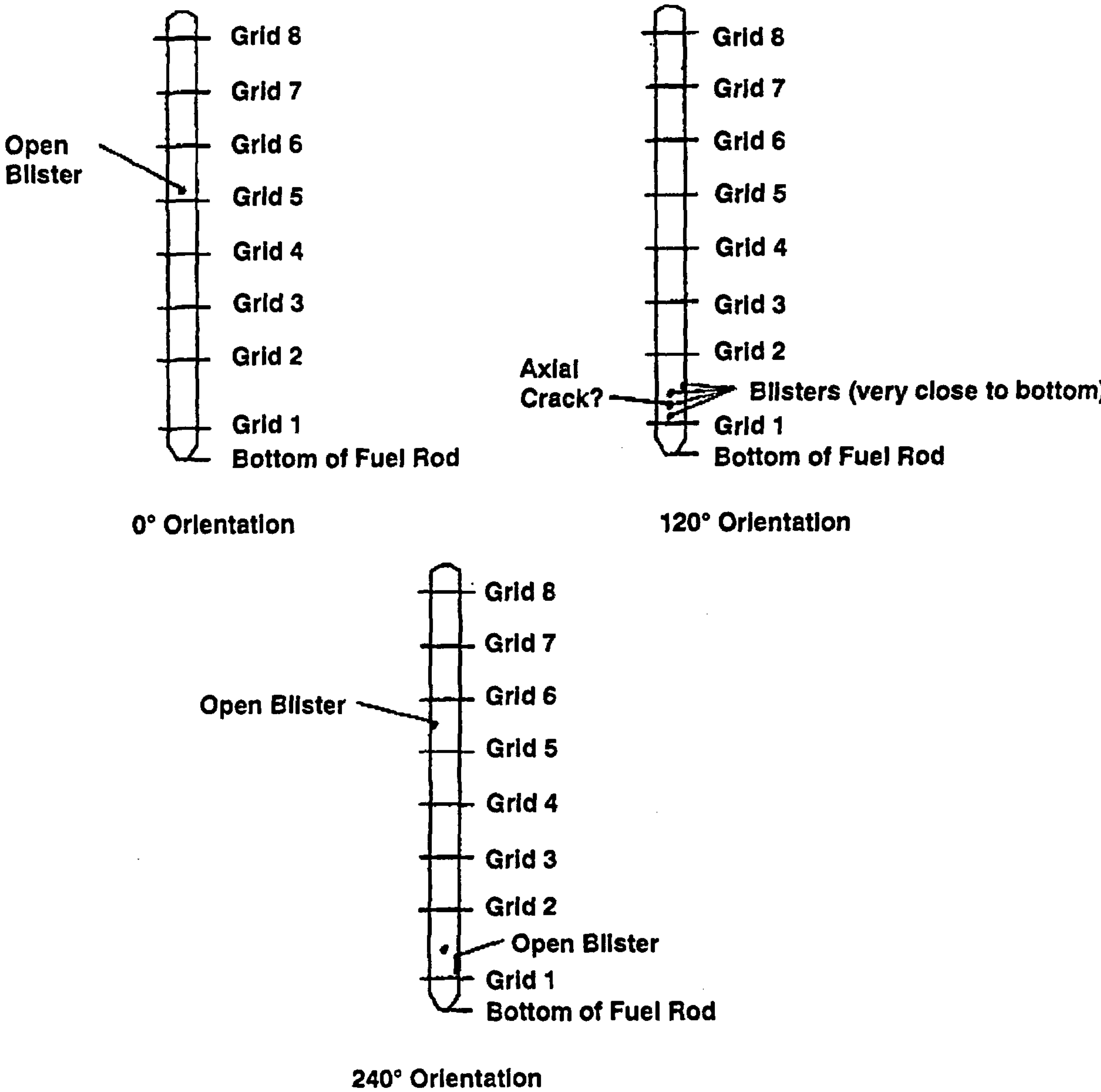


Figure 3.2-2. Byron 2 - Rod T74J/I16

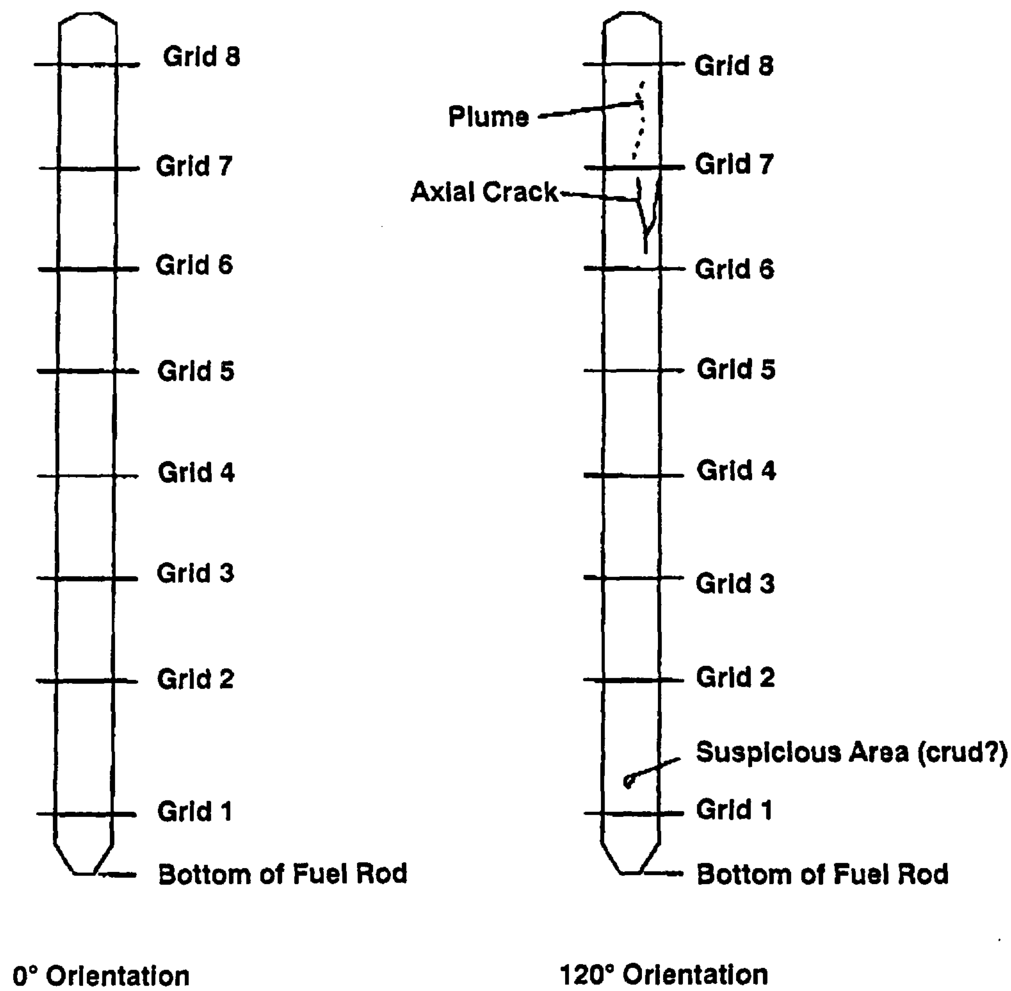


Figure 3.2-3. Byron 2 - Rod T77K/D02

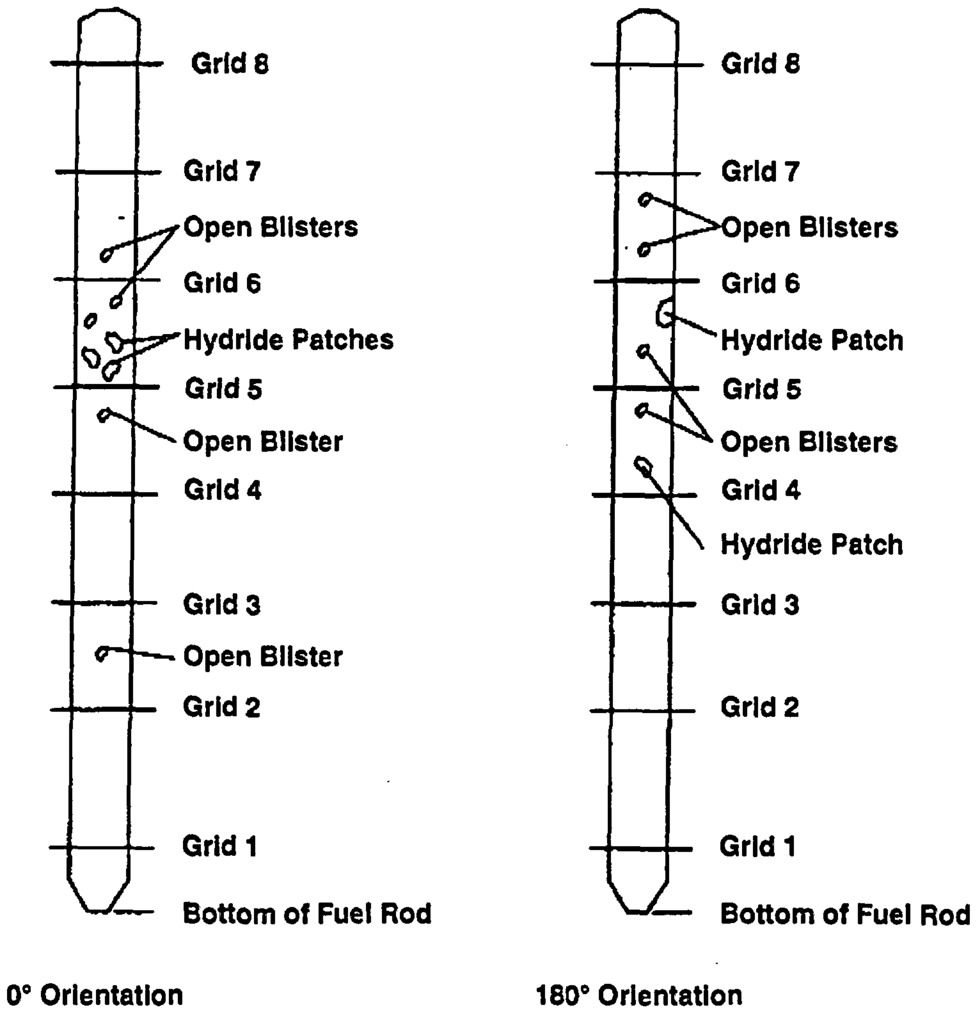


Figure 3.2-4. V.C. Summer - Rod G08/Q16

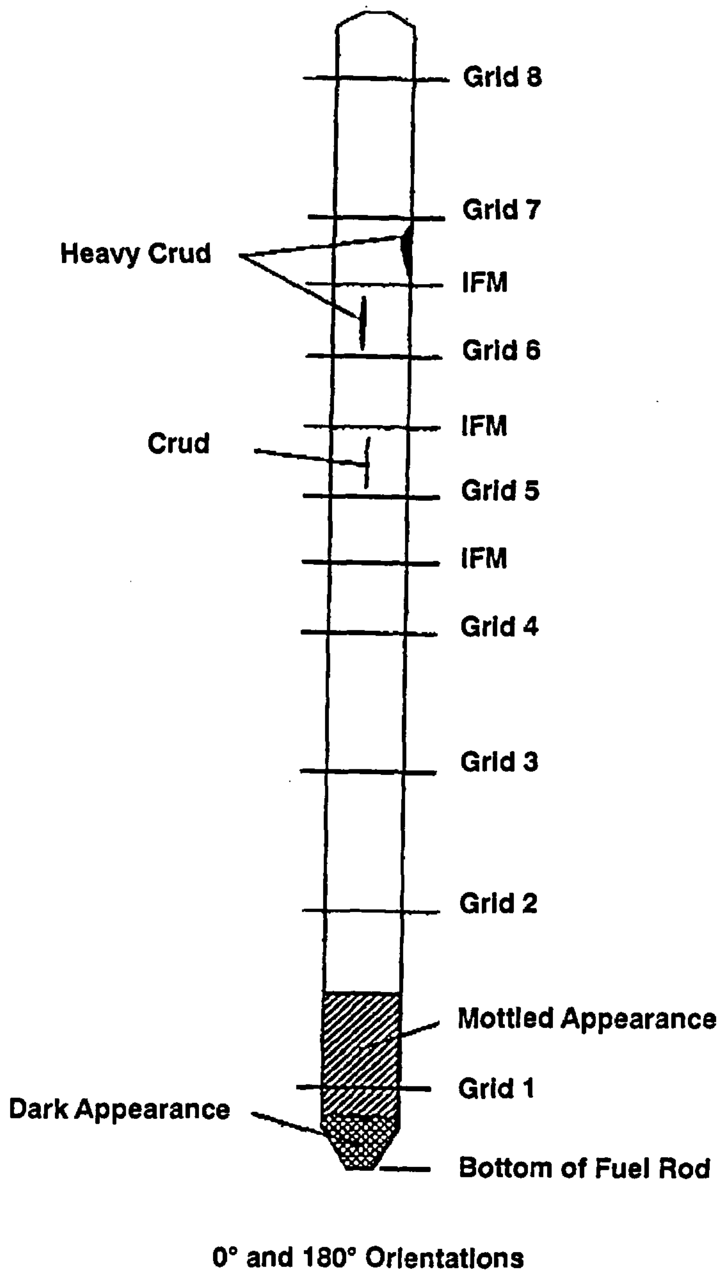


Figure 3.2-5. V.C. Summer - Rod VV2/D07

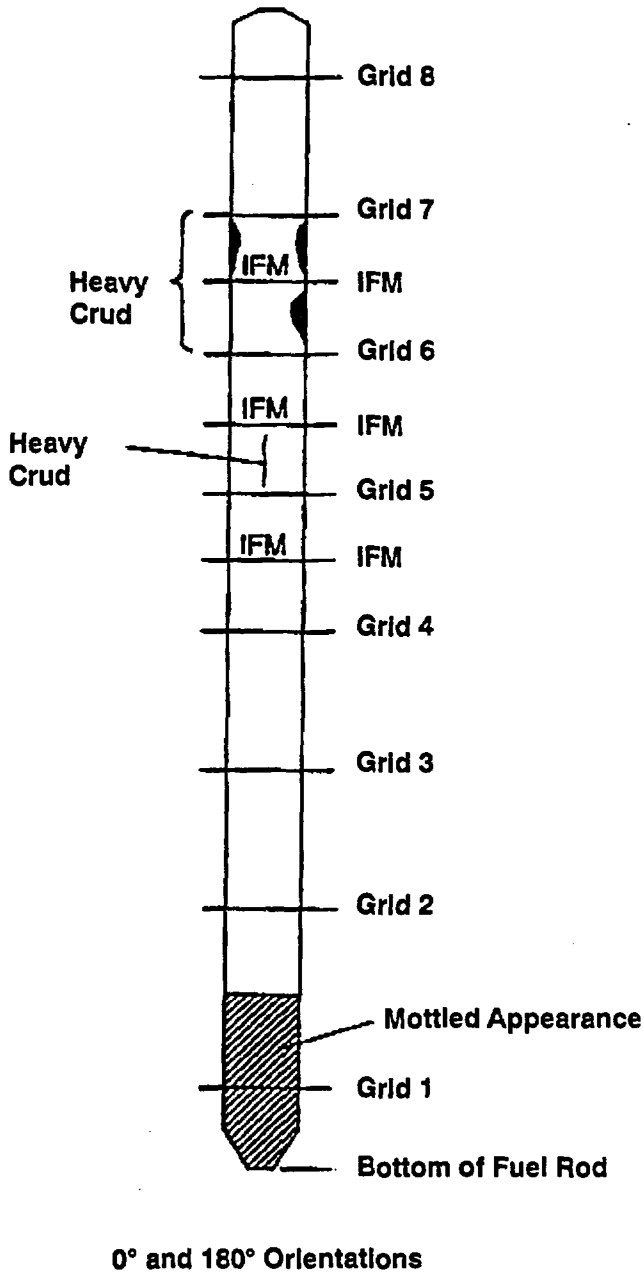
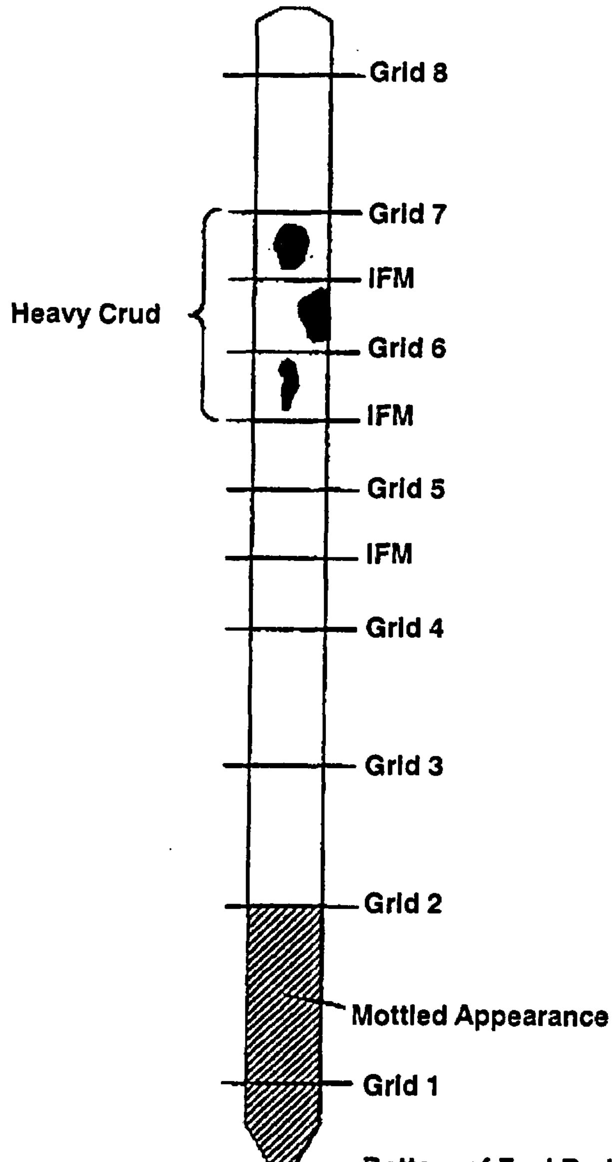


Figure 3.2-6. V.C. Summer - Rod VV2/J14



0° and 180° Orientations

Figure 3.2-7. V.C. Summer - Rod VV2/K14

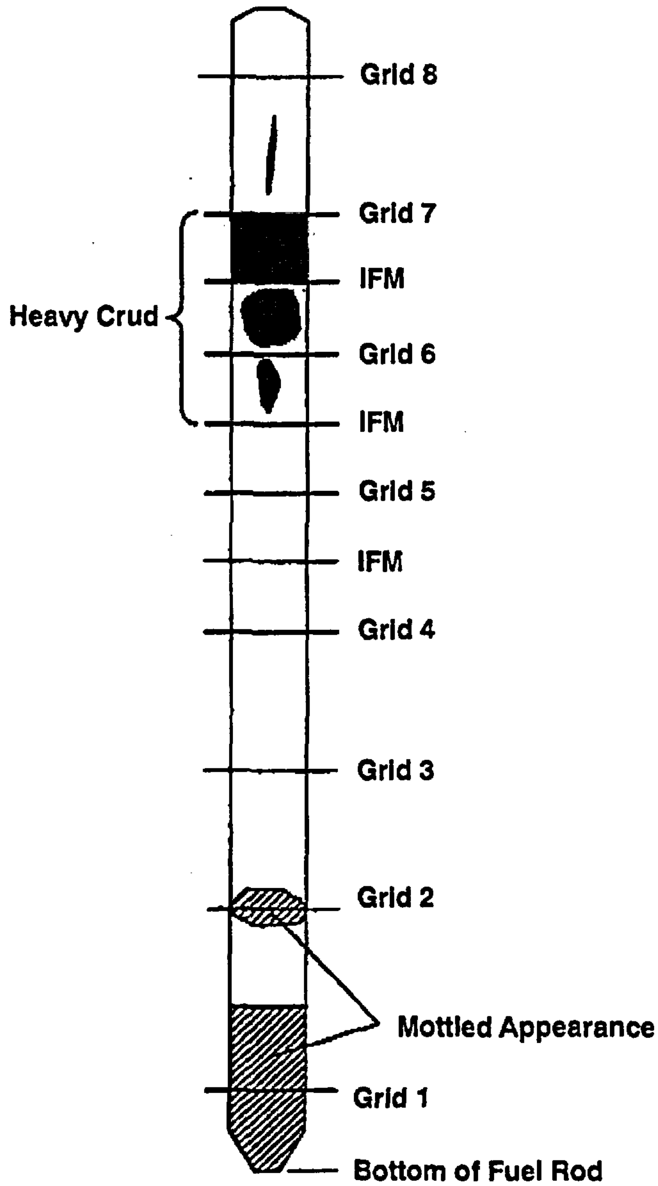


Figure 3.2-8. V.C. Summer - Rod VV2/J05

Fuel Rod Shipment

The fuel rods to be examined were sent to the AECL facilities in three separate shipments. The shipments were made in the NLI 1/2 cask owned by Nuclear Assurance Corporation (NAC). The first shipment was made from the V. C. Summer site to Chalk River, Canada in September, 1990. The cask had been used immediately prior to the V. C. Summer shipment to transport some fuel rods from the Calvert Cliffs reactor to Chalk River as part of an EPRI/Combustion Engineering program. Following the shipment from V. C. Summer to Chalk River, the cask was returned to NAC in Savannah River, South Carolina. High contamination levels were noted on the cask when it arrived at the V. C. Summer site from Chalk River. The next two shipments were made back-to-back from the Callaway site in April, 1991 and from the Byron site in May, 1991. Following the two shipments, the cask was returned to NAC in Savannah River, South Carolina.

The individual fuel rods were loaded into a specially designed sealed canister which isolated the fuel rods from the surrounding environment in the reactor spent fuel pools. The canisters were purged with helium so that the shipping environment was dry, and then transferred to the NLI 1/2 cask. A special fixture was designed to fit into the cask and accept the sealed container. The canister was placed into the cask and shipped to Chalk River. The cask was then placed into a fuel storage pool, the canister removed from the cask, and then stored in the pool area in a dry condition until transfer to the hot cell. Immediately prior to the hot cell examination, the canisters were transferred into an AECL on-site cask and transported to the hot cell. The end of the canister was then pulled into the hot cells and the rods removed into the cell. All transfers were made without incident.

The sealed canister proved to have several advantages. It served to simplify operations both at the site and at Chalk River during unloading. Since the canister was loaded with the fuel rods before the cask arrived on-site, the cask loading operations at the site involved only a single operation with the canister rather than multiple fuel rod transfers which could increase the amount of time the cask was on-site. Also, the operations in the fuel storage pool were considerably simplified. The canister was removed and placed in a storage location. This was of considerable value since the cask had to be unloaded in a horizontal position due to the fuel storage pool depth. Unloading of individual fuel rods which would subsequently require upending to a vertical position would have been considerably more complicated than for the single canister. It also served to protect the cask and surrounding areas from any contamination from any fuel degradation which could have occurred. Although no degradation occurred during shipping which could have caused problems, the sealed canister would have isolated any such contamination if it would have occurred.

Another critical operation was found to be the decontamination of the cask after it had been removed from the various pool areas. Care needs to be taken in the decontamination to insure that the cask is clean when it arrives at its destination.

3.3 TASK C: HOT CELL EXAMINATION

3.3.1 INTRODUCTION

This task was mainly funded by ESSERCO and Westinghouse with supplemental funding from EPRI.

The original hot cell workscope for the sixteen rods shipped was completed in early 1994. Because the results of 3 rods indicated some extent of fuel degradation, ESSERCO decided to expand the workscope to investigate the fuel degradation phenomena. The details of the hot cell examination will be published by ESSERCO at the completion of the extended project in 1995. This section summarizes the key findings obtained under the original workscope, which includes the following:

1. Rod puncture and fission gas analysis (12 rods: 2 sound reference rods; 6 rods with UT leaking indications but no visual defects; 4 V.C. Summer VANTAGE 5 rods)
2. Leak testing (4 rods)
3. Detailed visual examination (16 rods)
4. Crud analysis (4 VANTAGE 5 rods)
5. Metallography (16 rods)
6. Clam shell examination (one Callaway non-leaking rod; one Callaway UT overcall rod; one Byron 2 UT overcall rod)
7. Clad hydrogen analysis (4 VANTAGE 5 rods)

The original plan to perform neutron radiography was suspended because of unavailability of the NRX reactor at Chalk River during the period of this hot cell investigation. Clamshelling of some rod sections as listed above was performed as a replacement of neutron radiography.

3.3.2 SUMMARY OF RESULTS OF 12 RODS FOR LEAKAGE CAUSE INVESTIGATION

The leakage status (as based on the poolside inspection and the hot cell rod puncture and internal gas analysis) of the 12 rods examined are shown in Table 3.3-1. Of the 6 rods identified by on-site UT examination as leaking, five were determined to be sound. The remaining rod, Byron rod P05J/C01, was determined to be leaking because water was found seeping out of the punctured hole during rod puncture. The results confirmed that 5 out of the 6 UT identified leaking rods were due to UT overcalls.

TABLE 3.3-1

UT LEAKAGE DETECTION AND HOT CELL CAUSE IDENTIFICATION

Assembly/ Rod ID	Number of Operations	Poolside Inspection		Hot Cell PIE Results	
		UT	Visual Defect	Rod Puncture	Leakage Cause
Callaway					
B48/A1	2	Not leaking	Reference	Not leaking	Not leaking
C12/G01	2	Not leaking	Reference	Not leaking	Not leaking
C12/K07	2	Leaking	No	Not leaking	UT overcall
C12/M12	2	Leaking	No	Not leaking	UT overcall (fuel bonding)
C04/J13	2	Leaking	No	Not leaking	UT overcall
C04/M13	2	Leaking	No	Not leaking	UT overcall
Byron 2					
S22/C10	2	Leaking	No	Not leaking	UT overcall (fuel bonding)
P05J/C01	1	Leaking	No	Failed	Potential seal weld defect
T74J/I16	1	Leaking	Hydride blisters	N/A	Endplug piping
T77K/D02	1	Leaking	Hydride blisters	N/A	Endplug piping
Byron 1					
D79F/H12	2	Leaking	Hydride blister/ Flaking oxide	N/A	Possible hydrogenous contamination
V. C. Summer					
G08/Q16	1	Leaking	Hydride blisters	N/A	Possible hydrogenous contamination

Of the 5 confirmed leaking rods, it was found that 2 had end plug piping defects. One is suspected to have a defect at the upper end plug seal weld. The remaining two rods had no detectable defects at the end plugs and welds. Since they showed only hydriding, it was concluded that those two rods were most likely leaking due to hydrogenous contamination.

A. Primary Leaking Mechanisms

End Plug Piping

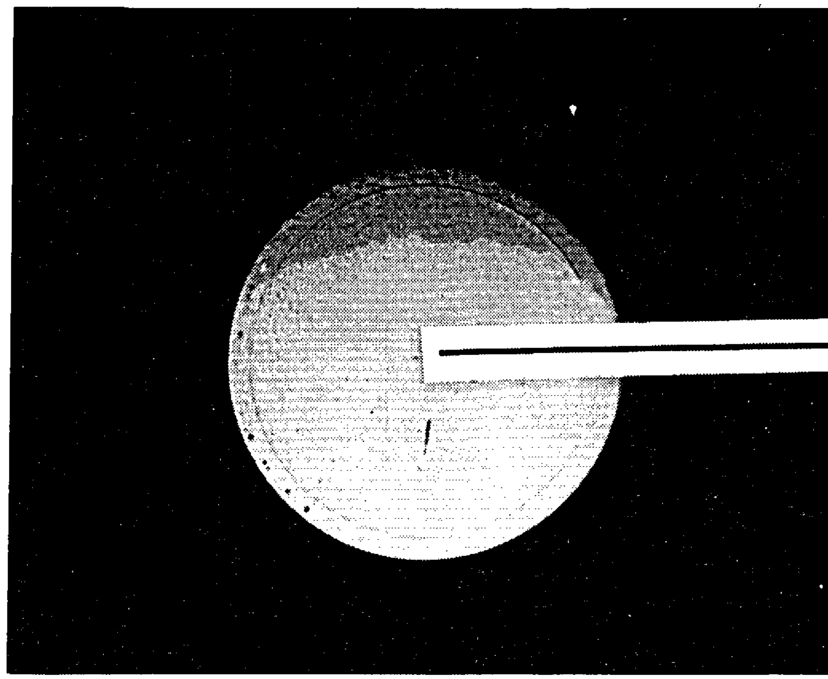
Byron rods T74J/I16 and T77K/D02 were determined to be leaking due to end plug piping in the bottom end plug. Figure 3.3-1 shows a typical example of the observed end plug piping. It is postulated that the coolant water would enter the rod through the end plug piping defect due to the pressure differential as soon as reactor operation begins. Hydrogen is produced from the ingressed water by radiolysis, cladding inner surface corrosion and possibly UO_2 oxidation. Since the defects are very small ($\leq$3 microns), a low H_2O/H_2 ratio develops close to the initial leak site and hydriding occurs in the vicinity of the primary leak. Both rods showed hydride blisters several inches above the bottom end plug. Very similar to small PCI cracks, the end plug piping defects could be re-sealed by corrosion and lubricants remaining from the fabrication process. Once the piping is sealed, the rod would be expected to behave like a rod defected by primary hydriding.

Possible Hydrogen Contamination

Because both rods D79F/H12 and G08/Q16 showed nothing but extensive clad hydriding, it is judged that the rods are most likely leaking due to hydrogenous contamination incurred during manufacture. Although significantly high waterside corrosion was observed on rod D79F/H12, it is believed that corrosion is not the root cause since no sign of significant clad thinning due to corrosion was noted. Once hydrogen is released from hydrogenous contaminants during reactor operation, it attacks the cladding and causes hydride defects in a similar manner as moisture in the fuel rod would. Since none of the other rods from the same manufacturing lot were found to be leaking, it is believed that these extraneous contaminations are isolated and random events. A number of process improvements have been made in the fuel pellet, tube, and fuel rod internal component areas to eliminate possible sources of contamination. Although D79F/H12 was a twice burnt assembly, a number of defect characteristics observed on rod D79F/H12 such as high corrosion, massive hydriding, and grain growth suggest that the rod could have been operated with high temperature for a long time, implying that the rod could have been leaking since the first cycle of operation. This is consistent with the coolant activity observed at the Byron 1 reactor.

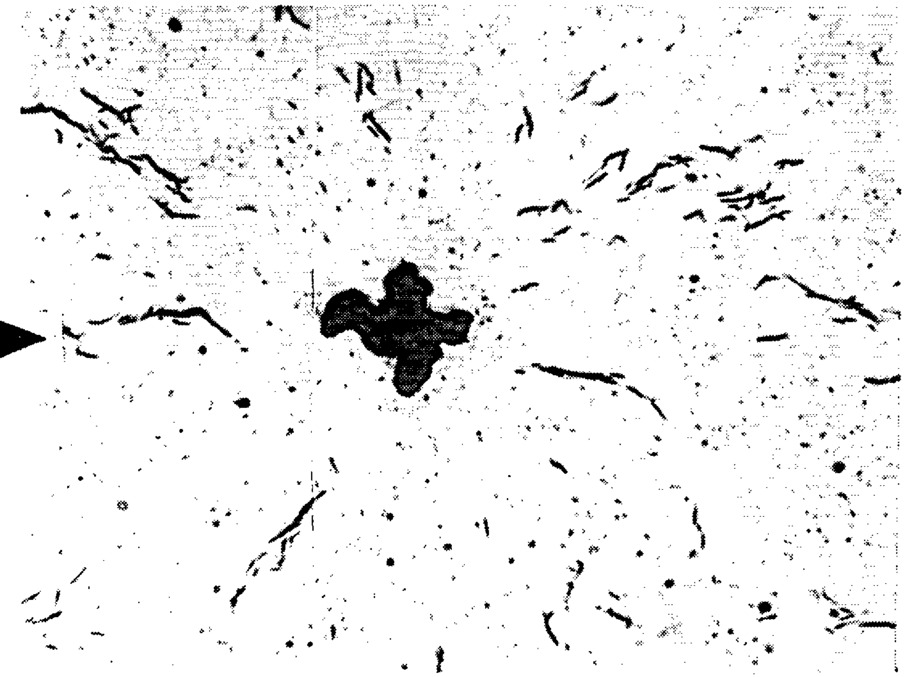
Possible Seal Weld Defect

Although rod P05J/C01 was found to have water inside, leak test, eddy current examination, and metallography did not positively identify any leak site. The only area found to be a potential leak site was the seal weld region of the top end plug.

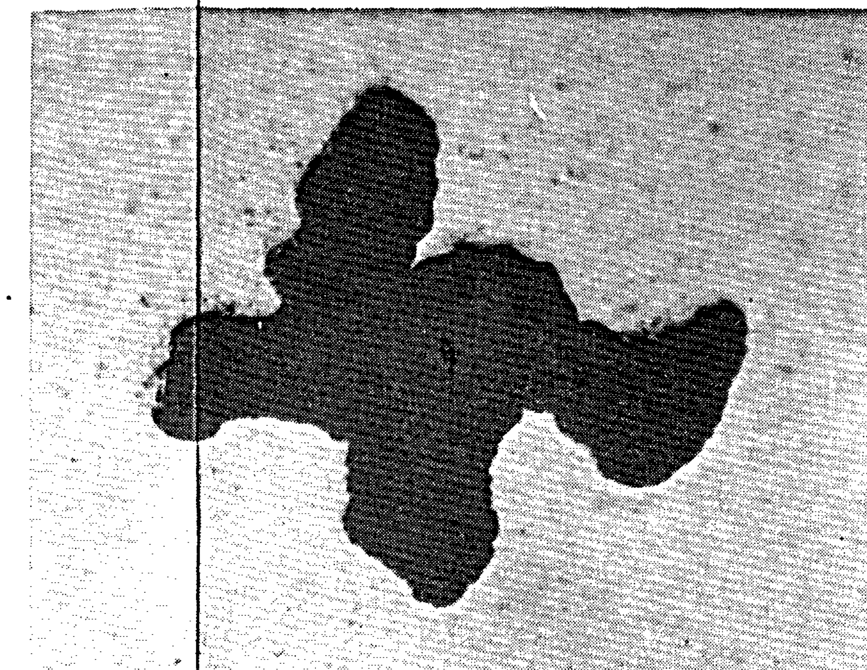


Cross Section of Bottom End Plug 5.75X

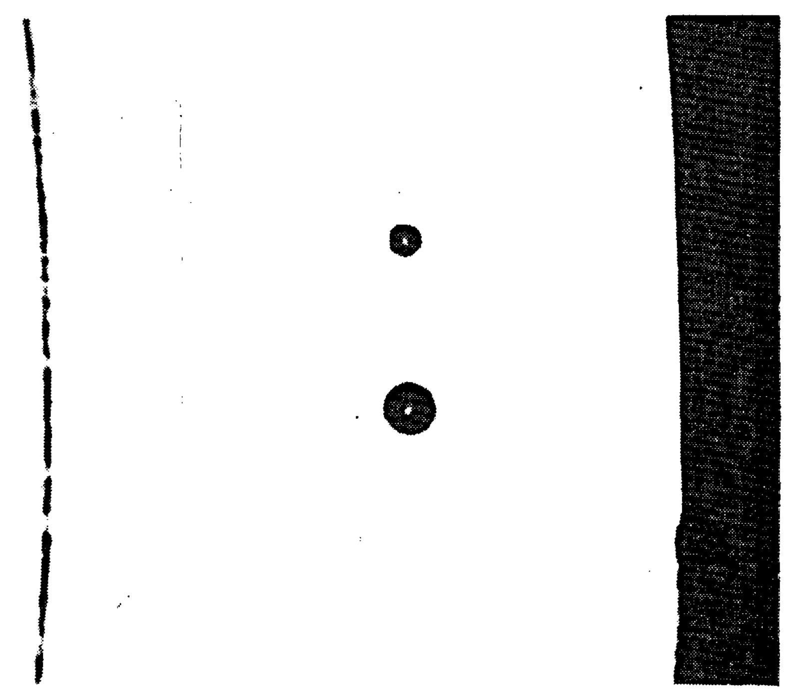
(Etched)



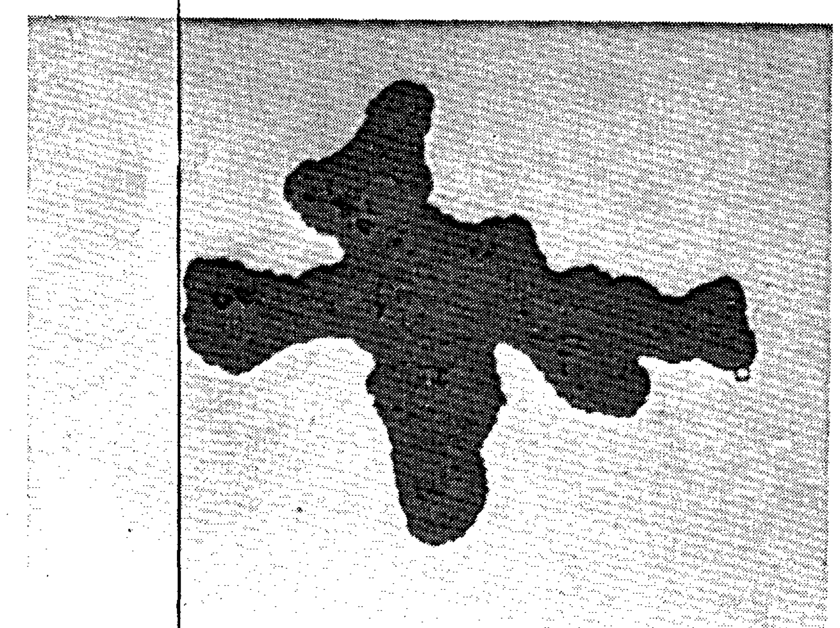
End Plug Piping 100μm 250X



End Plug Piping Rod T74J/I16 25μm 1000X

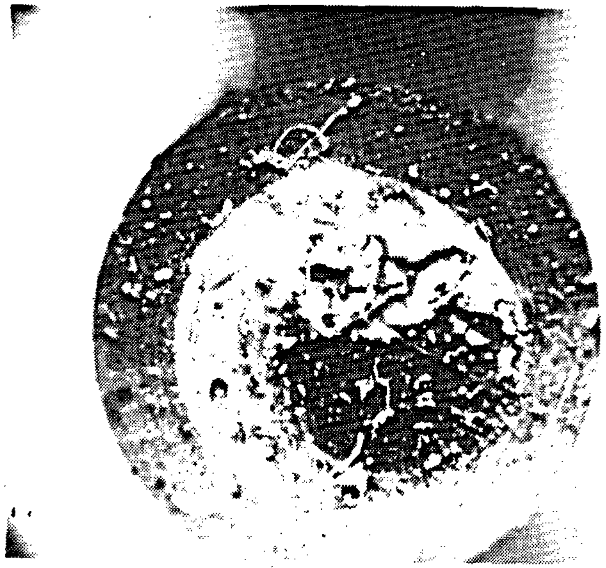


Porosities in Cladding 100μm 150X

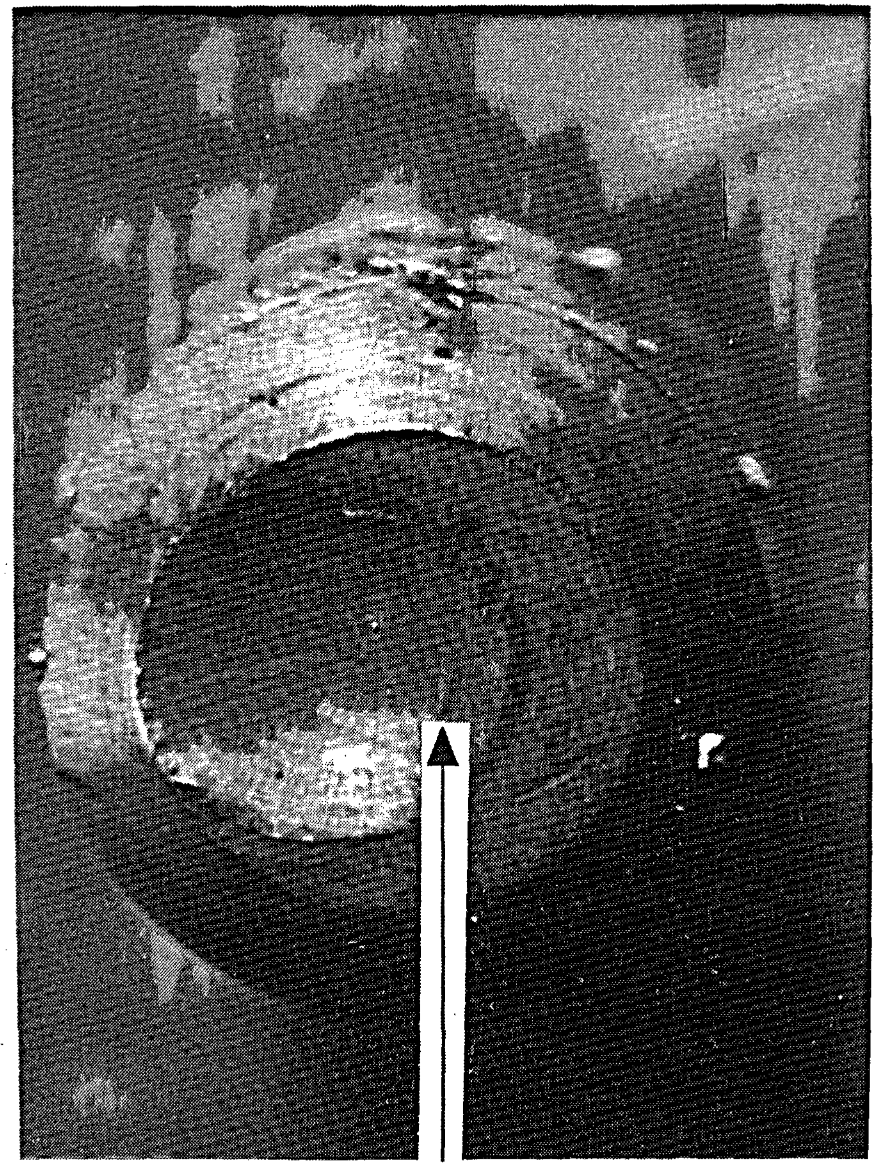


End Plug Piping Rod T77K/D02 25μm 1000X

Figure 3.3-1. End Plug Piping in Two Byron-2 Rods (T74J/I16 and T77K/D02)



Before Cleaning



After Cleaning

Suspicious discolored mark

Figure 3.3-2. Appearance of Top End Plug Seal Weld Region, Rod P05J/C01

Corrosion on the surface of the pressurization hole showed comparable thicknesses to corrosion on the outer surface of the top end plug, suggesting that the pressurization hole was exposed to the reactor coolant from the beginning of life. A suspicious discolored spot observed within the seal weld region (See Figure 3.3-2) suggested that the rod may have been leaking due to an improper seal weld. If this is the leakage cause, it is an extremely isolated event.

B. UT Accuracy

The four Callaway rods and two Byron rods, which were identified as leaking by UT but showed no leakage site, were examined at the hot cell. The hot cell examination revealed that only Byron rod P05J/C01 was leaking, suggesting that the reduced signals on the remaining rods were caused by something other than water in the rod. In order to determine reasons for the UT mis-classification, clamshell examinations were performed on two Callaway and one Byron rods at the lower sections where the UT inspection was performed. The comparison between the cladding inner surfaces of the non-leaking Callaway rod B48/A10 and UT identified leaking Callaway rod C12/M12 and Byron rod S22/C10 showed that the cladding inner surface of rod B48/A10 (See Figure 3.3-3) was fairly clean, indicating essentially no pellet-clad interaction. On the other hand, the cladding inner surface of rods C12/M12 and S22/C10 showed pellet fragments still adhering to the cladding wall. This indicates that the latter two rods had more extensive pellet-cladding contact and interaction. This examination result suggests that the pellet-cladding contact could have potentially caused the reduced UT signals. Although the exact cause of the stronger pellet-cladding contact at the bottom of the rod is not known, it was noted that both rods had some form of repair or extra handling during manufacture.

In conclusion, the hot cell results clearly suggest that reduced UT signals can be caused by effects other than water in the rod, resulting UT overalls. Strong pellet-clad interaction is a possible reason for the mis-classification. Since the hot cell data confirmed that UT testing sometimes has a large uncertainty in detecting leakers, it may be prudent to combine UT testing with other leak testing methods. It should be noted that UT testing is still the only available technique to determine locations of leaking rods in the assembly which is essential to reconstitute leaking assemblies.

C. Rod Secondary Degradation

Out of the 5 failed rods, only rod P05J/C01 from Byron 2 showed no evidence of secondary defects. Rod D79F/H12 from Byron 1 exhibited extensive oxide spalling at the high power locations. The remaining three rods (T74J/I16, T77K/D02 from Byron 2 and G08/Q16 from V. C. Summer) all exhibited secondary hydride damage in the form of hydride blisters and localized massive hydriding. One rod, T77K/D02 also exhibited short length axial cracks at hydrided locations. Metallographic examinations were performed to evaluate those secondary defects. The results are summarized below.

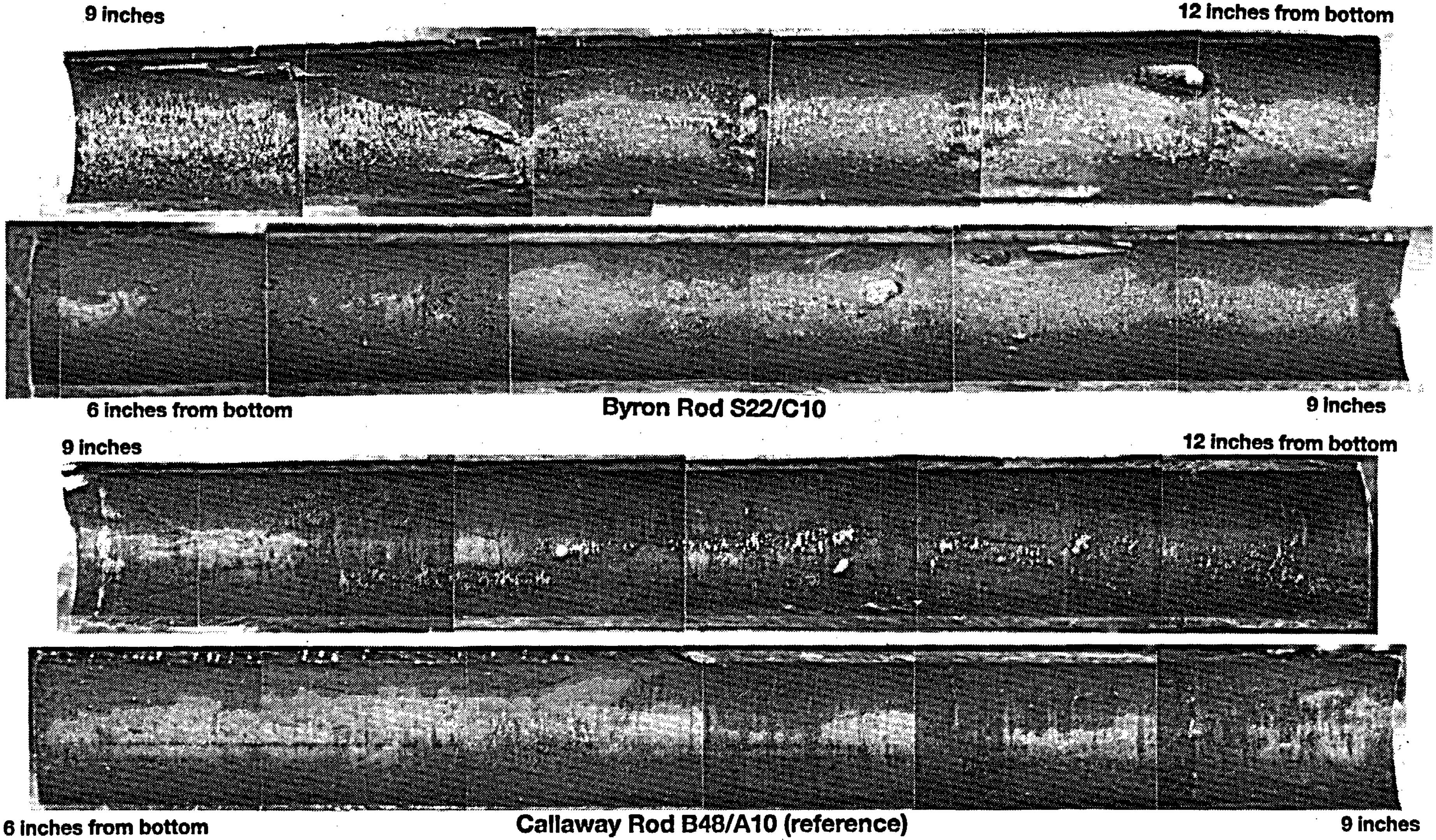


Figure 3.3-3. Inner Surface of Clamshelled Cladding

Cladding Axial Cracks

One of three axial cladding cracks detected on Byron rod T77K/D02 by leak test on the mid-section of the rod showed extensive hydriding and clad cracks, as shown in Figure 3.3-4.

Top End Plug Hydriding

Two Byron rods, T74J/I16 and T77K/D02 showed a circumferential cladding crack detected by leak test in the top girth weld region. This defect was found to be caused by massive hydriding of the top end plug (see Figure 3.3-5).

Extensive Oxide Spalling

Byron rod D79F/H12 showed extensive O.D. oxide spalling along the length of the rod, extending from 80 to 120 inches. The maximum corrosion measured in the oxide spalling region was 210 microns. The oxide thickness on the inner cladding surface was also large (typically about 110 microns) in this region. Figure 3.3-6 shows a cross section of the oxide spalled region.

Massive Hydriding at Pellet-to-Pellet Interface

Rod D79F/H12 was fractured in the hot cell during handling at a location showing the worst oxide spalling. The cross section of the broken surface showed that the break occurred at a pellet-to-pellet interface where solid hydride precipitation was observed. Hydrides in the oxide spalling region generally migrated to the oxide spalled areas and pellet-to-pellet interfaces as shown in Figure 3.3-7.

Significant Fuel Microstructure Changes

Fuel microstructure in rod D79F/H12 showed a number of indications that the rod experienced high temperature operation: a structureless cladding-fuel interaction zone; possible fuel oxidation; grain growth - columnar and equi-axed; formation of gas bubbles at grain boundaries; and metallic fission product precipitates at grain boundaries. Figure 3.3-8 shows a typical example of the observed fuel microstructure changes.

3.3.3 SUMMARY OF RESULTS OF FOUR V. C. SUMMER VANTAGE 5 RODS

Although the V.C. Summer VANTAGE 5 rods were not leaking, they were destructively examined to evaluate the unusual crud deposits and the higher than normal cladding O.D. oxide observed during the onsite examination. Internal rod pressure of the IFBA rod was also of interest.

Fission Gas Analysis

The ZrB_2 coated pellets in the IFBA rods produce helium ions by a B^{10} (n, alpha) reaction which results in the end of life internal rod pressures of these rods being higher than that of a non-IFBA rod. The measured rod pressures of the three IFBA rods were about 20 percent higher than the non-IFBA rod which was considerably lower than expected. Fuel microstructure examinations of the IFBA rods showed numerous small pores formed in the interaction zone between the zirconium diboride coating film and the UO_2 fuel, Figure 3.3-9. The reason for the lower than expected internal rod pressure of the IFBA rods is postulated to be due to trapping of helium in these pores, and the surrounding UO_2, ZrB_2, and cladding instead of being released into the rod internal gap.

The measured fission gas release ranged from 1.3 to 1.6 percent. The low gas release values were not un-expected considering the low power levels at which the rods operated. They were very consistent with the data from other low powered rods in different reactors at the comparable burnup levels. The low fission gas release was also consistent with the observed fuel microstructure. As discussed later, the fuel microstructure was very typical of low powered fuel that had been irradiated at low temperatures. Figure 3.3-10 plots the fission gas release values for V.C. Summer VANTAGE5 rods as well as the other rods examined at the hot cell.

Crud Analysis

During the on site examinations of the V.C. Summer VANTAGE 5 demonstration assemblies, long, narrow strips of crudded regions were observed on a number of rods at the upper spans where the IFM grids were located. All four V.C. Summer VANTAGE 5 rods examined at the hot cell showed evidence of these strips with varying degrees of surface coverage. In some places, the strip covered almost the entire rod circumference. However, the crud analysis showed that a large percentage of the collected material for each sample was found to be ZrO_2 and that very little Fe, Ni, and Cr, which are major constituents of crud, were found. The concentrations of lithium and boron were also very low. These results suggest that most of crud probably flaked off from the crudded regions of the cladding surface during rod handling at the site/hot cell and fuel rod shipment. It was reported by AECL that a high radiation level was detected at the bottom of the shipping canister when these V.C. Summer rods were unloaded into the Universal Cell, which is indicative that the crud had flaked off during the shipment.

Waterside Corrosion and Hydriding

The metallographic measurements of waterside corrosion (up to 81 microns for the clad circumferential average of the area excluding oxide spalling and oxide pit regions) showed the expected trend of increasing corrosion with increasing distance from the bottom of the rods. The results reflect the increase in metal/oxide temperature resulting from the progressive increase in coolant temperature up the rods. The waterside corrosion data from metallography were compared to the corresponding onsite eddy current data, Figure 3.3-11. The comparison revealed that essentially no bias exists between the two types of data. Oxide spalling was observed at the upper elevations of the rods examined. The spalling was caused by delamination at the base of the corrosion films due to thick oxide.

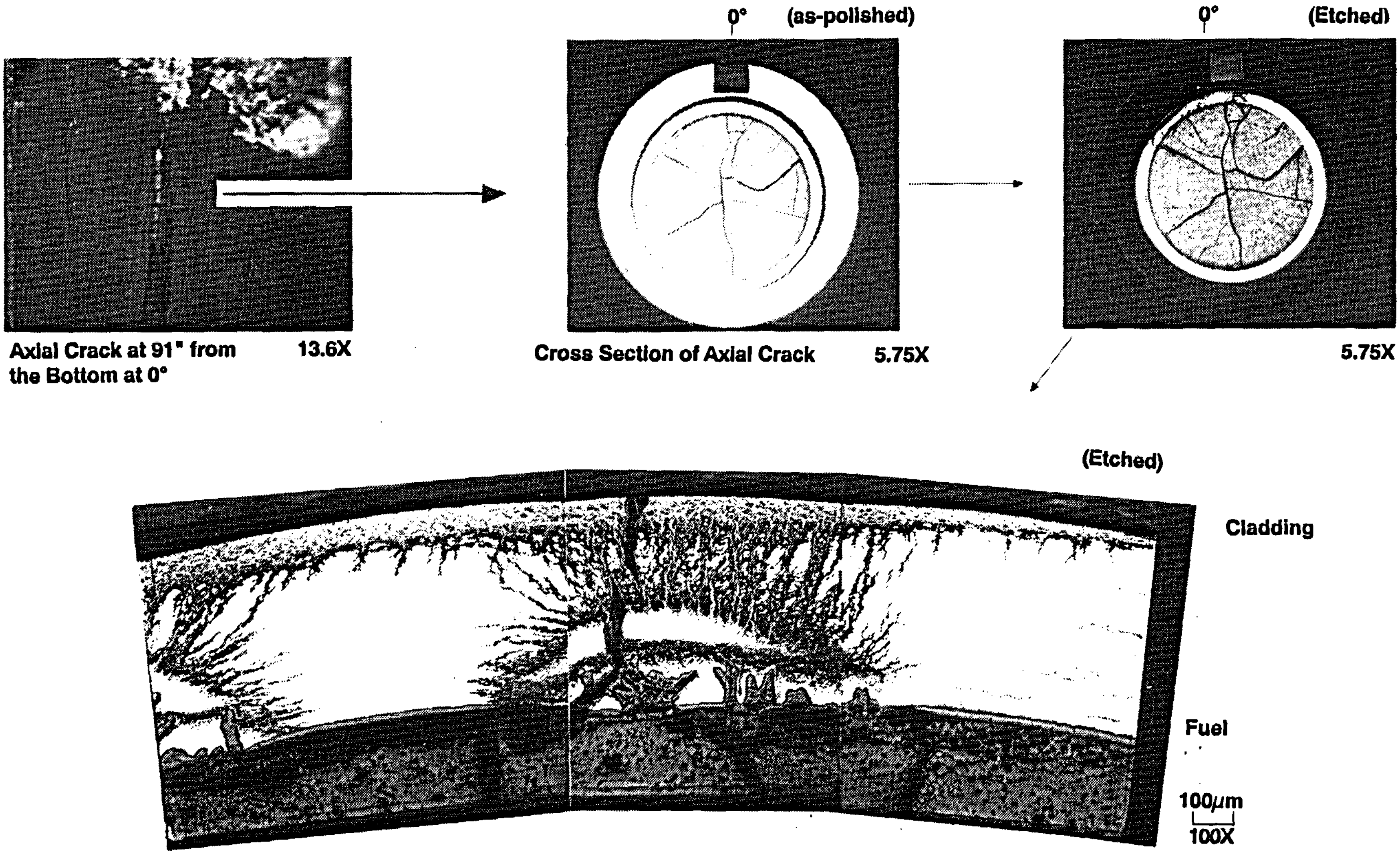
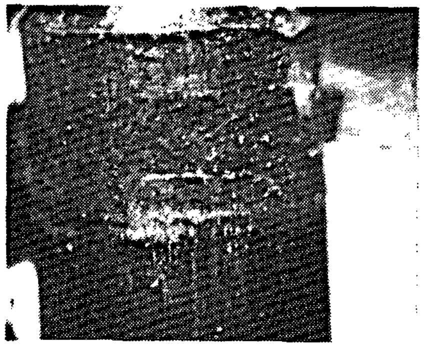
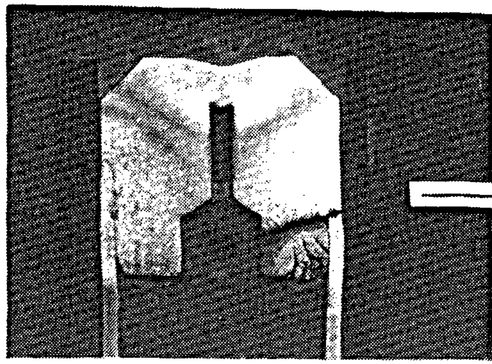


Figure 3.3-4. Axial Crack Due to Massive Hydriding, Rod T77K/D02, at 93" from the Bottom



Crack in Top End Plug Weld Region 7.4X

(Etched)



Longitudinal Cross Section of Top End Plug 5.75X

(Etched)

200μm 50X

Figure 3.3-5. Circumferential Cladding Crack in Top End Plug Weld Region Caused by End Plug Hydriding, T74J/I16

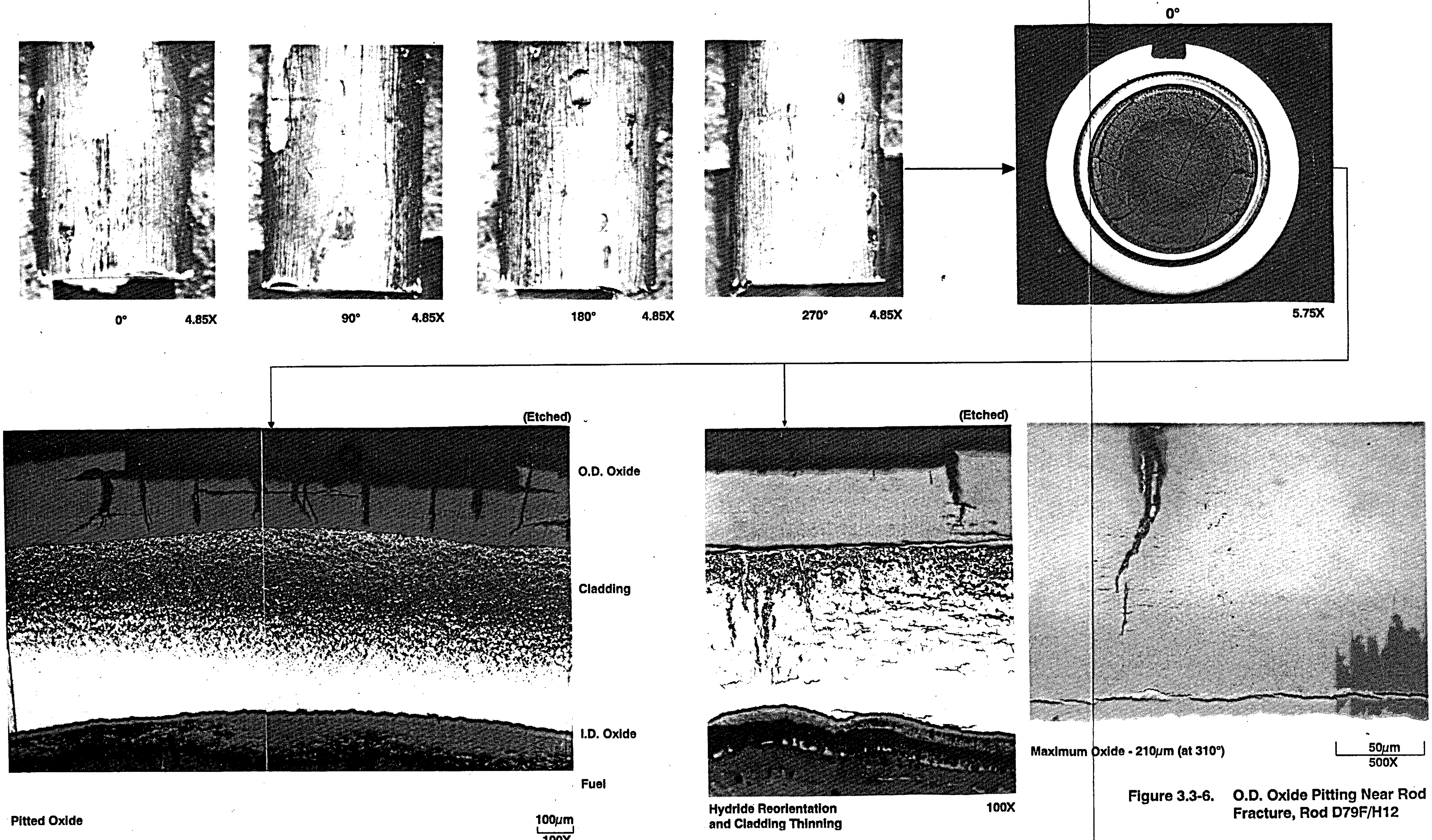


Figure 3.3-6. O.D. Oxide Pitting Near Rod Fracture, Rod D79F/H12

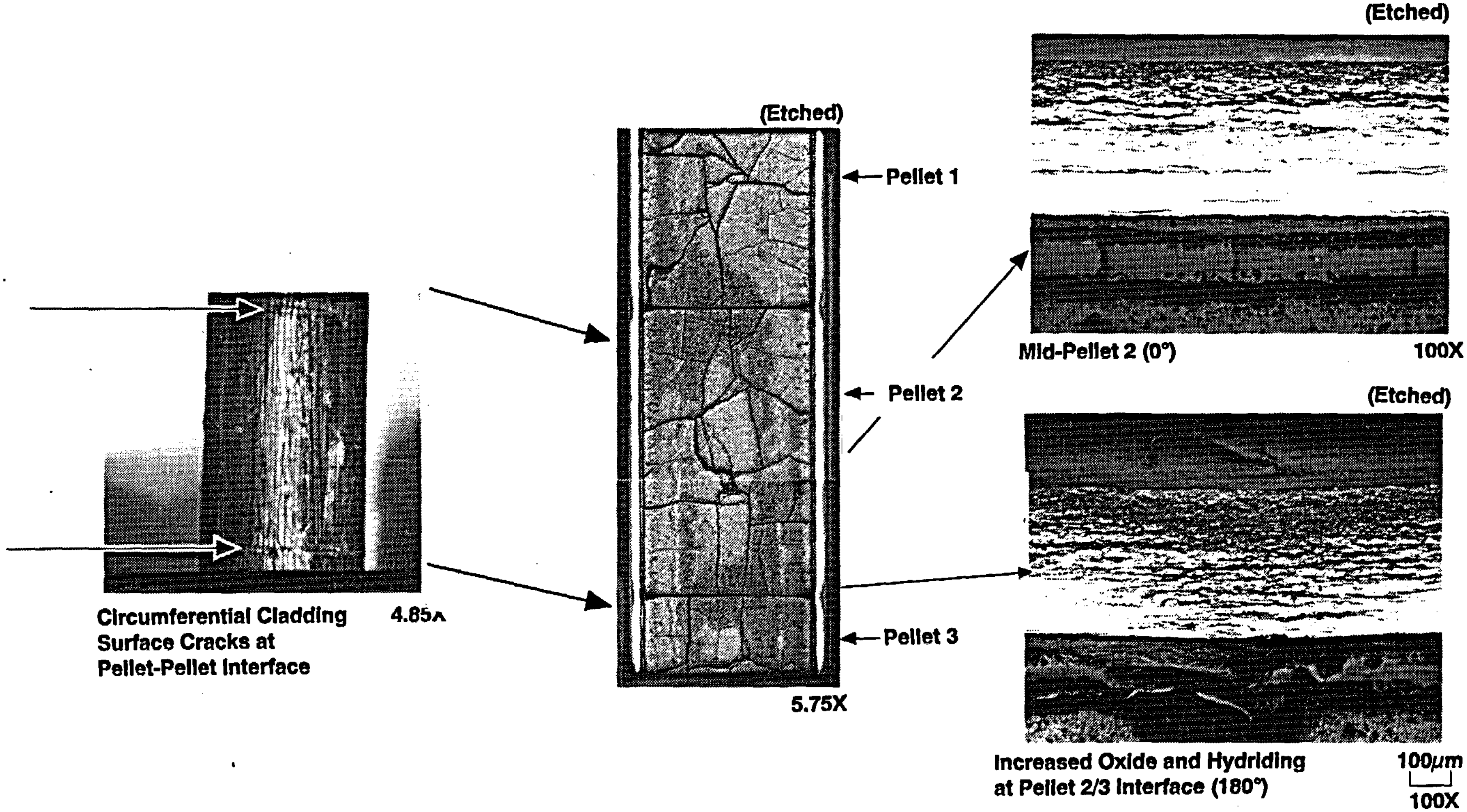


Figure 3.3-7. Increased O.D. Oxide and Hydride Precipitates at Pellet-Pellet Interfaces, Rod D79F/H12

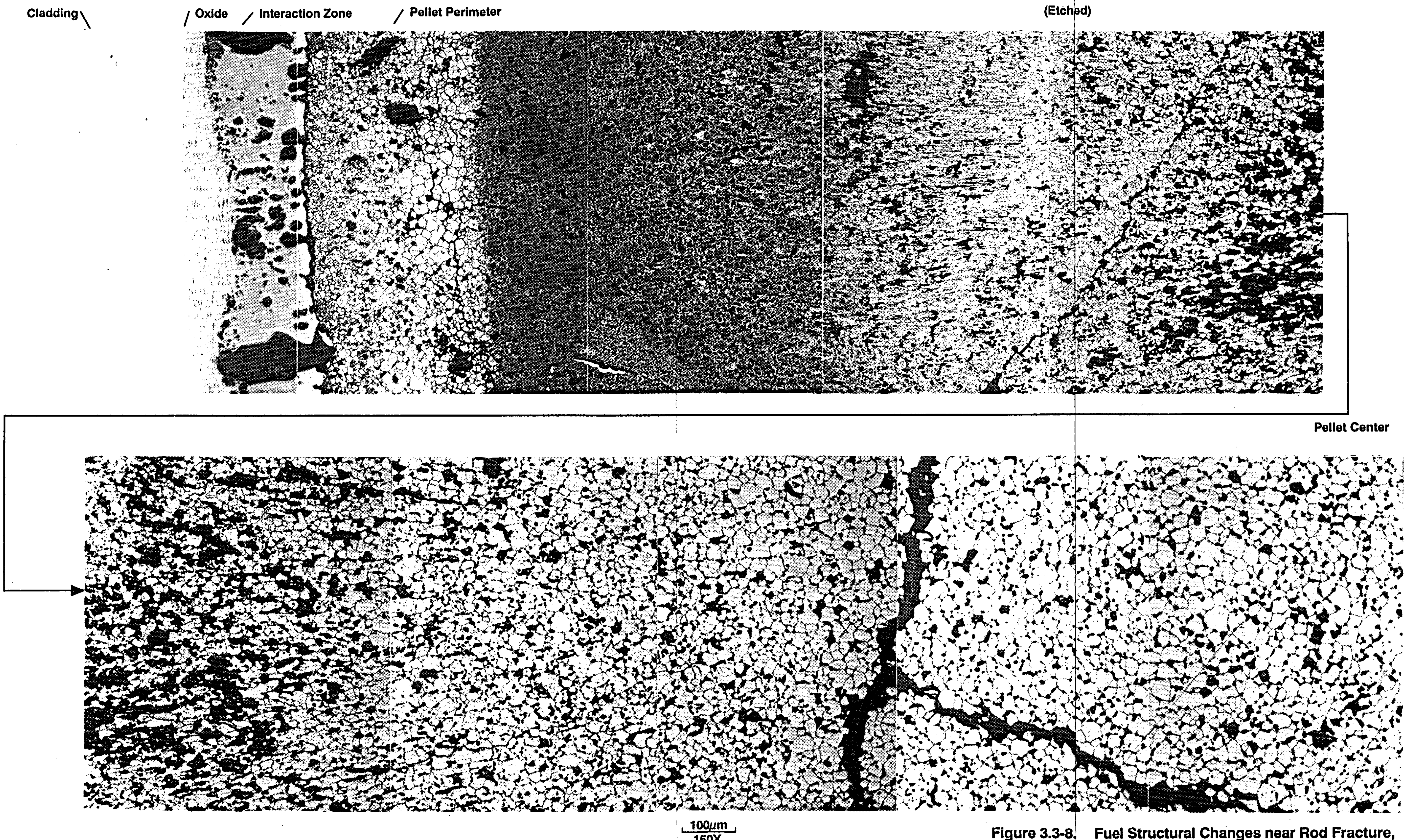


Figure 3.3-8. Fuel Structural Changes near Rod Fracture, Rod D79F/H12

Uniform thin clad I.D. oxide, ranging from 6 to 12 microns in thickness, was observed on the samples from a non-IFBA rod, VV2/J05. The IFBA rods showed essentially no I.D. oxide films between the clad inner surface and ZrB_2 coating.

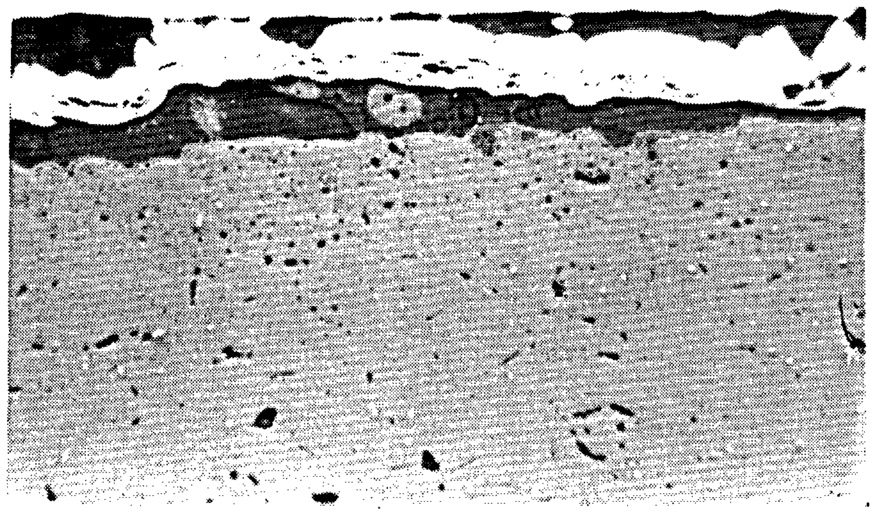
The local hydrogen content as a function of oxide thickness is shown in Figure 3.3-12. The highest hydrogen pickup was measured to be 595 ppm at about 130 inches from the bottom. The comparison between the cladding hydrogen pickup data and the average corrosion data shows that the amount of the hydrogen pickup is proportional to the corrosion thickness (see Figure 3.3-13). The cladding fractional hydrogen absorption calculated from the hydrogen and oxide data ranged from 13.4% to 21.6% with an average of 17.7%. It can be seen in the figure that the fraction is relatively constant with oxide thickness up to an oxide thickness of 3 mils.

Crud appeared to have affected local waterside corrosion since specimens from the crudded regions showed different O.D. corrosion and hydride precipitation characteristics than specimens from the non-crudded regions. Waterside corrosion of the non-crudded samples were generally uniform azimuthally. Waterside corrosion of the crudded samples generally showed several localized areas of oxide spalling, each covering the cladding azimuthally anywhere from 10 degrees to 45 degrees. The oxide spalling was associated with a significant local increase in waterside corrosion (see Figure 3.3-14). The maximum corrosion observed in these areas was 196 microns, about 2.5 times more than the thickness of the average corrosion of the non-crudded areas. These areas showed numerous oxide pits which had a smooth surface. Hydride concentration in this region was much less than the other areas.

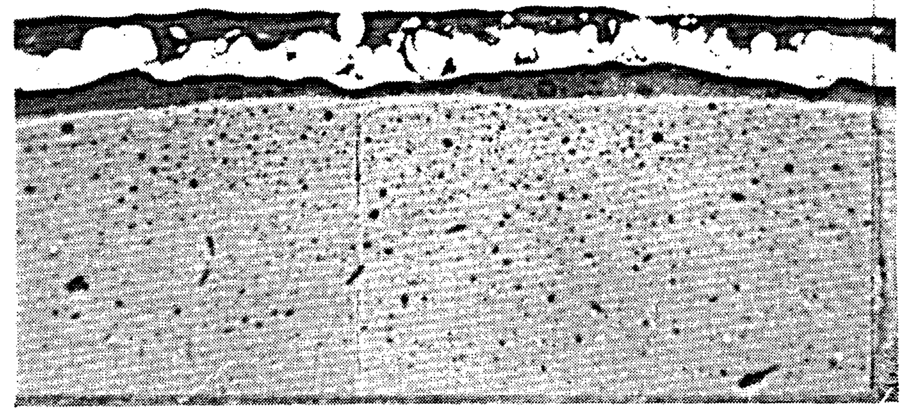
The oxide spalled areas showed two distinctively different local hydride concentrations. Some samples at spalled areas showed slightly less concentration of hydrides than at other areas, indicating that the spalled areas were hotter than other locations of the clad circumference during irradiation. This implies that thicker oxide at these locations was present on the cladding during irradiation and spalled off during subsequent fuel handling and/or transportation. On the other hand, other samples showed a solid hydride patch in the oxide spalled area at the outer region of the cladding (see Figure 3.3-15). It is believed that the thicker O.D. oxide films at these locations were spalled off during irradiation, creating cooler spots where hydrides tend to migrate during irradiation. In spite of the localized concentration of hydride precipitates at the oxide spalled areas, the average hydrogen pickup levels were comparable to the other data.

Fuel Microstructure

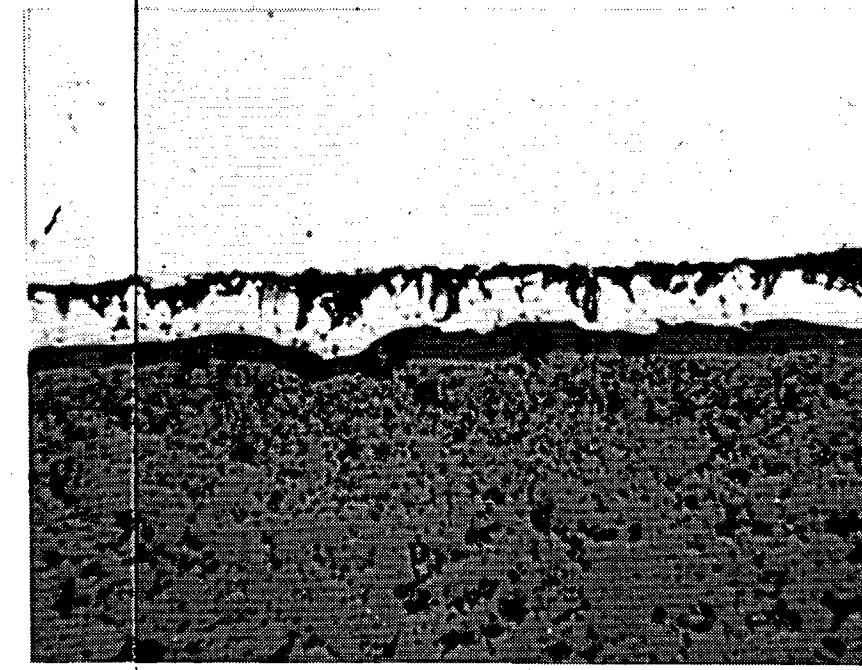
Fuel microstructure of both standard OFA rod and IFBA rods exhibited stable behavior. No structural difference was seen between the standard OFA and IFBA rods. Essentially, no restructuring phenomena were observed except the "rim effect" seen in the fuel peripheral region and the dark band seen in the fuel outer region. The rim region was characterized as a porous region (cauliflower microstructure) where the initial grain boundary structure has disappeared and seems to be replaced by a very small grain structure (1 micron size). The dark band was characterized as numerous pores in the grains. The fuel microstructures were generally consistent with the measured low fission gas release.



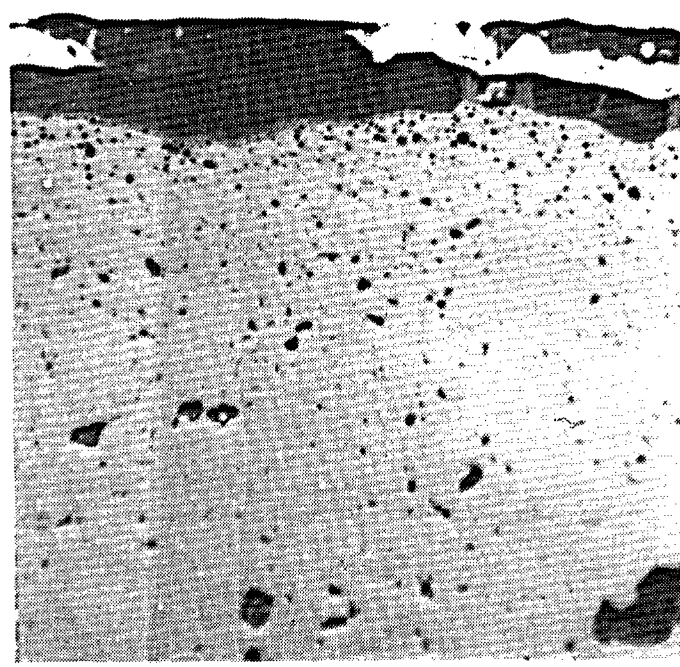
Rod VV2/K14 50µm 500X



Rod VV2/J14 500X



Rod VV2/D07 500X



Missing ZrB_2 Coating due to Pores 500X

ZrB_2 Coating at Pellet - Pellet Interface 500X

Figure 3.3-9. Appearance of ZrB_2 Coating, ZrB_2-Fuel Interaction Zone, and Pores in the Interaction Zone

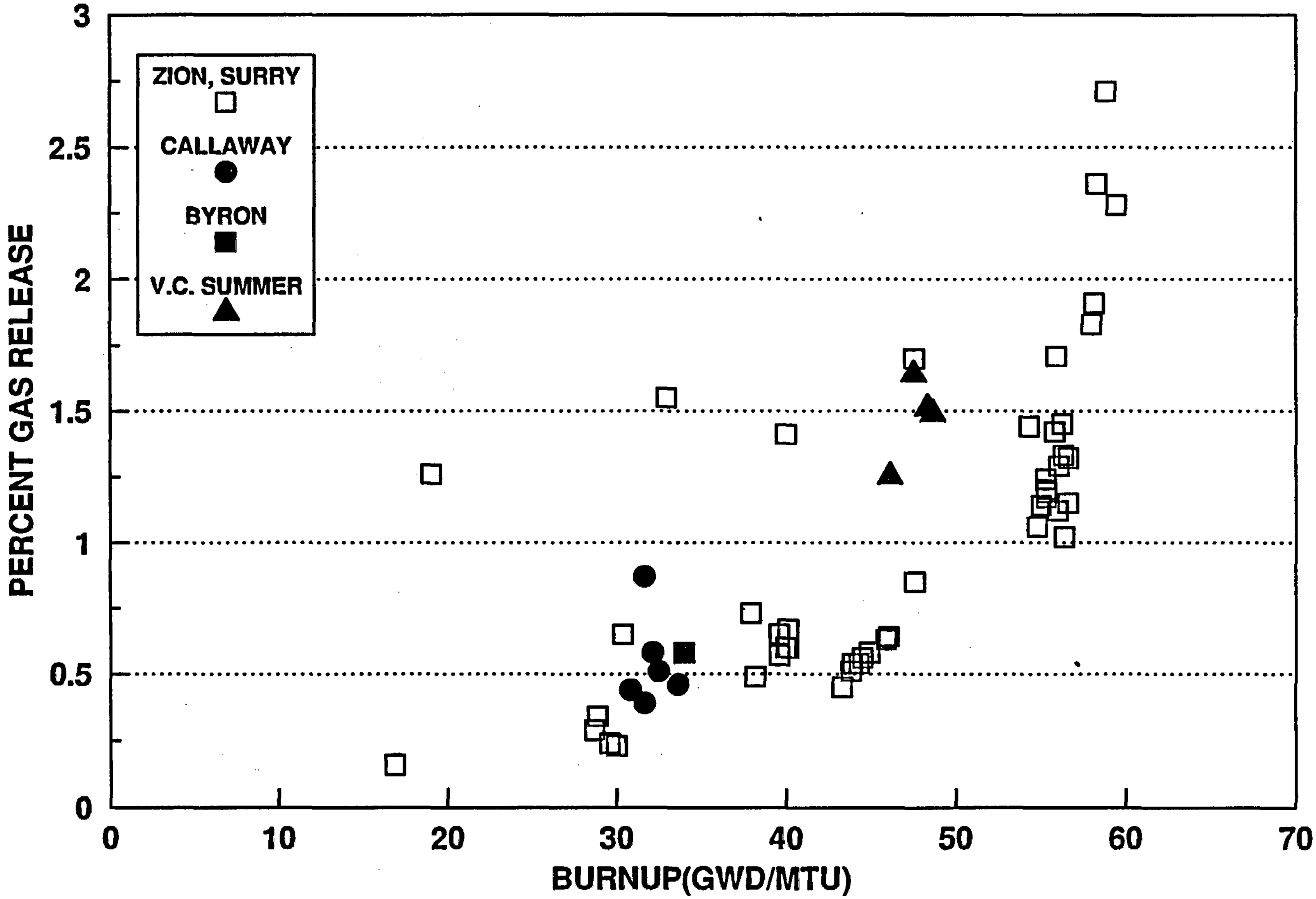


Figure 3.3-10. Fission Gas Release Data

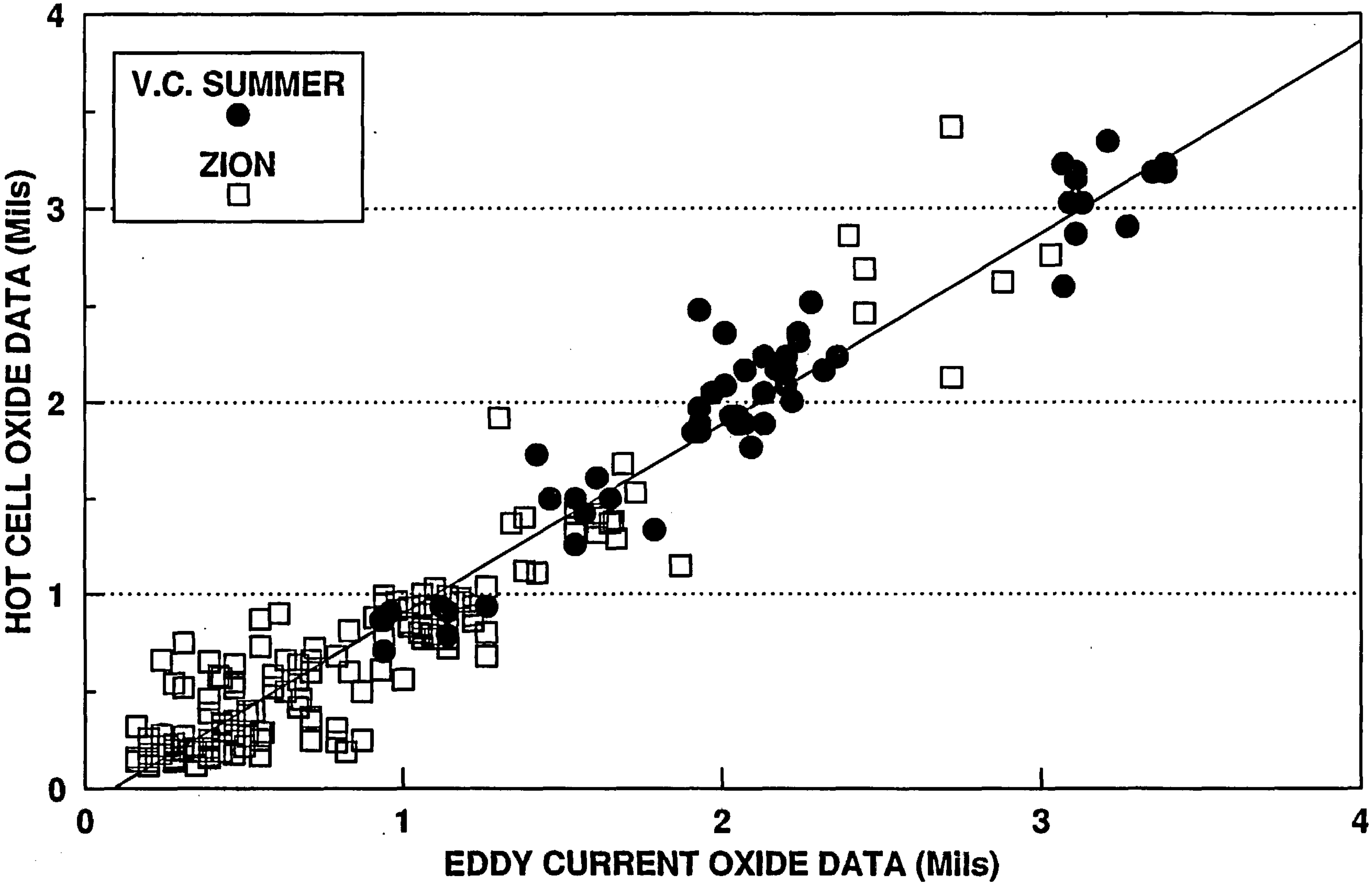


Figure 3.3-11. Comparison Between Hot Cell versus Eddy Current Oxide Measurements

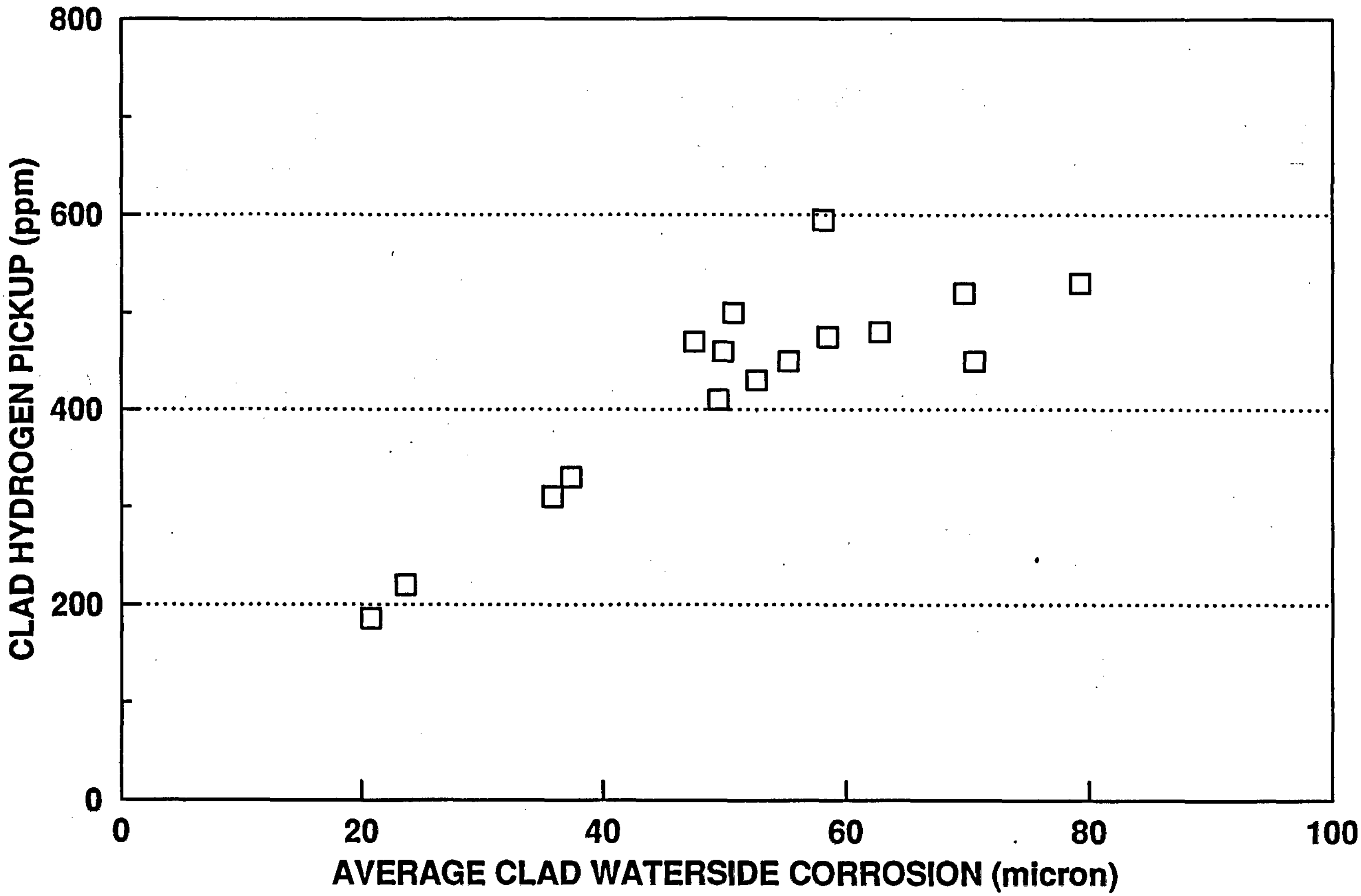


Figure 3.3-12. Clad Hydrogen Pickup versus Waterside Corrosion

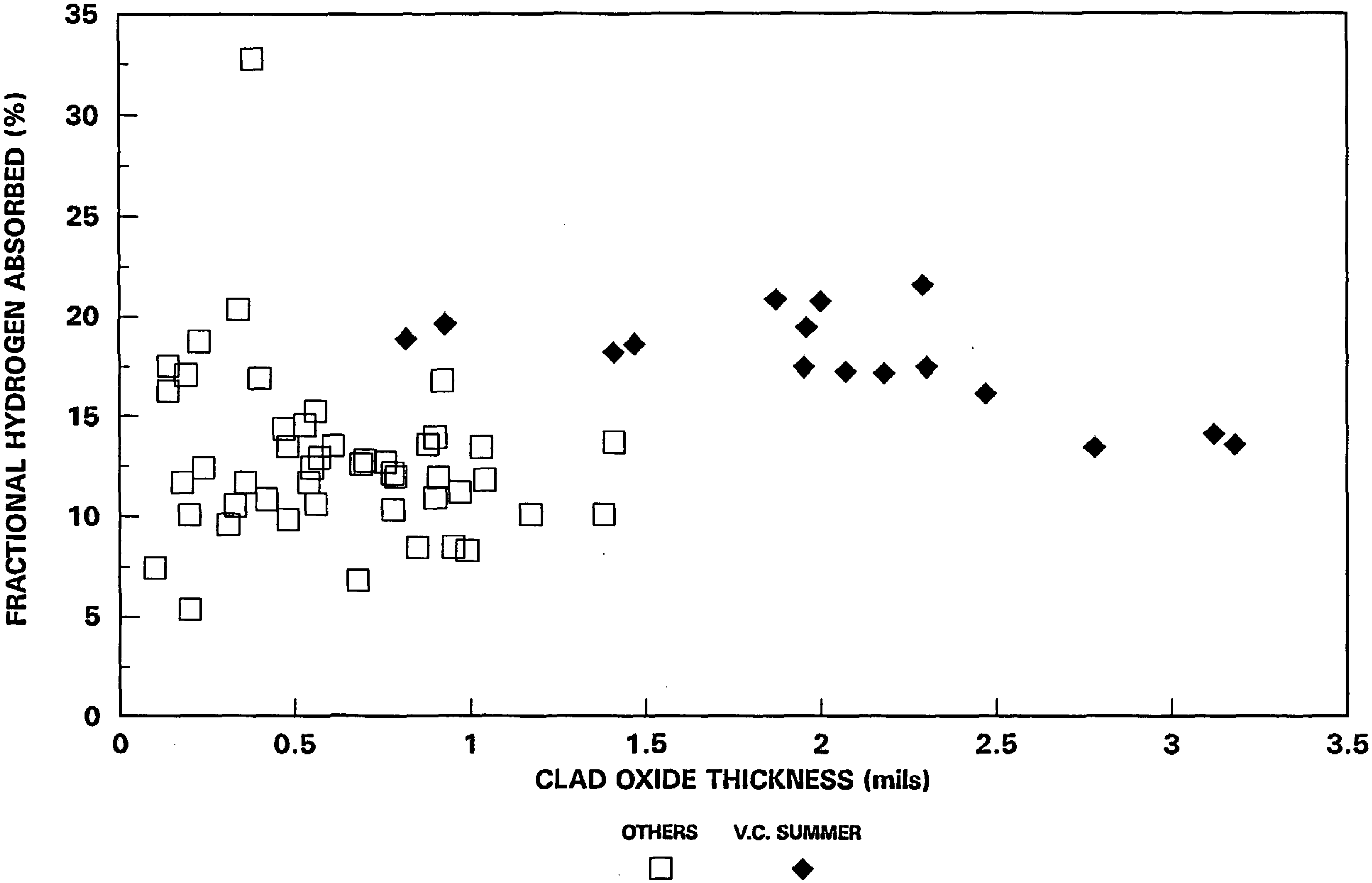
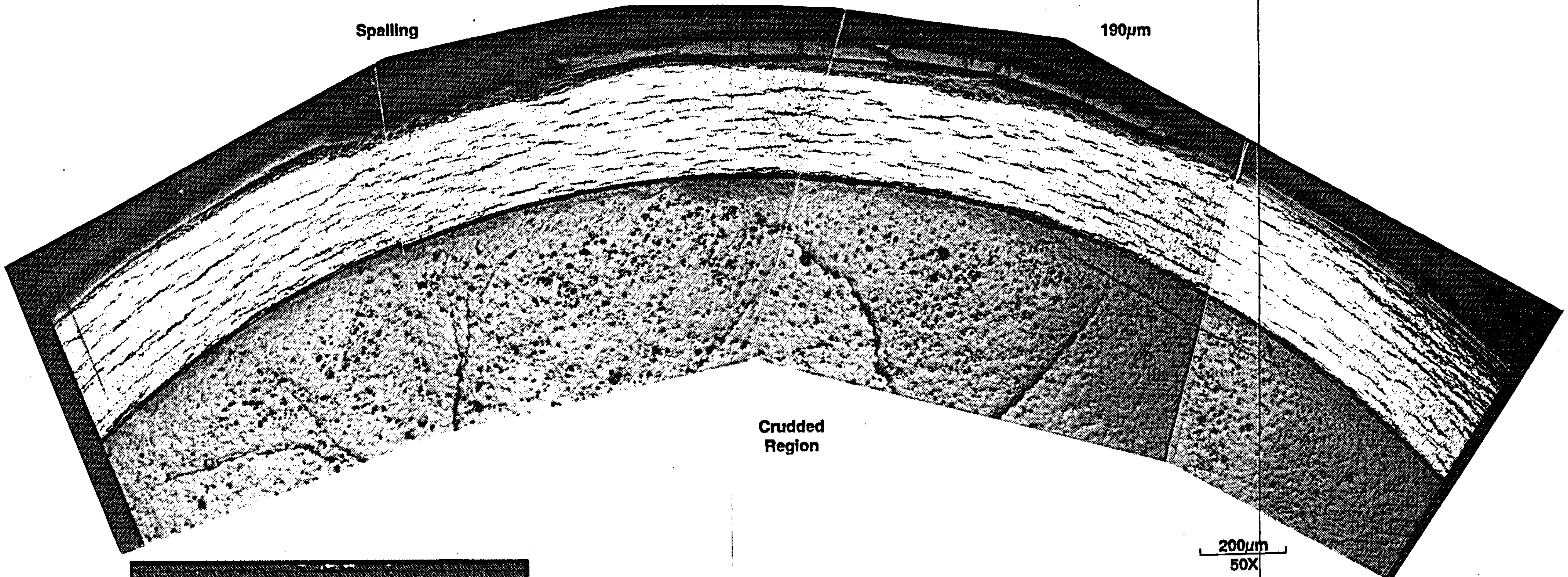


Figure 3.3-13. Fraction Hydrogen Absorbed vs. Clad Oxide



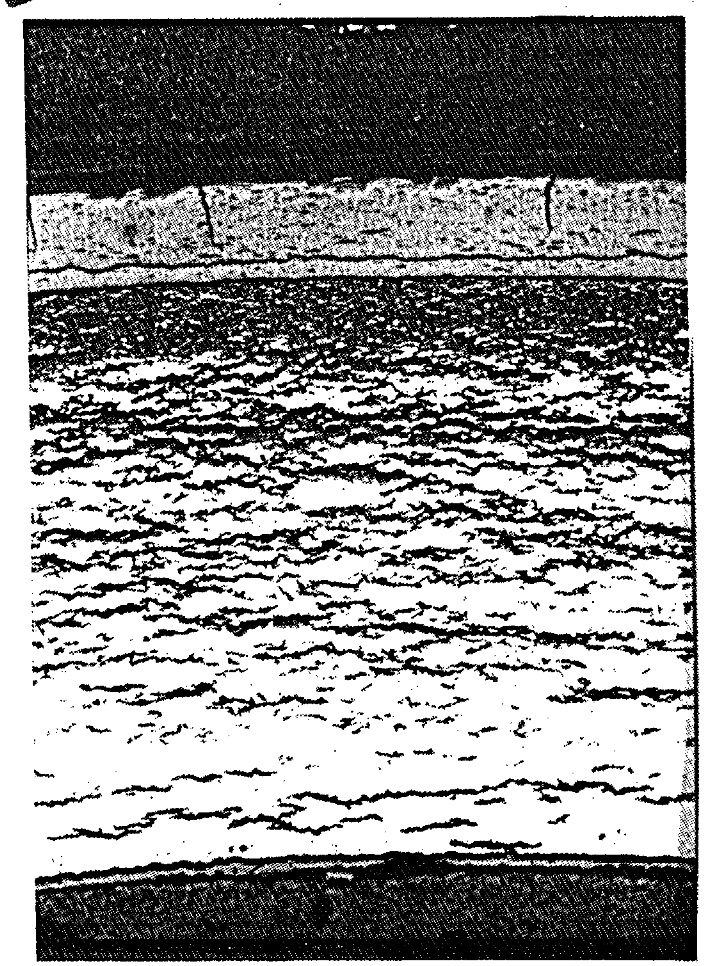


Figure 3.3-14. Increased Waterside Corrosion in the Crudded Region, V.C. Summer Vantage 5 Rod VV2/J05

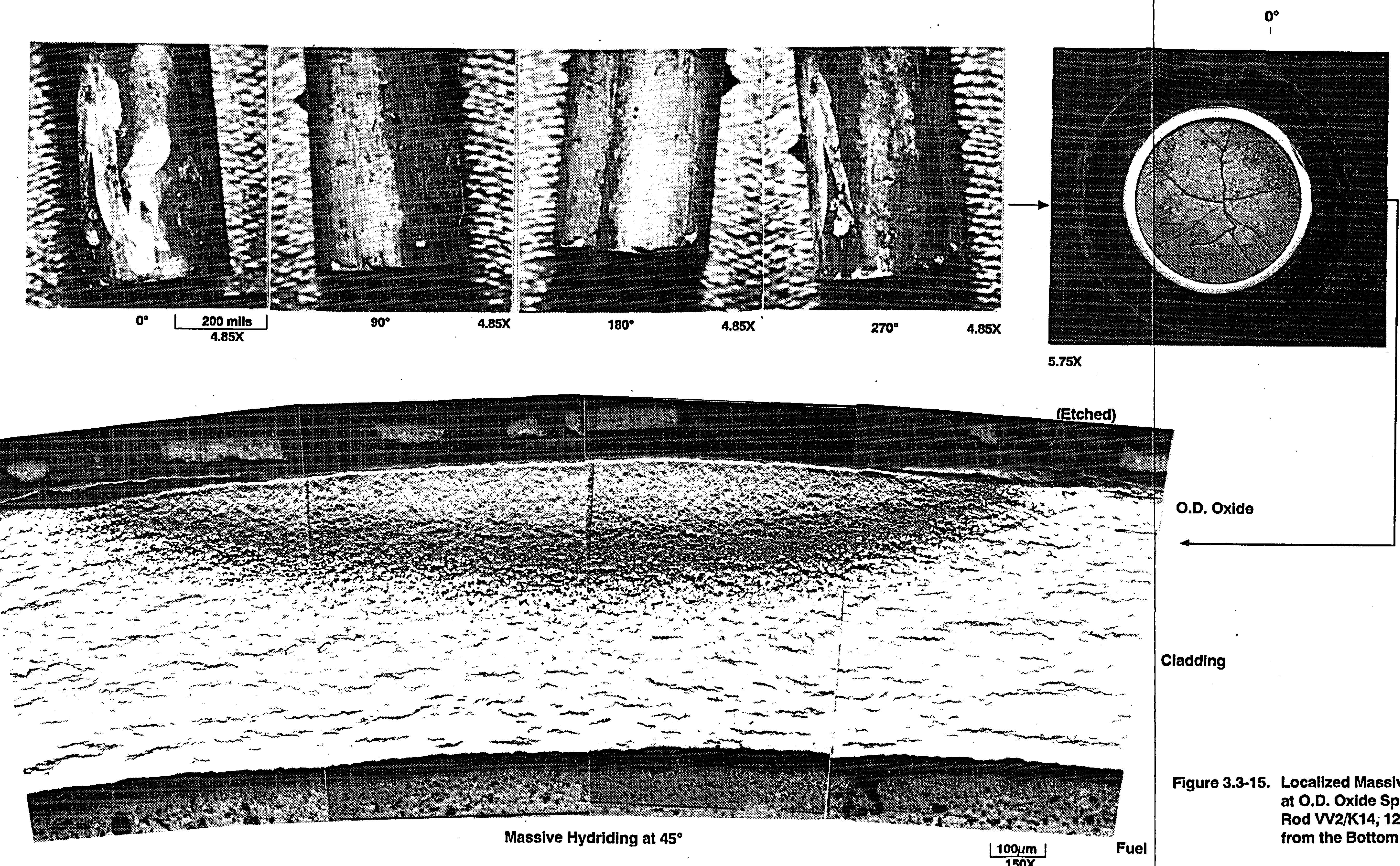


Figure 3.3-15. Localized Massive Hydriding at O.D. Oxide Spalled Area, Rod VV2/K14, 127 Inches from the Bottom

4.0 DISCUSSION OF LEAKAGE MECHANISMS AND CORRECTIVE ACTIONS

4.1 END PLUG PIPING

Two rods, Byron rods T74J/I16 and T77K/D02, were determined to be leaking due to end plug piping in the bottom end plug. Both rods showed hydride blisters several inches above the bottom end plug. During site examination campaigns of leaking fuel assemblies performed in the early 1990's, some rods were suspected to be leaking due to end plug piping. Metallographic examination of unirradiated end plugs from the suspected fabrication lots revealed a defect similar to those seen on the Byron rods. Evaluation showed that these piping defects were due to an extrusion defect which is introduced during manufacture of the bar stock used to fabricate the lower end plug. The occurrence of this defect was a very infrequent event. The observation of these defects in a leaking fuel rod was the first confirmation of this type of defect in an actual leaking fuel rod.

In order to understand the leakage mechanism and the corrective actions associated with the end plug piping defect, it is necessary to describe the process used to fabricate the Zircaloy bar material from which the end plugs are fabricated. The 8.5" Zircaloy billets are initially extruded to a smaller diameter and cut into 8" to 12" sections. During this extrusion process, a defect is introduced into the end of the extrusion as the billet is reduced in size. The end of the billet basically collapses onto itself creating a pipe-like defect at its end. This defect has been confirmed to be limited to the very end of the bar. The end of this defect is then located by a UT inspection and the entire defect is cut out. A second extrusion process is then performed to reduce the diameter of the billet further to approximately one inch. The end of the defect is again identified by UT and the defect is removed. The bar is then reduced to final diameter through a series of cold swaging operations. The final bar is UT and dye penetrant tested to verify the absence of the piping defect. The critical operation for identifying and removing the piping defect is the cropping operation and the inspection following the extrusion process.

An important characteristic of the defect is that it is filled with lubricant and carbon during the extrusion process which then hardens during the cooldown. This material can be quite tightly packed in the defect and can, essentially, plug the defect. This plugged piping prevents helium gas in the fuel rod from leaking during the leak test and allows the fuel rod to pass the inspection.

A review of the nature of the defects and the conditions surrounding some of the observed piping defects showed that the inspection processes in place at the time were not adequate to always detect the piping defect and, further, that the helium leak test of the fuel rod could not be counted on to always find defects (since they could be plugged). In addition, some of the piping defects seen in the past were believed to be due to a material mishandling problem where a bar that was to be reworked was inadvertently released without rework. Therefore, the implemented corrective actions focused on insuring that the extrusion defect was fully removed from bar material at the extrusion stage and that the following inspection would confirm, with 100% reliability, that the defect was not present. In addition, final inspections on the finished bar were also improved and changes were made to the material handling procedures. These changes are summarized below:

1. The cutoff of the extrusion was increased to 4 inches above the UT indication of the end of the defect. This was implemented as a conservative practice to provide added assurance that the defect has been completely removed.

2. A metallographic examination is performed on the bar ends after cropping following the second extrusion to confirm the absence of the defect. This is a much more sensitive technique than the pervious inspection technique (dye penetrant testing).

3. Two changes have been implemented in the UT inspection of the final bar. The electronics of the UT system have been improved to give a higher sensitivity to the type of defect being sought. A 0.002" sensitivity hole has been implemented in the UT standard for the final bar. These two changes provide a higher sensitivity in inspecting the final product. An enhanced dye penetrant examination of the final bar has also been implemented. In addition, following the setup of the UT system, a natural defect (a bar with a known end pipe defect) is inspected. The system is required to detect the known defect.

4. A center drilling operation on the 8.5" billet was eliminated. This operation had the potential for introducing an initiation site for the type of defect in question.

5. The accountability in the rework process was improved. This consists of immediate movement of all material needing rework to the appropriate holding area, requiring complete reinspection after rework, and placing individual bar identification on the final bar. These actions were implemented to preclude the possibility of mishandling material to be reworked.

Since the implementation of the above changes, no end plug piping defects have been found in the final bar material. This indicates that the above changes have been successful in eliminating the defect in the base material.

4.2 POSSIBLE HYDROGEN CONTAMINATION

Both D79F/H12 and G08/Q16 showed no visual defects other than clad hydriding. Leak testing performed on both rods found no new leak sites other than those visually observed. Metallography of the top and bottom end plugs of rod G08/Q16 and the bottom end plug of the rod D79F/H12 revealed that the end plugs and welds are intact. The top end plug of rod D79F/H12 was not examined metallographically since the plug had an open hydride blister at the girth weld. It is unlikely that the rod is leaking due to the top end plug weld defect since secondary hydriding normally occurs well away from the primary defect site. Based on these examination results, it was judged that the rods are most likely leaking due to hydrogenous contamination incurred during manufacture.

The visual observations on rod G08/Q16 showed numerous hydride blisters, which is typical of the appearance expected from a fuel rod leaking due to hydrogenous contamination that operated for one cycle. Rod D79F/H12 showed a somewhat different appearance. Extensive oxidation was observed on the cladding, but relatively few through-wall blisters were visible although they were present. Although significantly high waterside corrosion was observed on rod D79F/H12, it is believed that corrosion is not the root cause since no sign of clad perforation due to corrosion was noted. Once hydrogen is released from hydrogenous contaminants during reactor operation, the hydrogen attacks the cladding and causes hydride defects in a similar manner as moisture in the fuel rod would. Since none of the other rods from the same manufacturing lot were found to be leaking, it is believed that the hydrogenous contamination was an isolated and random event. Although D79F/H12 was a twice burnt assembly, a number of defect characteristics observed on rod D79F/H12 such as high corrosion, massive hydriding, and grain growth suggest that the rod could have been operated with high temperature for a long time, implying that the rod could have been leaking since the first cycle of operation. This appears to be also consistent with the coolant activity and operation history observed at the Byron 1 reactor, although it cannot be positively confirmed with the available coolant activity and inspection data.

The observation of the defect characteristics seen on rods D79F/H12 and G08/Q16 is very infrequent for rods of recent fabrication (1988 or later). Although the source of the hydrogenous contamination could not be specifically identified, a series of corrective actions have been taken to reduce or eliminate the potential for these defect types in general. Since the specific contaminants involved were not identified, the corrective actions focused on the potential for hydrogenous contamination at any step in the fabrication process. Typical actions are summarized below:

- Changes to the manufacturing process were made to prevent the possibility of fuel pellets being contaminated during specific steps in the fabrication process.
- Hydrogenous contamination is usually associated with the fuel pellets. However, the other fuel components could also be contaminated with moisture. Therefore, additional cleaning of the fuel rod components (springs, tubing, and end plugs) was implemented.
- Hydrogenous materials used in the fabrication area which may come into contact with the fuel pellets during fabrication and would not be removed by subsequent cleaning operations of the pellet were identified, removed from the area, and replaced with alternate materials.
- Equipment which had the potential to inadvertently introduce contamination into the fuel rods during rod loading were identified and modified.
- Additional steps were added to control the cleanliness of the containers in which fuel pellets were stored during the fabrication process.
- Urethane equipment components which come into contact with the pellet during the fabrication process were identified and replaced with stainless steel equipment.

- Training was provided to further sensitize the people in the fuel pellet, fuel rod loading and inspection areas to the significance of hydrogenous contamination.

4.3 POSSIBLE SEAL WELD DEFECT

Although rod P05J/C01 was found to be leaking, the leak test, eddy current testing and metallography (end plugs and welds) did not identify any leak site on the fuel rod. The only area found to be a potential leak site was the seal weld region of the top end plug. It should be noted that this area was not leak tested since the section contained the puncture hole and made sealing the rod difficult. Corrosion on the surface of the pressurization hole showed comparable thicknesses to corrosion on the outer surface of the top end plug, suggesting that the pressurization hole was exposed to the reactor coolant from the beginning of life. A suspicious discolored spot observed within the seal weld region suggested that the rod may have been leaking due to an improper seal weld. Since no other leak site was identified on the fuel rod by eddy current examination and leak testing of the fuel rod and metallographic examination of the end plugs and girth welds, the seal weld defect is believed to be the most likely cause.

The leakage cause described above is an extremely isolated event. This is the only defect of this nature in a leaking fuel rod which has been identified. There have been several improvements taken in the fabrication process which would further reduce the possibility of this type of defect from occurring in the future. The size of the fuel rod pressurization hole had been reduced. This will make the seal welding process more controlled. In addition, the power supply for the initiation of the fuel rod seal weld has been upgraded to a process which requires less power to initiate the weld. This will reduce the possibility of a defective weld in the fabrication process. Both of these changes have focused on reducing the possibility of a defect condition being introduced into the welding process.

4.4 DEBRIS INDUCED FRETTING

This is the most commonly observed leakage mechanism. Small pieces of debris circulating in the reactor coolant system can enter the fuel assembly and become lodged between the fuel rods. Hydraulically induced vibration then causes such debris to wear through the cladding. When this mechanism was first observed in the early 1980's, it was not uncommon to observe between 15 to 80 leaking rods due to this cause. The more recent examinations show much lower numbers of leaking rods when this mechanism is observed (typically 1 to 5 rods per outage where debris leakage observed). This reduction is due to utility and vendor efforts to remove existing debris from the system if it is present and to prevent the addition of new debris into the system. The Debris Filter Bottom Nozzle (DFBN), was introduced in 1988 to further reduce debris related leaking rods. The purpose of this design is to trap the debris below or in the bottom nozzle in a location where it cannot damage the fuel rods. This new feature, combined with the utilities' control of debris in the plant, further reduced the occurrence of this leakage mechanism.

4.5 GRID-ROD FRETTING

Vibrational contact between the fuel assembly grids and the fuel rod can cause wear-through of the fuel rod cladding. To prevent this occurrence, positive contact must be maintained between the fuel rods and the grid springs during operation. The bottom grid location is particularly sensitive to this mechanism due to the cross flows at the location from the lower core plate and the bottom nozzle. The first significant observation of grid-rod fretting by Westinghouse was made in June, 1983 in a demonstration assembly. The root cause of this occurrence was determined to be loose grid cells caused by damage during manufacture as a result of a non-standard procedure used to fabricate the specific assembly in question. Although this procedure was not used in standard production, a review of the production procedures revealed several procedures that had the potential for a similar effect. These procedures were modified to minimize the potential for future damage. These changes were initiated in July, 1983 and additional changes were implemented through January 1988. The inspection results indicate that these changes have been very effective in addressing this concern.

4.6 ROD CLADDING COLLAPSE

Cladding collapse is caused by an unsupported length of tubing becoming oval due to creep and eventually reaching instability, resulting in collapse along the minor diameter. Between 1986 and 1989, two rods with cladding collapse in the bottom six inches of the rod were observed. Analytical evaluations showed that the rods in question should not have collapsed after two cycles (both rods were twice burned) even if there were no pellets in the bottom six inches of the rod provided the initial ovality of the tube did not exceed the maximum specification limit. The tubing certifications obtained from Westinghouse's Blairsville Specialty Metals Plant confirmed the ovalities for the tube lots from which these rods were made were well within specifications. For the tube to have the high initial ovality necessary for calculated rod collapse, crimping must have occurred after the ovality was measured at Blairsville. An initial ovality in excess of 8 mils would have been necessary to allow these rods to collapse in two cycles, according to Westinghouse models. An ovality of that magnitude would also have been sufficient to prevent the pellets from being loaded past the point in question during pellet loading.

A review of the traceability for both rods exhibiting cladding collapse showed that the gamma scan inspection had correctly identified both rods, but both were later accepted due to operator error. Additionally, the rod weights for the two rods in question were considerably lower than the other rods in their respective regions. Rod weights were not reviewed prior to rod loading at the time when these two rods were fabricated. Since the time of fabrication of these fuel rods, procedures have been modified so that no rod with a weight discrepancy can be loaded into an assembly until the discrepancy is resolved. In addition, the source of the fuel rod crimping has been eliminated and procedures implemented to prevent inadvertent operator acceptance.

4.7 INCOMPLETE WELD

One fuel rod has been identified as leaking due to an incomplete end plug girth weld. A review of the manufacturing traceability showed that the rod had passed X-ray inspection, helium leak detection, and dimensional and visual inspection with no indication of an anomaly. The original radiograph was again reviewed by Level 3 inspectors to determine if the rod should have been originally rejected or if it was correctly accepted. The conclusion of the reviewers was that the original judgment had been correct; the radiograph contained a very slight indication, but not enough that the rod would be rejected (at most, the indication would have warranted an additional

X-ray inspection). Several corrective actions have been implemented to minimize the potential for additional occurrences of this type of occurrence in the future.

The primary inspection for this type of defect is the visual inspection. This rod should have been identified by the visual inspection, but was incorrectly accepted. Fuel rod UT inspection could also detect this defect. Corrective actions were implemented in the areas of training for the involved operators and inspectors. Visual standards have been prepared and the X-ray readers, dimensional and visual inspectors, and manufacturing engineers have all been trained to be more sensitive to this type of defect. Periodic refresher courses will be given to these groups of individuals to maintain the highest level of detection to avoid this defect type.

5.0 SUMMARY AND CONCLUSIONS

The results of this fuel rod examination program yielded significant information in several areas related to fuel reliability. Five leaking fuel rods were confirmed by the hot cell examination. The leakage mechanisms for these rods were: 1) end plug piping, 2) random hydrogenous contamination, and 3) a potential seal weld anomaly.

The end plug piping observation was particularly significant since, although the mechanism had been suspected as a possible leakage cause, it had not been previously confirmed in an actual leaking rod in the field using techniques available at the reactor site. In addition, the observation demonstrated that these events were present to a broader extent than previously thought, and resulted in explaining a number of leaking fuel rods in which the leakage cause had been previously unknown.

The random hydrogenous contamination mechanism has always been a possibility for the defects for which only hydride blisters are observed, although they could be due to some other primary defect which can not be identified by on-site techniques (such as end plug piping). The fact that no other potential primary defect site was observed on the rods during the hot cell examinations, either along the cladding or in the end plugs or girth weld areas, provides further support that this mechanism could be the leakage cause. The observation of possible primary hydride defects is very infrequent for recent vintage fuel.

The observation of the potential seal weld defect is the first time that a defect of this nature has been found. Based on the past experience, this mechanism is a very isolated occurrence.

Corrective actions have been taken to address each of these observed leakage causes.

The possibility of incorrect UT examination results, particularly at higher burnup, is an issue in the industry. The confirmation of the UT miscalls and the identification of a possible cause will provide significant information for both the utilities and the UT testing vendors in making decisions on inspection techniques and in interpreting UT data.

Although the V.C. Summer demonstration rods were not leaking, significant information concerning potential leakage causes for higher burnup fuel were obtained. The excessive flaking oxide and hydride localization associated with the cold spots resulting from the spalling oxide could be of significance for fuel integrity in higher burnup applications.

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