# POTENTIAL IMPACTS OF CRUD DEPOSITS ON FUEL ROD BEHAVIOR ON HIGH POWERED PWR FUEL RODS

W. WILSON, R.J. COMSTOCK
Westinghouse Electric Company,
Commercial Nuclear Fuel Division,
Columbia, South Carolina,
United States of America

## Abstract

Fuel assemblies operating with significant sub-cooled boiling are subject to deposition of surface deposits commonly referred to as crud. This crud can potentially cause concentration of chemical species within the deposits which can be detrimental to cladding performance in PWRs. In addition, these deposits on the surface of the cladding can result in power anomalies and erroneous reporting of fuel rod oxide thickness which can substantially hamper corrosion and core performance modeling efforts. Data is presented which illustrates the importance of accounting for the presence of crud on fuel cladding surfaces. Several methods used to correct for this phenomenon when collecting and analyzing zirconium alloy field oxide thickness measurements are described. Various observations related to crud characteristics and its impact on fuel rod performance are also addressed.

## 1. Introduction

Crud deposits on PWR fuel rods have been observed during visual examination of fuel assemblies. These observations contain several common features in terms of the amount and location of the deposits. Typically, the deposits are located in the upper spans of the fuel assemblies with the amount of crud being the highest in the high powered assemblies. Figure 1 shows a schematic diagram of a Westinghouse fuel assembly and the axial locations where crud deposits are typically observed.

The presence of crud impacts fuel rod performance in several ways. First, crud in the upper spans of the fuel rod interferes with eddy current probe measurement of oxide thickness on the fuel rod. The eddy current probe measures the offset from the underlying base metal and therefore provides a measure of oxide plus crud. In addition, the presence of crud can provide an additional thermal barrier resulting in an increase in the oxide-to-metal interface temperature and higher corrosion rates. Unless crud is properly account for, these effects can hamper corrosion modeling efforts. In addition, a relationship between Axial Offset Anomaly (AOA) and crud deposits has been observed.(1) The postulated mechanism is the concentration of boron within the crud due to sub-cooled boiling on high-power fuel.

Due to these impacts on fuel rod performance, Westinghouse initiated studies to characterize the nature and impact of crud deposits on fuel rod performance. The results of these studies are the subject of this paper.

## 2. Crud Characterization Studies

Characterization of crud deposits on PWR fuel rods was performed using several techniques. The simplest form of characterization was visual examination of the fuel rods to identify preferred locations on the rod where crud deposits form. Typically, a high magnification video image of the fuel rod is obtained during eddy current measurements of fuel rod oxide thickness. This video record of the fuel rod is reviewed to identify locations on the rod where crud is present and to segregate eddy current measurements which are potentially impacted by the presence of crud.

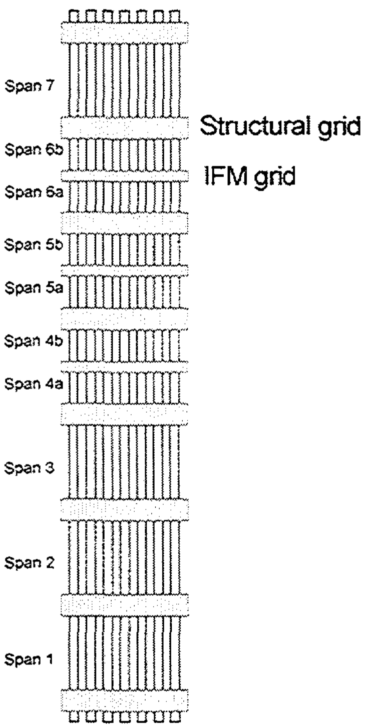


Figure 1: Schematic drawing of a Westinghouse PWR fuel assembly. Crud deposits are typically observed in spans 4 through 7.

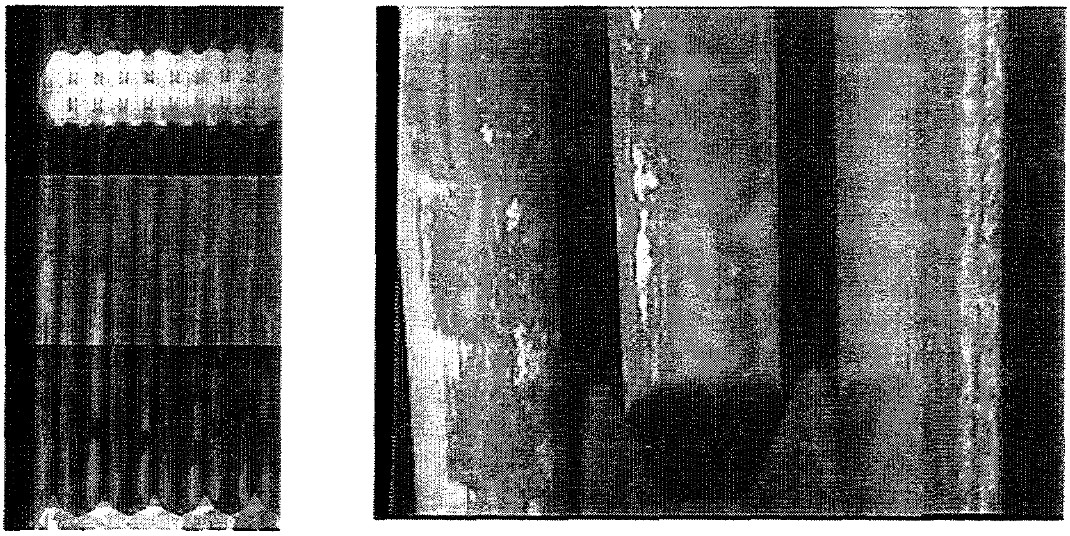
A second means of assessing crud deposits was from crud scrapings as previously described [1, 2]. Surfaces of selected fuel rods were scraped in the spent fuel pool and particles of crud suspended in the spent fuel pool liquid were transferred into sample bottles via a vacuum system. The crud suspensions were then filtered and rinsed with de-ionized water to remove any boric acid remaining from the spent fuel pool liquid. Estimates of crud thickness were obtained from the crud mass, area of the crud scraping, and an assumed crud density of 1.2 g/cm$^3$ [2].

Estimates of crud thickness were also obtained from measurement of the eddy current probe lift off both before and after the crud scraping. The initial measurement included the thickness of both the oxide and crud with the presence of crud confirmed visually. Following the removal of crud by scraping, the eddy current measurement of the oxide was repeated over the same area on the rod. The crud thickness was estimated by the difference between the two measurements. In addition, intact crud flakes were obtained during the scraping and sent to the hot cell for examination. Selected flakes were mounted on edge, metallographically polished, and examined in the scanning electron microscope (SEM).

A final assessment of crud and the impact of crud on corrosion was performed by sending fuel rods to the hot cell for destructive evaluation. The destructive examinations included cutting transverse cross-sections of the cladding for subsequent metallographic examinations. These examinations were performed to measure oxide thickness on the rod both in and away from crud-impacted areas on the rod. In addition, the thickness of crud was measured from the metallographic samples.

## 3. Results

Video images of crud deposits on PWR fuel rods are shown in Fig. 2. The lower magnification image in Fig. 2a shows the presence of crud in Span 6a of a fuel assembly. The higher



(a) (b)

Figure 2: Video images of crud deposits in span 6a of PWR fuel.

magnification image in Fig. 2b shows the preferential deposition of crud associated with the fuel pellet height.

The visual examinations show the locations in the fuel assembly where crud is deposited but provide no information on the relative thickness of the crud. This was assessed by crud scrapings from the fuel rods in the outer rows of the assembly. Scrapings were from different axial spans as well as from both one cycle and two cycle assemblies. Estimates of the crud thickness were made as described above and are summarized in Table 1 [1].

The results reveal several trends regarding deposition of crud [1]. The thickest crud deposits were observed in Span 6 and decreased in the lower spans with no crud observed below span 4. In addition, thicker crud was observed on the higher powered rods. These observation are consistent with the thicker crud being associated with higher fuel duty. Span 6 has the highest rate of sub-cooled boiling as well as the thickest crud. For these rods, thicker crud deposits were observed on the twice-burned fuel as a result of deposition during two cycles.

Table 1
Estimated Crud Thickness from Scrapings

| Number of Cycles | Span | High Powered Rod (microns) | Avg. Powered Rod (microns) |
|---|---|---|---|
| 1 | 6 | 9 | 2 |
| | 5 | - | 0.4 |
| | 4 | 0.4 | - |
| 2 | 6 | 20 | 15 |
| | 5 | 6 | - |
| | 4 | 7 | 3 |

To provide a more quantitative measure of crud thickness, eddy current measurements were performed on an improved Zircaloy-4 and ZIRLO™ fuel rod with burnups of about 45 GWD/MTU. The eddy current measurements performed along the full length of the rod are plotted in the Fig. 3. Significant increases in thickness were observed at rod elevations above 80 inches where crud was visually observed. The rods were then sectioned and four metallographic mounts were prepared from each rod corresponding to axial locations of about 15 inches, 60 inches, 77 inches and 125 inches from the bottom of the rod.

Oxide thickness measurements were made around the tube circumference along with maximum crud thickness. These data are plotted in Fig. 3. At axial elevations below 80 inches where no crud was present, there was good agreement between the eddy current measurement and metallographic measurement. In Span 6b (~125 inches), the oxide thickness from metallography was significantly lower than the eddy current measurement. A one-to-one comparison between the two techniques was not possible since the rod azimuthal orientation was not maintained during sectioning. However, reasonable agreement was obtained when comparing the eddy current data with the sum of the average oxide thickness and maximum crud thickness. Micrographs of the oxide and crud deposit are shown in Fig. 4. Apparent in the micrographs are crud deposits approximately 20 microns thick.

Another example of eddy current measurements being impacted by crud deposits is shown in Fig. 5. Axial traces were performed on a peripheral fuel rod following one cycle of irradiation with the results from Span 6b provided in the figure. The measurements were performed both before and after cleaning the fuel rod. The pre-cleaning measurements revealed a sharp increase in thickness from less than 20 microns to a maximum thickness of about 100 microns. The abrupt increase in thickness suggested the presence of crud which was confirmed by visual inspection of the rod (Fig. 6a). The eddy current measurement was repeated following mechanical cleaning and removal of the crud (Fig. 6b). The thickness measurements were about the same in the crud-free region and significantly reduced in the region previously covered by crud. The difference between the

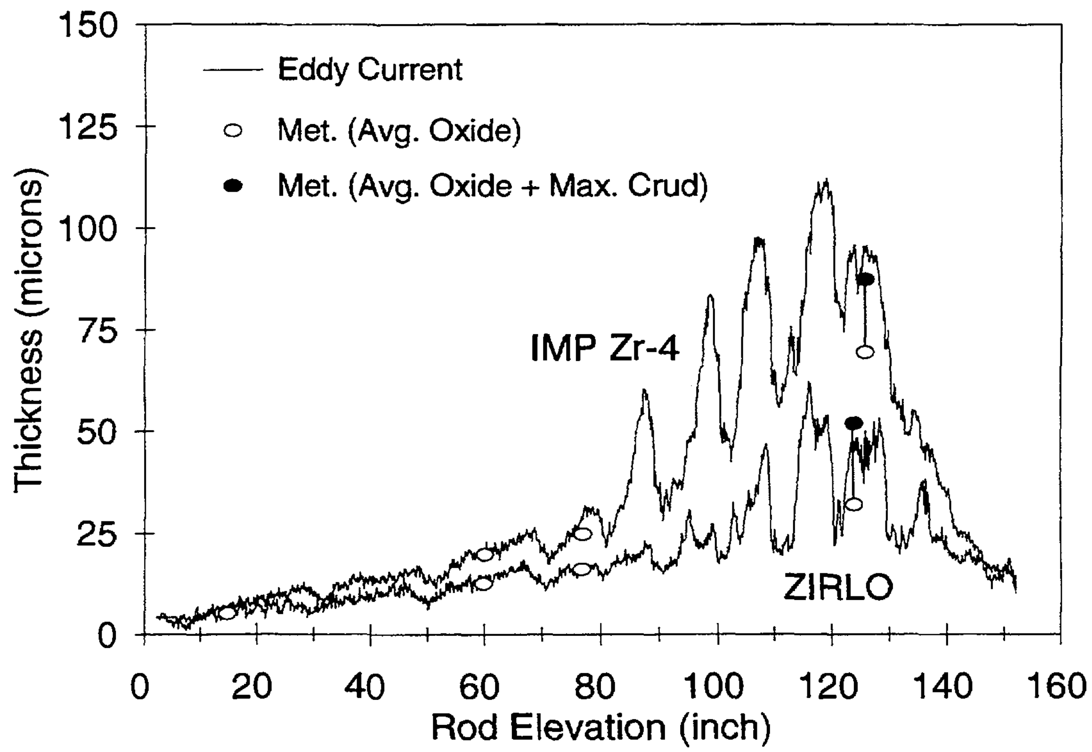


Figure 3: Eddy current and metallographic thickness measurements on improved Zircaloy-4 and ZIRLO fuel rods.

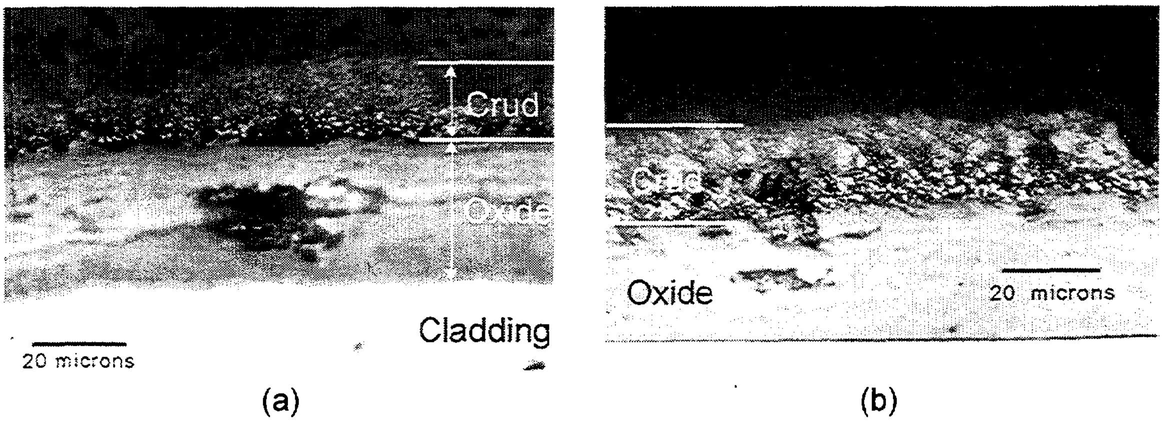


Figure 4: Metallographic cross-sections of fuel rods in crud-affected regions.
(a) ZIRLO rod at axial elevation of 124 inch with 18 microns of crud and 32 micron of oxide, and (b) Zircaloy-4 rod at axial elevation of 125 inches with 20 microns of crud and 69 microns of oxide.

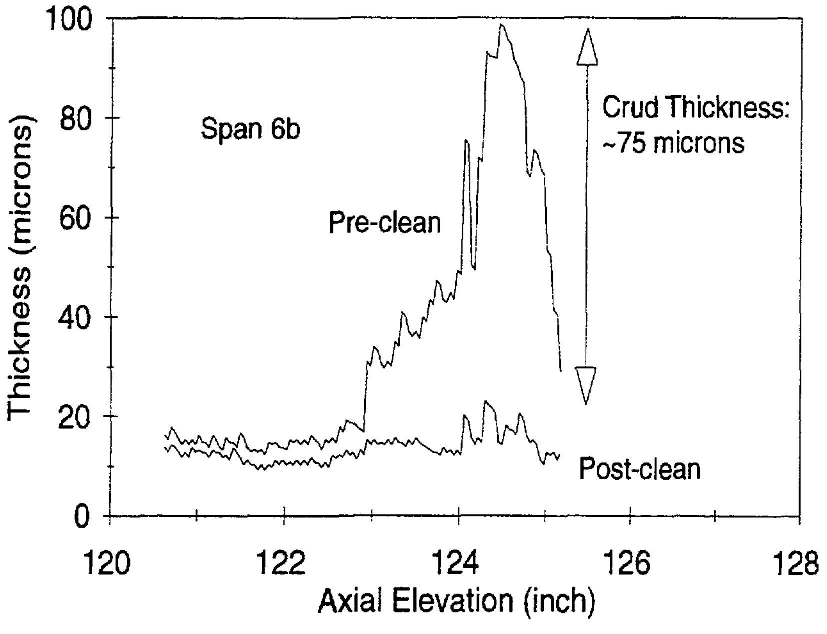


Figure 5: Eddy current probe measurement of oxide thickness in span 6b of a fuel rod before and after removal of crud deposits.

measurements before and after cleaning suggested a crud thickness as high as 75 microns. Despite the thick crud, average oxide thickness beneath the crud and in crud-free zones was similar.

This indirect measure of crud thickness was confirmed by examination of a crud flake collected during the cleaning operation. A scanning electron micrograph (SEM) of the cross-section is shown in Figure 7a where the crud thickness measured between 72 and 79 microns which was consistent with the estimated thickness from the pre- and post-cleaning eddy current measurements. Higher magnification examination of the crud flake showed the presence of boiling chimneys within the crud.

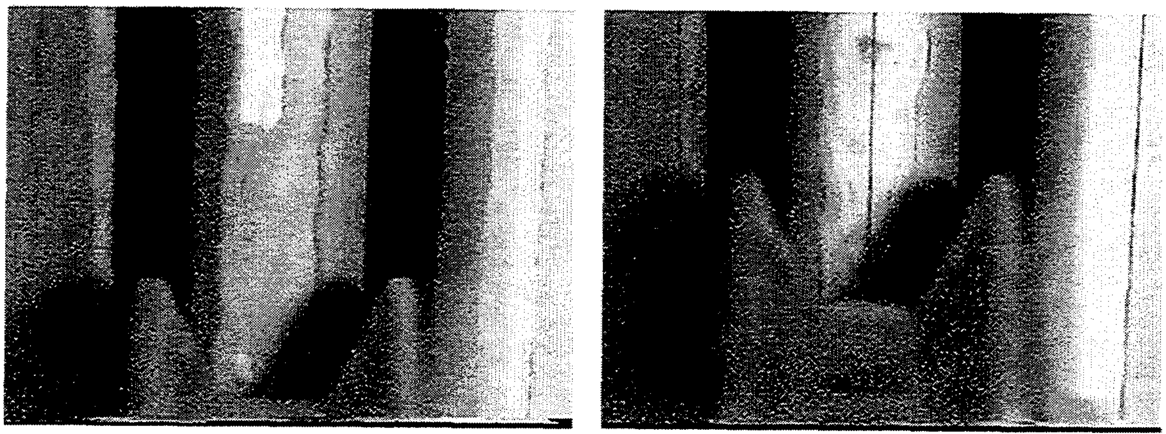
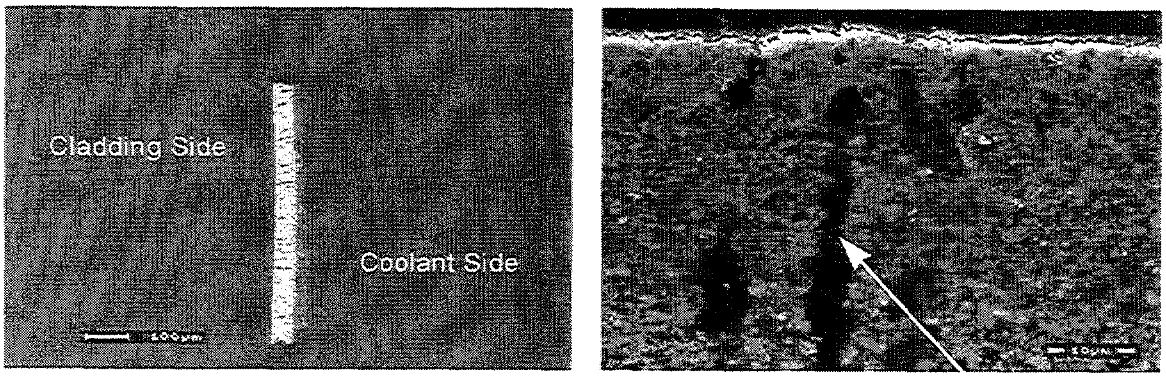

(a) (b)

Figure 6: High magnification video image of fuel rod. (a) before removal of crud deposits and (b) after removal of crud deposit.



Boiling chimneys

(a) (b)

Figure 7: SEM micrograph of crud flake cross-section.

Additional rods sent to the hot cell were examined to determine the impact of crud deposits on oxide thickness. Visual examination of the rods at the reactor site showed the presence of local areas of crud on the fuel rod. The crud was not present around the entire circumference but rather appear as axial bands of crud covering only a portion of the circumference. The crud apparently flaked off during shipment to the hot cell as the crud was no longer present on the rod upon arrival at the hot cell. Even though the crud was no longer intact, the crud-free and crud-affected regions could still be visually identified. Transverse metallographic cross-sections of the rods from both the crud-free and crud-affected areas were prepared for destructive examination of the oxide thickness.

Results of the measurements from two rods are provided in Table 2. Measurements included the average oxide thickness around the circumference as well as the peak oxide thickness. The small difference between the peak and average oxide in the crud-free region of the rods indicated a rather uniform oxide around the rod circumference. Contrasted to this was the large difference between the peak and average oxide thickness at the axial locations where crud was present. The peak oxide thickness was restricted only to a portion of the rod where the crud was present. The oxide thickness around the remainder of the circumference was more typical of the oxide thickness expected at the designated elevations.

Table 2
Impact of Crud on Cladding Corrosion

| Rod | Elevation (inch) | Avg. Oxide (micron) | Peak Oxide (micron) | |
|---|---|---|---|---|
| 1 | 106.9 | 55.3 | 58 | No Crud |
| | 127.9 | 80.8 | 144 | Crud Present |
| 2 | 96.9 | 49.5 | 54 | No Crud |
| | 105.9 | 62.8 | 118 | Crud Present |

## 4. Discussion

The examinations performed on crud characterize the locations in the fuel assembly where crud can deposit as well as provide information on crud thickness and its impact on corrosion. From these studies, there is a clear correlation between crud deposits and rod power. Higher power assemblies with sub-cooled boiling are prime locations for crud deposition with the thickest crud deposits generally observed near the top of the assembly in span 6.

The impact of crud on fuel rod performance is multifaceted. In addition to complicating the interpretation of eddy current measurement of oxide thickness, crud can also result in higher local corrosion as well as provide a location for precipitation of boron resulting in a flux depression and the phenomenon know as AOA. A first step in quantifying these effects is understanding the nature of the crud which forms on high power fuel assemblies.

These initial studies quantify the crud thickness which can form on fuel rods as well as provide data regarding the effect of crud on the underlying oxide thickness. Examples have been shown where crud deposits have minimal impact on oxide thickness (i.e., Fig. 5) as well as impacting oxide thickness (i.e., Table 2). Furthermore, characterization of the cross section morphology of crud provides evidence of boiling within the crud (Fig. 7b) and supports a mechanism for AOA by precipitation of boron containing species within the crud. Additional work to understand the nature of crud and to minimize its formation is warranted so as to eliminate associated performance concerns such as corrosion and AOA.

## 5. Conclusions

1. The presence of crud deposits impact eddy current measurement of oxide thickness and may result in local increases in oxide thickness.
2. Crud deposition is associated with sub-cooled boiling.
3. Crud deposits up to 80 microns thick have been observed.
4. Boiling chimneys were observed in thick crud flakes.
5. Thick crud and boiling can lead to precipitation of boron components within the crud resulting in axial power anomalies.

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