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EVALUATION OF DEBRIS FRETTING FAILURE ON PWR FUEL BY POST-IRRADIATION EXAMINATION AND MODELING IN THE DEGRAD-1 CODE

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ABSTRACT

One of the major recognized causes of fuel rod failures is fretting of the clad due to the entrapment of debris in a fuel rod spacer. Such debris, inadvertently dropped into the primary system during maintenance operations, includes various sizes of particles. Intermediate size particles, such as metal cuttings, electrical connectors, metal fittings, pieces of wire, and small nuts and bolts can become trapped between fuel rods in a spacer where hydraulically induced vibrations can cause fretting failure of the fuel rod.
An evaluation of debris fretting failure on PWR fuel is presented. The inquiries on fuel rods failures are based on results of analysis using post-irradiation non-destructive examination. The complementary analysis includes a modeling approach by code DEGRAD-1 to characterize the degradation phenomenon after primary failure integrated in the reactor operational history.

1. INTRODUCTION

The possible scenarios for cladding failure occurrence and evolution are relatively well known. The worldwide most frequent one in PWRs, is an initial perforation of the cladding (wear by debris generally located under the lower spacer grid - fretting corrosion by grid/cladding interaction) and an optional secondary defects occurrence (hydriding of the cladding) with possible UO_2 release in the coolant. The secondary hydriding speed depends on two mains parameters: temperature of the cladding, related to the local linear power of the rod, and gap closure at the moment of the first perforation, related to the rod burnup. As a result of both activities evolutions analysis in operation and poolside, we observed a quick evolution when the initial perforation occurred in the first cycle of the rod.

2. EVALUATION OF DEBRIS FRETTING FAILURE

2.1. Survey of Experience Occurred in PWRs

The overwhelming majority of debris failures have occurred in PWRs. Debris is a significant contributor to the overall fuel failure rate and PWRs are more prone to debris failures.

In PWRs, the flow velocity at the single phase inlet to the core can range between about 3.5 and 5 m/sec depending upon the specific reactor design. The higher flow velocity in the PWR is capable of supporting larger pieces of debris and carrying them into the core. A piece of debris which might sink to the bottom of a BWR reactor vessel and remain there during operation might be carried along by the higher velocity of the PWR coolant, become lodged in the grid of a fuel assembly and cause a failure.

Although a number of debris failures have been observed at the upper elevations of the PWR fuel rods, the vast majority of such failures, over 90%, occur at or below the bottom grid of the affected fuel assembly. This is due to the mechanisms by which most debris failures occur.

Based upon the experience to date, it appears that the great majority of the debris which enters a fuel assembly will either become lodged in the bottom grid spacer or it will pass through the fuel assembly without doing significant damage. Once the debris has been trapped by the grid, it frets against the fuel rod (perhaps, more than one fuel rod) until the clad is penetrated.

A higher incidence of debris failures has been found in the outer rows of PWR fuel rods than in the center of the PWR fuel assembly. This may be due to the flow patterns as the coolant enters the assembly or to the cycling of the flow. As the core flow decreases, debris may settle on the lower end fitting. As flow increases, there is a chance that the debris will work its way toward the outside of the assembly. As the flow cycles, the debris moves toward the intra-assembly gap. Thus, failures are found in the two peripheral rows of rods.

In some instances, the debris failures tended to be close to the corner of the assembly. This has been explained by an eddy in the flow pattern caused by the feet on the lower end fitting. Debris failures can be identified visually with reasonable certainty, and as a result the debris failure statistics are quite reliable.

The relationship between the fuel exposure (or in-core cycles number) versus time of debris failure has been examined also. Westinghouse has reported that the preponderance of the debris failures occur in the first operating cycle of the fuel; however, the experience of Fragema and Siemens do not support this trend. The reason for higher failure rate in first cycle fuel is not known, but it has been suggested that the lack of a wear resistant oxide film on the cladding early in life, makes new fuel assemblies more susceptible to debris failures.

Perhaps the most consistent trend has been the location of the debris fretting failures at below the first spacer on the bottom of PWR fuel assemblies. The small flow area spacer serves as a debris trap in PWRs. This has given clear directions to the designers of debris resistant fuel assemblies. The debris fretting failures have significantly decreased thanks to presence of antidebris filters; but even though be very effective in the reduction of wear occurrence induced by debris, do not eliminate this possibility totally [1].

2.1.1. Visual appearance of debris fretting failure

Visual failure characteristics identified during examinations can be used to differentiate debris failure from other types of fuel failure. The most striking feature is the presence of wear scars (or wear holes) in the cladding, of the type shown in Fig.1. The specific characteristics of these scars are that they are usually clean and show evidence of wear. The vibration of small, hard particles by flow-induced vibration, result in abrasion through the clad that is visibly detectable.

2.1.2. Fuel rod degradation

Defects from 10 microns of equivalent diameter typically can be generated by grid fretting, debris-induced fretting, or handling damage. General rule, typical fretting with spacer grids deteriorates at tolerable rates for some months and then it develops large defects, always in secondary places and associates the massive hydriding of cladding. There are cases of medium sized primary defects that developed secondary hydride defects within a few or ten of days, while others survive 100 days or more [4, 5].

Table 1. Typical characteristics of various fuel failure mechanisms in PWRs [6]

Possible cause	**Time in cycle**	**Activity characteristics**	**Typical activity ^{131}I/failed rod** (10^{-3} μCi/cm^3)	**$^{131}I/^{133}I$ ratio**
Grid Fretting	Any time	Multiple failure events, usually constant iodine activity following each event	3- 50	0.3 – 0.6
Debris Fretting	Typically 0 – 60 days but could be any time	Instantaneous increase following each event; usually followed by gradual iodine activity decrease; typically results in high tramp (^{134}I)	3- 50	0.5 – 0.7
Handling Damage	0 – 60 days	Similar grid fretting	3- 50	0.3 – 0.6
Secondary Damage	Following power changes	Somewhat abrupt increases	> 50	0.3 – 0.5

In respect to debris fretting, the characteristic of the generated defects is that a substantial sized hole can develop quickly, the rate depending on the size, shape and attitude of the object that is causing the fretting. In such defects, the pressure equalization will be rapid and the flow through the defect will not limit the supply of H_2 for attacking the cladding. With such immediate availability of H_2O to the rod internals no hydriding to the primary defect is all likely, but internal oxidation of cladding, both local to the defect and for some distance axially, in both directions, is expected. The same factors govern secondary hydride defects, as in the case of the small primary defects, but here an increment in the size of the primary defect over a long period of time is not necessary in order to make H_2 at a sufficient rate.

In other words, the leak size is not rate determining for the massive hydriding formation. If there is a significant fuel/clad gap at the time of the penetrating primary defect formation, then the necessary high $p(H_2)/ p(H_20)$ ratio is less likely to be achieved than with small gap, because the diffusion of the H_2O as steam or oxidizing radiolytic species will be faster. So critical ratio $p(H_2) / p(H_20)$ (or critical high hydrogen partial pressure) to be achieved means a faster rate of oxygen consumption is necessary. The local internal conditions of the rod (internal temperature of cladding, UO_2 temperature gradients, and connected porosity or cracks) will have influence. Also the axial rating gradient of heat can be of importance in terms of local gap variation. It is the combination of all these factors that determine whether secondary hydrides form and if so where in relation to the primary defect generated by debris fretting.

In summary, for initially large primary defects, the deterioration rate can be large in terms of rate of increase of activity release because of the abundant supply of O_2 to react with UO_2 close to the defect. The formation of hyperstequiometric UO_2 (U_4O_9 or U_3O_8) over an increasing distance together with local clad bore surface oxidation and degradation of gap conductance over a long length of rod to a leads to a large increase in fission product release over a short period of time. In such cases, a thick layer of U_3O_8 can be found close to the primary defect and this fragile material can escape into the coolant. This is the more severe failure spectrum [5].

2.2. Simulation of Failed Fuel Rod Degradation Case by Debris Fretting

2.2.1. Description of case

During cycle 6 of irradiation in the NPP Angra-1 (1996-97), it was found a severe failed fuel rod with indication of debris fretting. The peculiarity of this case is the presence of primary failure in the rod in the position below of spacer grid 8 (bottom, axial region j=1) and probably degraded by secondary hydriding (blister and long axial crack completely opened) between grids 2 and 3. The fuel element had operated for one cycle (burnup 7.8 MWd/kgU). This large failure could explain the high I-131activity at the beginning of cycle 6 [2, 7].

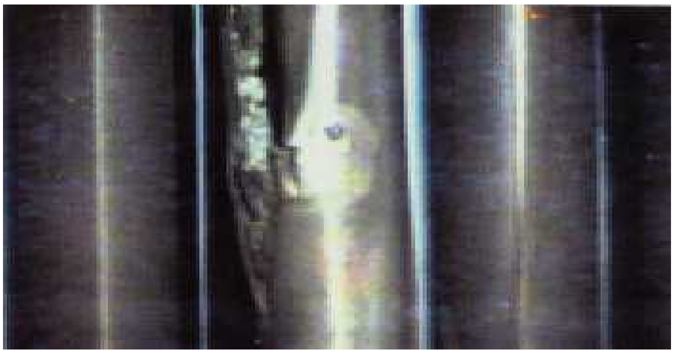
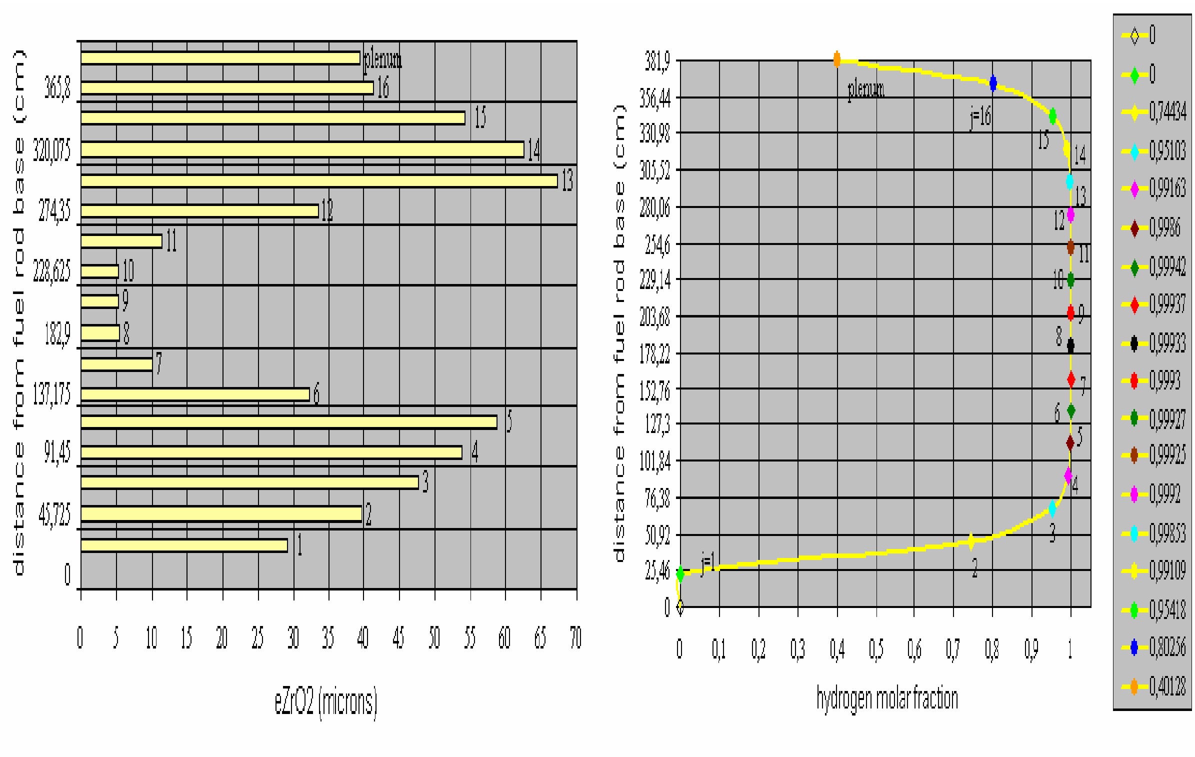


Figure 1. Severe failed fuel rod between grids 2 & 3, cycle 6, Angra-1 [7]

Profiles predicted by the best estimate failed fuel performance code DEGRAD-1 after 253 days in cycle 6 are shown in the Fig. 2a and 2b. The code simulation is base don the nuclear design report for the fuel cycle of the unit. The joint analysis of these data indicates that the axial regions j = 6 to 12 as potential sink to massive hydrogen absorption. These regions correspond to those between the spacers grids 2 to 6. Such result presents reasonable agreement with the comments of the visual inspection [2].

The susceptible level of the massive hydriding can be estimated following order of axial positions: j = 6 (27,43%) – j = 7 (61,13%) – j = 10 (62,20%) – j = 11 (62,22%) – j = 9 (62,62%) – j = 8 (64,58%) – j = 12 (75,28%). The axial region located in spacer grid 3 was identified as that one hydrided more aggressively. This prediction confirms axial crack position identified during the visual inspection. The tip of crack possible is originated in this region, growing axially to direction of the spacer grid 2. The others identified areas are possible regions where the hydride precipitate were still not fully developed in the end of the irradiation cycle.

On the basis of these data, evaluations could have been made to estimate the secondary failure occurrence time, on the basis of the measured equivalent iodine activities [7].



a) b)

Figure 2. Profiles predicted by the best estimate failed fuel performance code DEGRAD 1 after 253 days in cycle 6: a) oxide thickness axial profile on internal surface of the clad; b) hydrogen axial molar fraction in fuel rod gap and plenum.

2.2.2. Aspects about the deterioration evolution

The secondary hydriding and heat flow relation can be applied. Considering the Locke's failure threshold curve, then good part of the fuel operating in PWR Angra-1 would not have risk of failure by hydriding, taken in account the operational limitations to the heat flow in the fuel rod. Theoretically, the Angra-1 fuel operating at heat flow average rate, would lead about 2182 days to achieve failure threshold by hydriding, about 100 days at heat flow maximum rate, and at heat flow critical rate the failure threshold would develop immediately after the primary defect. By analogy with fission gases release kinetic, the progression of failure degradation is strongly dependent of the fuel rod burnup and power. Low burnup implies in opened gap, increasing axial communication of steam and fission gases. High power implies in high temperature, increasing the diffusion of gases generated in the chemical processes operating during the clad degradation and fission gases from fuel. Then, a low burnup fuel rod working at relatively high power is susceptible to develop a secondary defect (and high fission gases release).

About the presented case, the failed rod by debris fretting during the cycle 6 irradiation in Angra-1 was located in the reactor core periphery (submitted to lowest temperatures), but the rod was located face to face with baffle of the reactor vase. It means that the environment can also have influence. But the preponderant factor for the hydrided regions formation were the free axial communication made possible by gap still relatively opened. The gas could move in direction to the peak of power and heat flow positions in the rod, the hydrogen penetrated sites with defect or discontinuity in the oxide film (less thick) deposited on the internal surface of clad.

3. CONCLUSIONS

The causes of failures in PWR fuels present the following distribution statistics: grid-to-rod fretting (40-45%), debris fretting (40-45%), <5% for conditional causes for breaking of the fuel production technology (primary hydriding, weld defects, defects in the cladding pipe), remain failures due the no determined causes [2].

It is acknowledged that fuel failures and fuel related concerns can be quite costly. Although typical failure costs are difficult to quantify, even a single failed LWR rod can cost more than US$ 1 million in outage time and fuel and power replacements costs.

The nuclear power plants can control only certain variables, such as power and operation time, in order to mitigate the fuel rod degradation. In a PWR, if the option will be to reduce the power that is made in all of core having for consequence loss of energy. Since that the suppression of the power is not possible in a PWR, attempts to mitigate the degradation are difficult. A time that indications of clad crack or break occur, restrictions to the ramp rate and to the power oscillations must be considered, what it will help to prevent additional deterioration.

The best way of preventing debris fretting is to keep debris out of the primary circuit obviously. There are three main components in any debris prevention program: a) preventive maintenance on debris producing components; b) improved maintenance and operating procedures that do not produce debris or reduce the quantity produced, and c) establishment of a debris inspection and cleanup program.

REFERENCES

1. A. Strasser, J. Gingold, "Evaluation of Debris Fretting Failures and Preventive Methods", Proceedings of Technical Meeting on Fuel Failures in Normal Operation of Water Reactors: Experience, Mechanisms and Management, Dimitrovgrad, Russian Federation, 1992, IAEA TECDOC-709, pp. 138-143 (1993).
2. M. Castanheira, Thesis "Análise dos Mecanismos de Degradação de Varetas Combustíveis Falhadas em Reatores PWR", IPEN/USP, São Paulo, Brazil (2004).
3. I.I. Loktev; V.V. Rozhkov; A.B. Aleksandrov; Y.K. Bibilashvily, "General Behavior of Leaky Fuel Rod Depending on Defect Size", Proceedings of International Topical Meeting on LWR Fuel Performance, Park City – USA, 2000, CD-ROM (2000).
4. D.O. Pickman, "Failure Developments in Leaking LWR Fuel Rods - A Literature Survey", Studsvik Nuclear, Nyköping, Sweden, NF(R) -89/83, (1989).
5. C. Leuthrot, et al. "Relationships Between the Characteristics of Cladding Defects and the Activity of the Primary Coolant Circuit: an Aid For The Management of Leaking Fuel Assemblies in PWR", Fuel for the 90's: Proceedings ANS/ENS International Topical Meeting on LWR Fuel Performance, Avignon, France, 1991, Vol. 1 (1991).
6. IAEA, "Review on Fuel Failures in Water Reactors". TRS-388, Vienna, Austria (1998).
7. J.L.C. Chapot, R. Suano, N. Couto, J.A. Perrotta, J.E.R. Silva, L.A.A. Terremoto, M. Castanheira, "Fuel Failures at Angra-1: Cause and Mitigation", Proceedings of Technical Meeting on Fuel Failures in Water Reactors: Causes and Mitigation, Bratislava, Slovakia, 2002, IAEA TECDOC-1345, pp. 92-116 (2003).