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FUEL FAILURES AT ANGRA 1: CAUSE AND MITIGATION

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**PRODUÇÃO TECNICO CIENTÍFICA
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Abstract

Angra 1 Nuclear Power Plant, a Westinghouse-designed 657 MWe PWR, was prematurely shut down in cycle 4 due to high activity in the reactor coolant system. Inspections revealed failures in one-sixth of the fuel assemblies (FAs). According to the fuel vendors the grid-to-rod fretting failures were caused by grid spring force losses. In order to prevent the recurrence of the fretting failures, a new spring design was developed. A new reload batch using the new spring design was loaded in the core for cycle 5. In cycle 6, eight of these FAs failed, showing friction marks at outside strips of spacer grids, due to excessive amplitude of FA vibrations. Flow tests in laboratory were performed using a full-scale fuel assembly, and peaks of resonance due to flow induced vibration were observed. Analysis and modeling of the fuel assembly mechanical behavior can explain the resonance observed. All these analyses supported the need for a new fuel assembly design. In cycle 7, the reactor core was loaded with FAs of the same design inserted in cycle 5. Two leaking assemblies were detected during the fuel inspections conducted at the end of cycle 7. A new core was purchased from Angra 1 former fuel supplier (cycle 1), to load cycle 8. The use of a proven fuel design got rid of the fuel failures. The reload batch for the cycle 9 came also from the same origin as cycle 8. The zero-defect aim was also attained in cycle 9. For cycle 10 it was decided to use twelve once burned assemblies, which had composed cycle 7, with a damping system that, according to flow tests, could reduce the FAs vibration. Cycle 10 is presently under operation with no indication of fuel failures. This paper discusses Angra 1 fuel performance with emphasis to the fuel failures, the inspections and out-of-pile tests performed, the mechanical modeling, the corrective actions proposed by the fuel vendors and the failures mitigation.

1. INTRODUCTION

Angra 1 is a Westinghouse-designed 657 MWe PWR, 130 km from Rio de Janeiro, Brazil. The plant is operated by ELETRONUCLEAR, a government utility. Angra 1 began commercial operation in 1985. On 31 May 2002, the plant reached about 90% of the planned burn-up for cycle 10. The reactor core comprises 121 (16x16 array) fuel assemblies (FAs). Each FA contains 235 Zircaloy-4 fuel rods (FRs) supported at intervals along their length by eight Inconel-718 spacer grids. The first core (batches A, B and C) was supplied by Westinghouse. Siemens and Indústrias Nucleares do Brasil (INB) have provided the reloads for cycles 2 to 7. Due to the failures occurred in cycles 4, 6 and 7 a new core with 121 original Angra 1 FAs (standard project) was purchased from Westinghouse to load cycle 8. Later on INB has implemented a contract of technological transfer with Westinghouse in order to produce the standard project. New reloads of Angra 1 (started with the 10th cycle) use this FA fabricated by INB with Westinghouse design. Table I show the core configuration and the failures occurred during the ten operation cycles of the plant.

2. FUEL FAILURES: CYCLES 1 TO 5

During its first three cycles fuel performance at Angra 1 was very good. The fuel inspections carried out showed: no failures in cycle 1; one failed rod in cycle 2 (undefined cause); one failed rod in cycle 3 (undefined cause). In cycle 4, the reactor was loaded with 120 FAs fabricated by Siemens/INB (batches D, E and F) and one assembly that remained from the initial core. During this fourth cycle

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fuel failures led to increasing activity levels in the reactor coolant system (RCS) and the reactor was prematurely shut down on 5 March 1993, as shown in Fig.1 and discussed in Ref.[1].

Table I. Angra 1 Fuel Assembly Failures

Cycle	Period	Fuel Assemblies				FA Leaking Indication	Inspection Test	Comments
		Batch	Vendor/Design	Enrich. (wt %)	Number of F.A			
1	01/85 to 01/86	A B C	W/W W/W W/W	2.1 2.6 3.1	41 36 44	No No No	-	No indication of fuel failure.
2	10/86 to 10/89	A B C D	INB/KWU	3.3	1 36 44 40	No No 1 No	Sipping can	One failed fuel (estimation of 1 fuel rod). Mechanism and root cause not determined.
3	01/90 to 08/91	C D E	INB/KWU	3.4	41 40 40	1 No No	Sipping can	One failed fuel (estimation of 1 fuel rod). Mechanism and root cause not determined.
4	05/92 to 03/93	C D E F	INB/KWU	3.4	1 40 40 40	No 17 4 1	In-mast sipping; Visual; Ultrasonic test.	Main mechanism rod-to-grid fretting; secondary damage; loose fuel rods; some fuel rods slipped down onto end fitting. One FA of batch F was damaged by handling.
5	12/94 to 03/96	A B C F G	INB/KWU	3.4	36 8 1 36 40	No No No No No		Batch G has a new design with a higher spacer grid spring force. (No flow test was performed and no design change was done to the spacer grid mixing vanes).
6	06/96 to 09/97	G H J	INB/KWU INB/KWU	3.2 1.9	40 40 41	8 1 No	In-mast sipping; Visual; Sipping can	Debris or handling failure in batch H. Loose fuel rods in batch G, rod-to-grid fretting wears in batch G. Secondary damage observed. Grid-to-grid fretting (west and east faces, higher in FA middle position) for all FA.
7	12/97 to 10/98	F H J L	INB/KWU	3.3	4 36 41 40	1 1 No No	In-mast sipping; sipping can; Visual	Failure mechanism was not determined. May be the same as cycle 4 and 6. Batch L grid-to-grid fretting (west and east faces, higher in FA middle position). Some FA from batch L showed handling damage.
8	12/98 to 03/00	M N P	W/W W/W W/W	2.1 2.6 3.3	41 40 40	No No No	In-mast sipping	No indication of fuel failure.
9	03/00 to 04/01	M N P Q ^{*1} R	INB/S ^{*1} W/W	3.4 3.4	21 40 40 4 16	No No No No No		No indication of fuel failure.
10	04/01 to now	M N P Q ^{*1} R L ^{*2} S ^{*3}	INB/W	3.4	1 8 40 4 16 12 40			90% of the cycle completed, with no indication of failure.

(*1) - New Siemens F.A design with split mixing vanes in the spacer-grids, manufactured by INB.

(*2) - F.A with dampers inside the guide-thimbles.

(*3) - Westinghouse design, manufactured by INB.

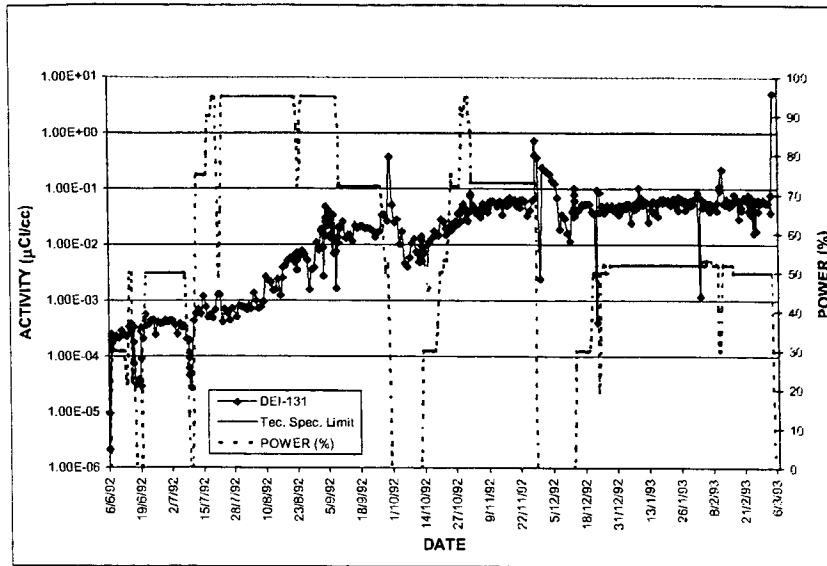


FIG. 1 - Angra 1 cycle 4: dose equivalent I-131

Ultrasonic testing performed during outage found 64 leaking FRs in 17 FAs of batch D, that had been loaded in cycle 2 (Figure 2).

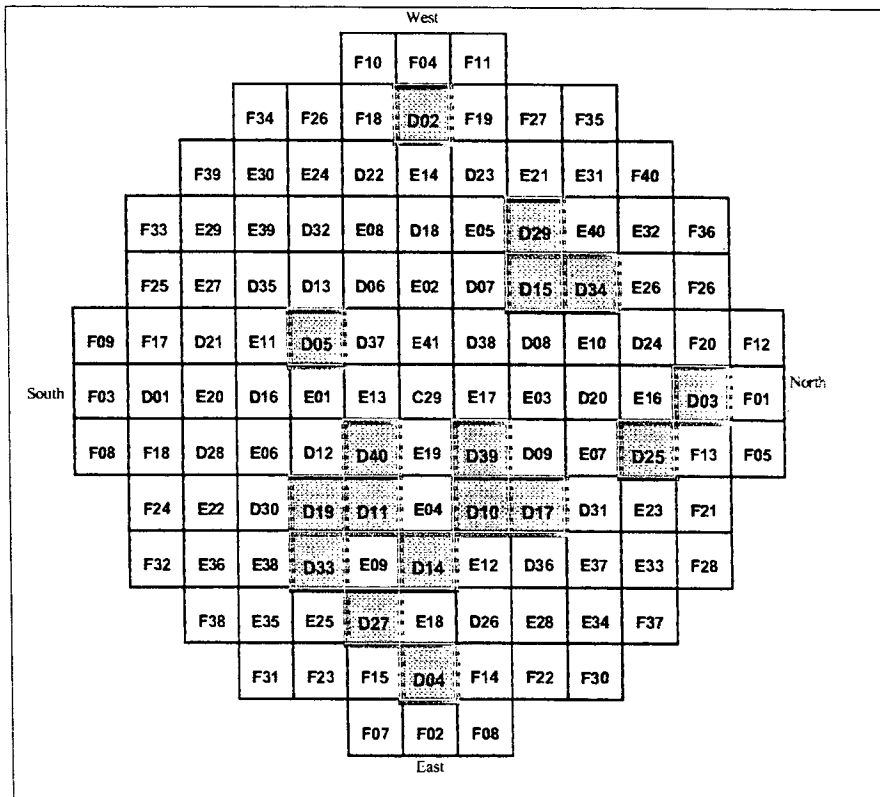


FIG. 2. Angra 1 cycle 4: Failures location

The visual inspections identified grid-to-rod-fretting as the main failure mechanism of the leaking assemblies. Seventy-six "loose" and / or fretted FRs were observed in the failed 17 FAs of batch D (see Fig. 3). The RCS trend plots recorded during cycle 4 showed that the FA containing the first failed FR had an average burn-up ranging from 19 to 24 MWD/kgU.

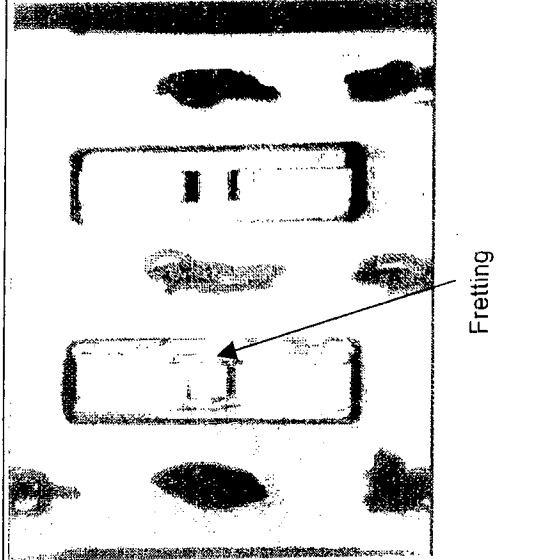
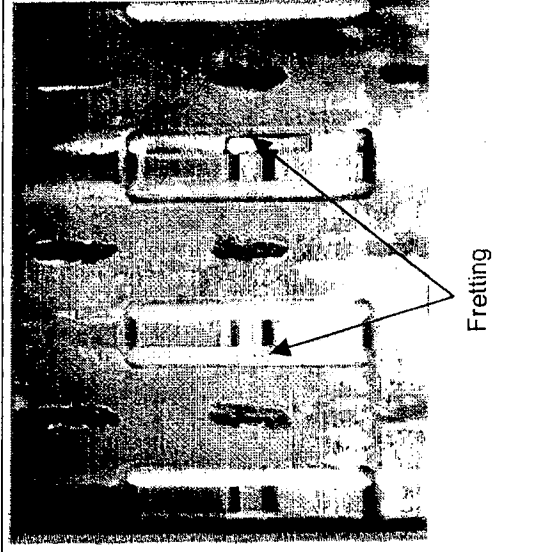
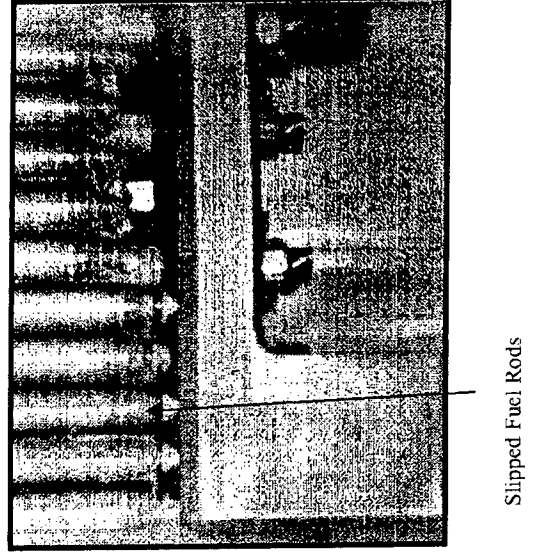
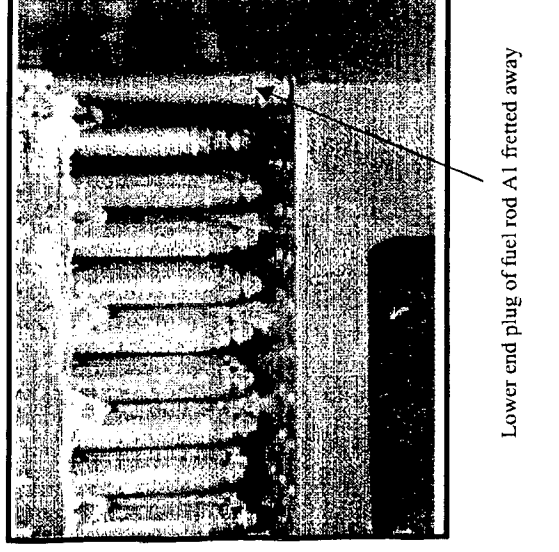
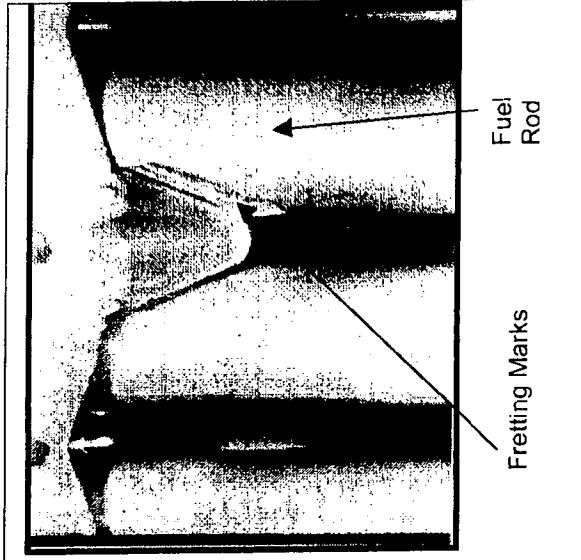
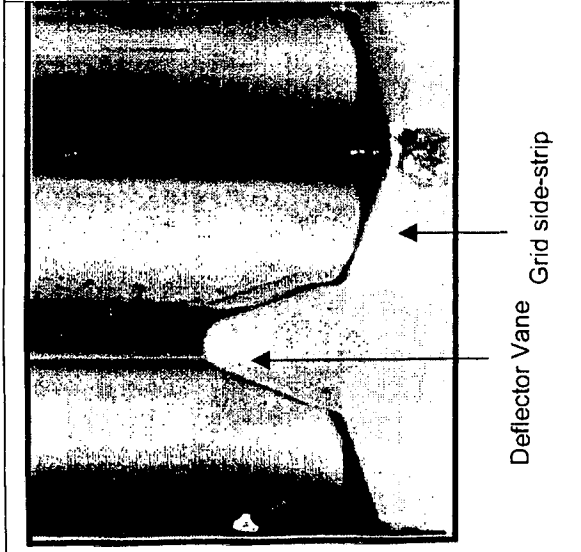


FIG.3. Angra 1 cycle 4: Fretting on batch D FAs.

In February 1994, Siemens issued a report, Ref.[2], evaluating the root-cause of the failures. According to Siemens they were caused by grid spring force losses occurred when the fuel rods were inserted in the skeleton, possibly in combination with loads sustained during transport to the site. In order to prevent the recurrence of the fretting failures, Siemens developed a new spring design whose main characteristics were a new shape and a higher initial force.

The cycle 5 core loading came from three sources:

- A new reload batch G (40 FAs), manufactured by Siemens/INB using the new spring design;
- Thirty-six FAs from batch F used in cycle 4 (average discharge burn-up of 5 MWD/kgU). The batch F assemblies have the same spring as batch D, so the burn-up of batch F was conservatively limited to 18.5 MWD/kgU in cycle 5. Assemblies from batch E could not be used because they have an average discharge burn-up of 15 MWD/kgU, and they would soon reach the limit of 18.5 MWD/kgU. This would risk fretting failures similar to those found in batch D;
- Forty-five Westinghouse FAs that had been stored in the spent fuel pool since they were unloaded after the three first cycles.

No failure was detected during cycle 5 operation.

3. FUEL FAILURES IN CYCLE 6

In cycle 6 Angra 1 core was loaded with 121 Siemens/INB FAs discriminated as follows:

- Forty G FAs used in cycle 5;
- Forty new FAs enriched to 3.2% (batch H);
- Forty-one new FAs enriched to 1.9% (batch J). This additional reload batch had been purchased to be used exclusively in cycle 6 because of the fuel failures in cycle 4.

Cycle 6 started on 8 August 1996 with a low RCS activity level. On 28 August, with the reactor at 93% of nominal power, the dose equivalent iodine-131 (DEI-131) was $1.3 \times 10^{-3} \mu\text{Ci/g}$, and the sum of noble gases activities was $7.7 \times 10^{-3} \mu\text{Ci/g}$. However, on 30 August the RCS activities increased very significantly. On 4 September, DEI-131 reached $0.1 \mu\text{Ci/g}$ and the sum of gases $1.6 \mu\text{Ci/g}$. Following Angra 1 Fuel Failures Action Plan the chemical and volume control system letdown rate had to be increased from 220 to 440 lpm and the primary system periodically degassed. DEI-131 activity decreased continuously up to mid-January 1997 (see Fig. 4).

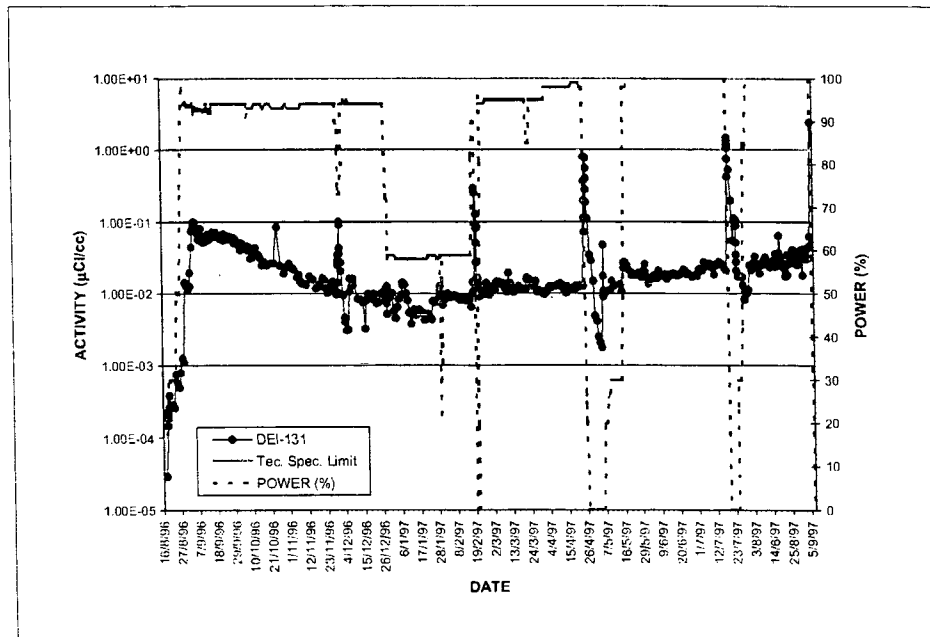


FIG.4. Angra 1 cycle 6: dose equivalent I-131

From mid-January, DEI-131 started to increase smoothly up to about the end of July. However, from August to the end of cycle (EOC) the rate of activity increase was significantly higher than in the previous 6 months. On 05 September 1997, the last DEI-131 measured before the scheduled plant shut down was about 0.05 $\mu\text{Ci/g}$. This value is twice as high that one detected one month before, but approximately the half of the maximum DEI-131 value measured during cycle 6 (0.1 $\mu\text{Ci/g}$, on 4 September 1996). Therefore, it should be emphasized that dose-equivalent I-131 remained significantly below the Technical Specifications limit (1 $\mu\text{Ci/g}$) during cycle 6.

A number of different inspections were carried out: in-mast sipping (IMS), wet sipping and visual inspection, Ref.[3,4,5,6,7,8]. The tests identified the following:

- Eight failed FAs in batch G [G12, G16, G19, G21, G26, G28, G29 and G40] and one in batch H [H07] (see Fig.5);
- Fretting wear on spacer grid side-strips of several FAs.

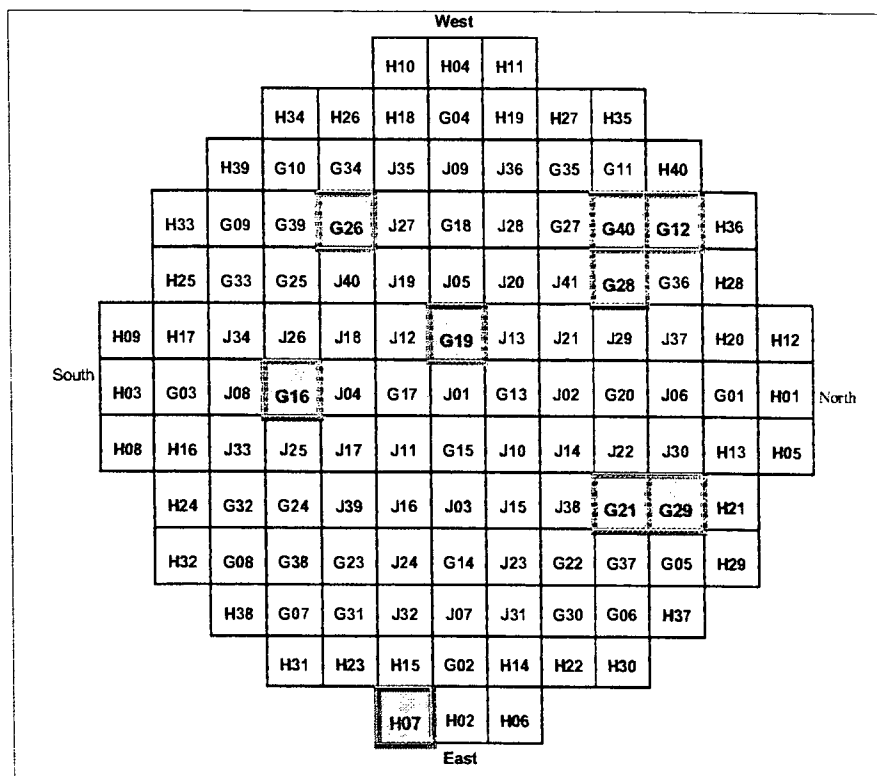


FIG5. Angra 1 cycle 6: Failures location

The main observations on grid side-strip fretting wear were:

- Fretting limited to west and east faces; and hammered out areas on south and north faces;
- Fretting most severe on grids 4 and 5, less on grids 3 and 6.
- Fretting marks observed in batches G, H and J (see Fig.6).

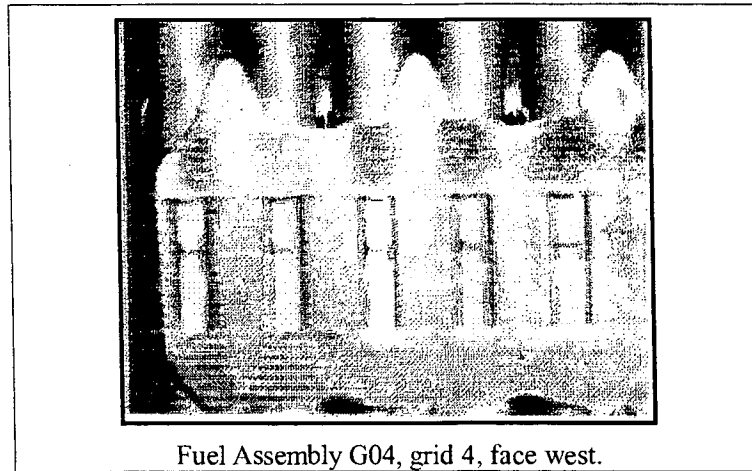
The key observations on the fuel failures are shown below:

Batch G

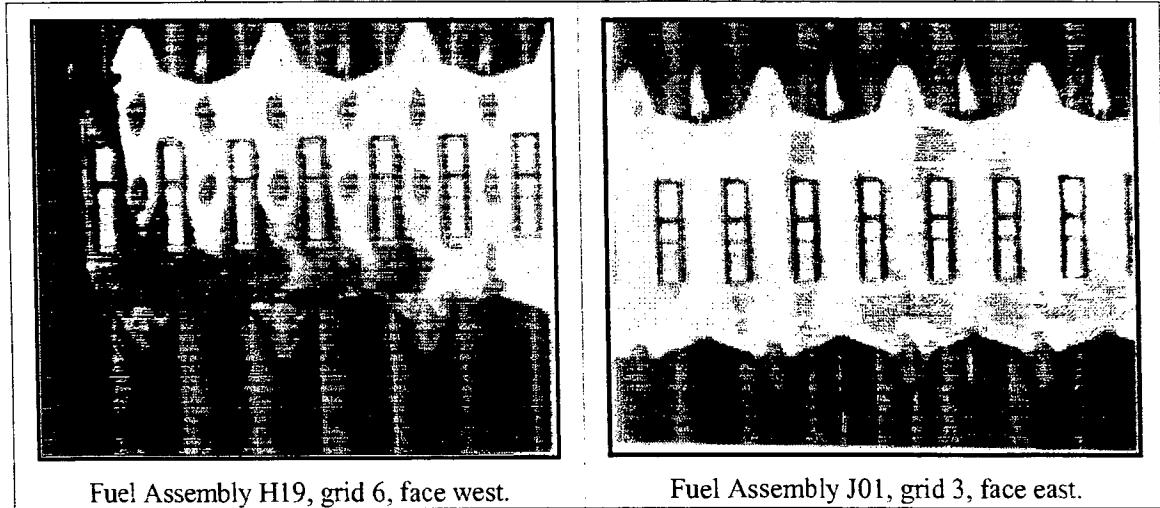
- At least 5 “loose” rods (rod movement): 2 rods on east face of G28 and one corner rod each in G16, G19, and G21.
- Rod fretting wear under contact spring: G21 south left corner: G19 east corner (both “loose” rods).
- Hydride blister: G28 east; G21 south.
- No apparent primary failure locations.
- All eight FAs appeared to maintain good structural integrity; no degradation except the “loose” rods.

Batch H:

- Severe damage on FA H-07 at FR 14, at face north below grid 2. Possible debris mark below grid 8 (bottom) on same rod. A metallic debris found at face north, above grid 8, between rods 6 and 7 (see Fig.7)



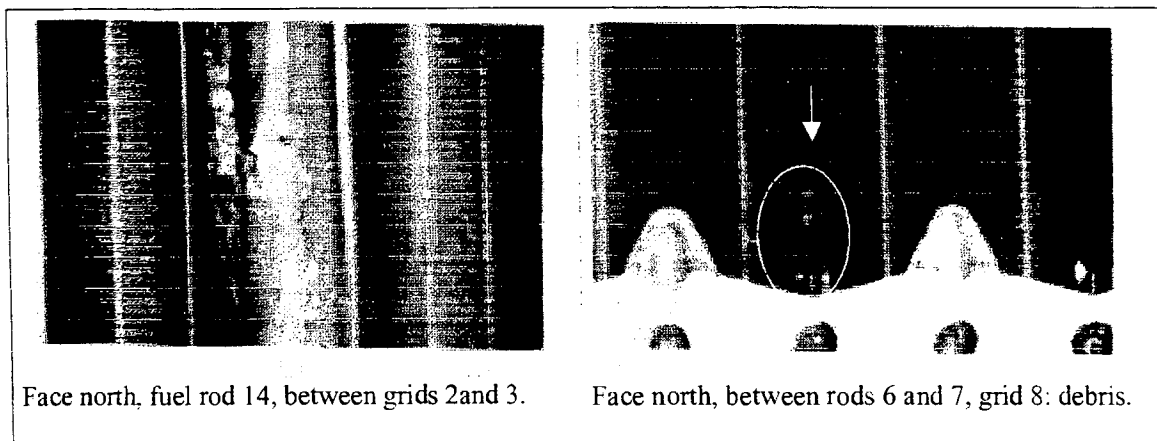
Fuel Assembly G04, grid 4, face west.



Fuel Assembly H19, grid 6, face west.

Fuel Assembly J01, grid 3, face east.

FIG. 6. Angra 1 cycle 6: wear marks on spacer grids side strips.



Face north, fuel rod 14, between grids 2 and 3.

Face north, between rods 6 and 7, grid 8: debris.

FIG. 7. Angra 1, cycle 6. fuel assembly H07

3.1 Root cause evaluation

3.1.1. Fuel assembly H07

H07 is most likely to have failed by debris or by damage during core loading. The FR 14 probably degraded by secondary hydriding below grid 2. This large failure could explain the activity behavior in cycle 6. Our interpretation is that the high I-131 activity at the beginning of cycle has been caused by FR 14 failure early in cycle. It should be still emphasized that the high RCS activity due to H07 failure masked batch G failures.

3.1.2. Batch G

The root-cause analysis presented below is based on the information available at the end of 1997, Ref.[9]. The visual inspections could neither show the primary failure locations of batch G nor determine conclusively the failure mechanism. However, the failures and the fuel damages detected in cycle 4 can help us interpreting the event observed in cycle 6. As stated in item 2, grid-to-rod fretting has been identified as the failure mechanism of batch D in Angra 1 cycle 4. Comparisons between the predominant characteristics registered by the inspections carried out during the outages of Angra 1 cycles 4 and 6 are shown in Table II. The analysis of this table shows that there are significant differences between the visual observations in cycles 4 and 6. However, the wear marks on some batch G fuel rods, together with "loose" rods on leaking FAs, are strong evidences that grid-to-rod fretting was the main failure mechanism of batch G in cycle 6.

Table II. Comparison between Angra 1 cycles 4 and 6 fuel failures.

	CYCLE 4 (BATCH D)	CYCLE 6 (BATCH G)
FRETTING MARKS ON THE FUEL RODS	<i>MANY</i>	6
SLIPPED FUEL RODS DOWN ONTO THE FUEL ASSEMBLY LOWER END FITTING	<i>MANY</i>	<i>NONE</i>
"LOOSE" RODS IN THE GRID CELLS	<i>MANY (grids #1 to #8)</i>	<i>5 (mid-grids/corner rods)</i>
GRID SIDE-STRIP FRETTING WEAR	<i>RARE</i>	<i>MANY (mid-grids/east-west direction)</i>
AVERAGE DISCHARGE BURN-UP (MWD/kgU)	26	22.8
SECONDARY DAMAGE (HYDRIDE BLISTERS)	<i>YES</i>	<i>YES</i>

The number of leaking FRs in cycle 4 was much higher than in the sixth cycle; no sliding of FRs through the grid cells was observed in cycle 6. Therefore, apparently the rod/spring grid contact of batch G was better than that one of batch D. Nevertheless, as can be seen from Table II, the average discharge burn-up of batch D in cycle 4 was 3.2 MWD/kgU higher than the average discharge burn-up of batch G in cycle 6. A simple calculation shows that, in order to reach the same discharge burn-up as batch D, fuel assemblies G would have to remain more 103 EFPD in the core. Probably, the damages caused by fretting during an additional period of about 3.5 effective full power months would not be negligible. However, as we have no means to predict the future fuel deterioration, we were constrained to evaluate the failure root-cause in function of the evidences arising from the inspections. These evidences pointed out to a better rod/spring grid contact of batch G, when compared to batch D. Nevertheless, in spite of the higher grid spring force of batch G, there has been a recurrence of fretting in cycle 6. Undoubtedly, the friction observed on spacer grids side-strips of

several FAs is the key for understanding this phenomenon.

Rare in cycle 4, the wear marks were the dominant characteristic of cycle 6 event, indicating that occurred a unidirectional contact (east-west) between neighbour FAs during operation. Abnormal vibrations of the FAs probably caused the grid-to-grid contact. The unexpected vibrations were most likely induced by the reactor coolant flow. In other words, flow-induced vibration (FIV) would have been again the root-cause of the fretting failures in Angra 1. The new spring design introduced in batch G, having as main characteristics a new shape and a higher initial force, did not correct the problem, because FIV is fundamentally related to the mixing vane design (shape/orientation), which was not changed from batch D to batch G. The reinforced springs led to a better rod / spring grid contact, resulting in less "loose" rods in cycle 6. On the other hand, the higher spring forces changed the vibrational characteristics (amplitudes and frequencies of the different modes) of the FAs. Due to mechanisms not clearly understood, under the action of the coolant flow the vibrations of the reinforced FAs were intensified, leading to the strong grid-to-grid interactions showed by the visual inspections in cycle 6. Although these hypotheses were reasonable - the fuel vendor agreed in general with them, Ref.[5] - they had to be confirmed by experimental tests (as it will be shown in item 6).

4. FUEL LOADING CYCLE 7

The cycle 6 fuel failures had some important effects:

- The Regulatory Authority has imposed tougher licensing requirements.
- During cycle 7, the RCS radiochemistry analyses were performed at least once a day.
- Batch G was discarded.
- Cycle 7 startup delayed approximately 2 months.
- Cycle 7 was very short (223 EFPD).
- Batches H (twice burned) was discarded at the end of cycle 7.
- An entire new core with 121 original Angra 1 fuel assemblies has been purchased from Westinghouse to load cycle 8.

Cycle 7 core loading came from four sources:

- A new reload batch L (40 FAs), manufactured by Siemens/INB using the same design as batches G, H and J.
- Forty-one assemblies from batch J used in cycle 6.
- Thirty-six assemblies from batch H used in cycle 6.
- Four F assemblies that had been used in cycles 4 and 5.

Batch G was scheduled to return to the core in cycle 7. However, due to the systematic failures detected, ELETRONUCLEAR decided to discard the 40 G FAs. They were replaced by J batch that had been originally purchased to be used exclusively in cycle 6. Besides, H07 and its three symmetric FAs were replaced by four F assemblies, which had been used in cycles 4 and 5. As the residual reactivity of batch J was very low, cycle 7 length was the shortest one of Angra 1 operation history: 223 EFPD.

The Brazilian Regulatory Authority (CNEN) main requirements to license cycle 7 operation were related to the estimation of the fuel failures propagation in cycle 7 as a function of burn-up, and the evaluation of the mechanical integrity of the 81 FAs that would return to the core in cycle 7. For the first item, ELETRONUCLEAR estimated the limiting burn-up as a function of cycles 4 to 6 experience. For the second item, Siemens, INB and the Brazilian research institute IPEN/CNEN-SP analyzed the influence of the friction at the outer surface of the spacer grids on the operational behavior of the FAs, and the influence of impacts due to vibrations on the integrity of guide thimbles. The results arising from experimental tests, Ref.[10], and theoretical calculations pointed out to the conclusion that the FAs would remain functional during cycle 7. Therefore, safety related control rod insertion malfunctions and loss of fuel assembly cooling geometry were not expected to occur. Based on these analyses, CNEN allowed ELETRONUCLEAR to operate cycle 7 initially during only 80

EFPD, and could grant an extension depending upon the RCS activity level detected at the end of this licensed period.

Cycle 7 started on 04 December 1997. Next to the end of the licensed operation period (80 EFPD), theoretical calculations based on the RCS activities led to a number of about 2 leaking fuel rods in the core. However, due to the relatively low activity levels detected, which were well below the Technical Specifications limit (see Fig. 8), CNEN authorized the continuation of the cycle operation. Cycle 7 ended on 17 October 1998. Inspections performed during outage showed 2 failed assemblies: H36 and F29 (see Fig. 9). It should be stressed that the single failure of batch H was on H36, the lowest burnt FA of this region (18.1 MWD/kgU).

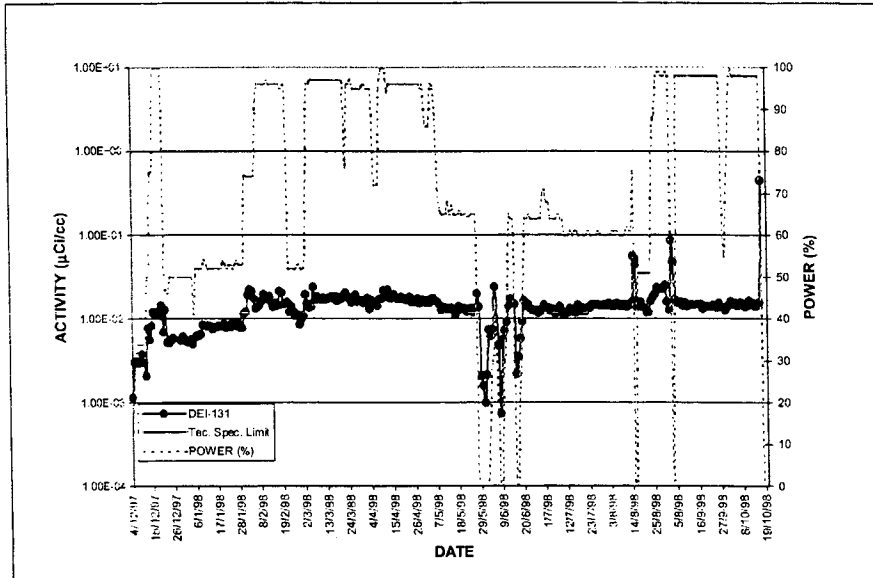


FIG. 8 – Angra 1 cycle 7: dose equivalent I-131

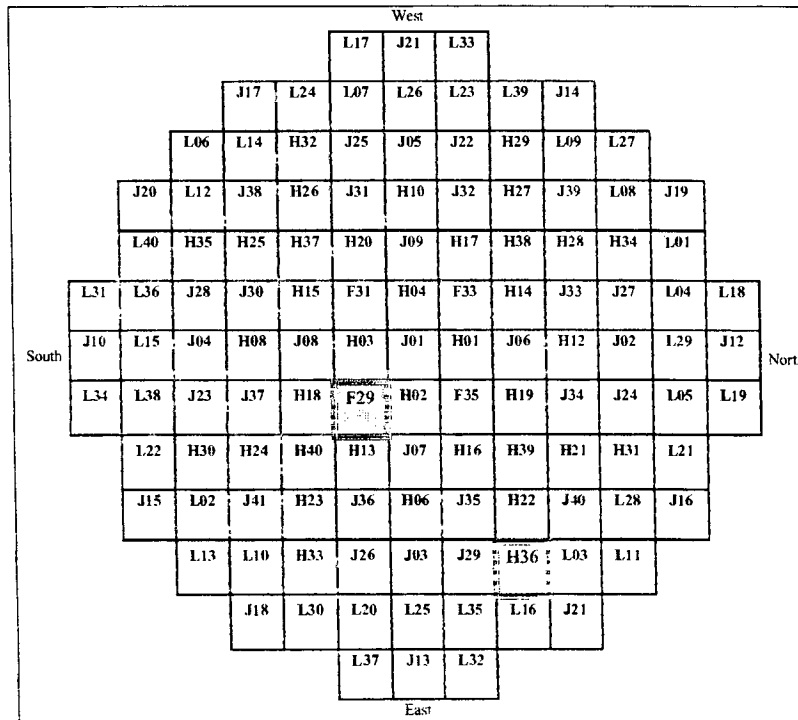


FIG.9. Angra 1 cycle 7: Failures location

5. CYCLE 8 FUEL PERFORMANCE: THE FAILURES MITIGATION

Perhaps the most important consequence of the failures in cycle 6 was that an entire new core with 121 original Angra 1 fuel assemblies was purchased from Westinghouse to load cycle 8. This *corrective action*, i.e., the use of a proven fuel design, was expected to eliminate the fretting failures experienced by Angra 1. Additionally, as the FAs supplied by the plant designer have built-in anti-debris filters it was also expected that the recurrence of failures by debris would be minimized.

Three batches composed the cycle 8 core:

- M (41 FAs enriched to 2.1%)
- N (40 FAs enriched to 2.6%)
- P (40 FAs enriched to 3.245%)

Cycle 8 length was 394 EFPD. It started on 11 December 1998 and ended on 19 April 2000. The fuel performance was very good. No failures were observed.

6. FLOW EXPERIMENTS OF ANGRA 1 FUEL ASSEMBLIES

Along 1998, Siemens/INB performed laboratory flow vibration tests in order to assess the susceptibility of G fuel assemblies to flow-induced vibration, Ref.[11,12,13,14]. The tests were done in a low-pressure loop ($< 110^{\circ}\text{C}$, $< 6,5\text{ m/s}$, $< 10\text{ bar}$). At select locations, the flow velocity, and the vibration of the rods and that of the fuel assembly were measured. Inductive displacement measurement devices were applied to determine the distance between the spacer grids and the inner test channel wall. Several windows, in the test rig wall, allowed measurement of the flow velocity.

The main observations were:

- The vibration was only significant perpendicular to the cross flow direction, determined by the unidirectional mixing vane pattern. It was assumed that this self-induced excitation was directly related to cross flow. There was a sharp resonance, for the fuel assembly vibration perpendicular to the mixing vane direction, in the range of 25-27 Hz.
- The amplitude of vibration was dependent on the coolant flow velocity. For flow velocities from 5.2 to 5.6 m/s the amplitude increased and for flow velocity from 5.7 to 6.1 m/s the amplitude decreased. The maximum FA vibration amplitude was on the range of 100 microns.
- The resonance seemed only to occur for sufficient strong grid spring forces, related to the beginning of life (BOL) condition. The resonance was not observed for the simulation of end of life (EOL) condition, with very low force at the grid spring.
- For BOL condition the fuel assembly, including the cage and fuel rods, was vibrating in a highly synchronized manner. The neighbour spacer grids were vibrating with a phase difference of 180° , and the motion of the rods in each span was fully determined by the corresponding spacers.
- The resonance was considerably reduced by the insertion of a damper inside the fuel assembly (rods inside the guide tubes).

Based on the test observations, Siemens/INB recommended the reinsertion of the partially burned FAs (Batch L) in the core, but using dampers inside them.

Based also on the test information, it was developed a new mixing vane design, using split pattern. Tests carried out on a modified fuel assembly (PS4) using the new spacer grid design showed that the resonance was not any more a problem and no restriction was found to the usage of this new design related to the fuel rod fretting behavior.

7. CYCLE 9 FUEL PERFORMANCE

Since the end of cycle 7 there were more than 150 FAs prematurely stored in Angra 1 spent fuel pit, due to propensity for fretting failures. As the remaining reactivity of batches E, F, G, H (twice burned) and L (once burned) is highly significant, ELETRONUCLEAR analyzed the viability of starting a fuel assembly reconstitution program. Nevertheless, there was an obstacle for

accomplishing that goal: the lack of a qualified Siemens/INB skeleton. However, the flow test results presented in item 6 indicated that, under laboratory condition, the new FA designed by Siemens/INB (PS4) had no susceptibility to flow-induced vibration. Eletronuclear decided then to launch a qualification program for the PS4 design. Four lead test assemblies (batch Q - 3.4% enriched) were then inserted in the Angra 1 core in cycle 9. The other FAs came from the following sources:

- A new reload batch R (16 FAs - 3.4% enriched), manufactured by Westinghouse (the same design as batches M, N and P).
- Twenty-one assemblies from batch M used in cycle 8.
- Forty assemblies from batch N used in cycle 8.
- Forty assemblies from batch P used in cycle 8.

Cycle 9 started on 11 July 2000 and ended on 07 April 2001. The goal of zero fuel failures was achieved again.

8. CYCLE 10: REINSERTION OF PARTIALLY BURNED FUEL ASSEMBLIES WITH DAMPING DEVICES

At the end of cycle 7, the burn-up of batch L (Siemens/INB design) ranged from 5 to 11 MWD/kgU. As a result of the flow experiments discussed in item 6, the fuel vendor recommended the reinsertion of **partially burned** FAs of batch L, with damping device, into Angra 1 core. Due to the high remaining reactivity of those elements, ELETRONUCLEAR decided then to use 12 L FAs to compose cycle 10 core.

Before the use of the batch L fuel assemblies all them (40 FAs) were visually inspected, Ref.[15]. The main observations of the inspection were:

- All FAs showed wear marks at the side strip of spacer grids, fretting limited to west and east faces; and hammered out areas on south and north faces (see Fig.10);
- FA L04 had one of the grids damaged by excessive wear (see Fig.11);
- 25% of FAs showed also wear at the grid spring of the side strip, which can cause loss of the FR fixing force and can lead to fretting (see Fig.12);
- FAs L08 and L01 showed damage in spacer grids due to improper handling during core loading or unloading (see Fig.13).

The pattern of wear verified in batch L, which has a low average burn-up, matches well with the flow induced vibration for beginning of life conditions simulated in flow test at laboratory as shown in item 6. Nevertheless the amplitude of vibration observed were much bigger (more than 10 times) in reactor than in laboratory rig.

Based on the visual inspection results, 12 batch L fuel assemblies were chosen for being used with dampers. Besides these 12 FAs, Angra 1 cycle 10 core was loaded with:

- a new reload batch S (40 FAs - 3.4% enriched), manufactured by INB using Westinghouse technology;
- one assembly from batch M used in cycle 8;
- eight assemblies from batch N used in cycle 9;
- forty assemblies from batch P used in cycle 9;
- four lead test assemblies (batch Q) used in cycle 9;
- sixteen assemblies from batch R used in cycle 9.

Cycle 10 started on the 6 June 2001 and will finish at 20 of July 2002. No failures had been detected up to the middle of June 2002. Visual inspections of cycle 10 FAs are scheduled for being done during the next outage, when the mechanical behavior for flow induced vibration will be verified.

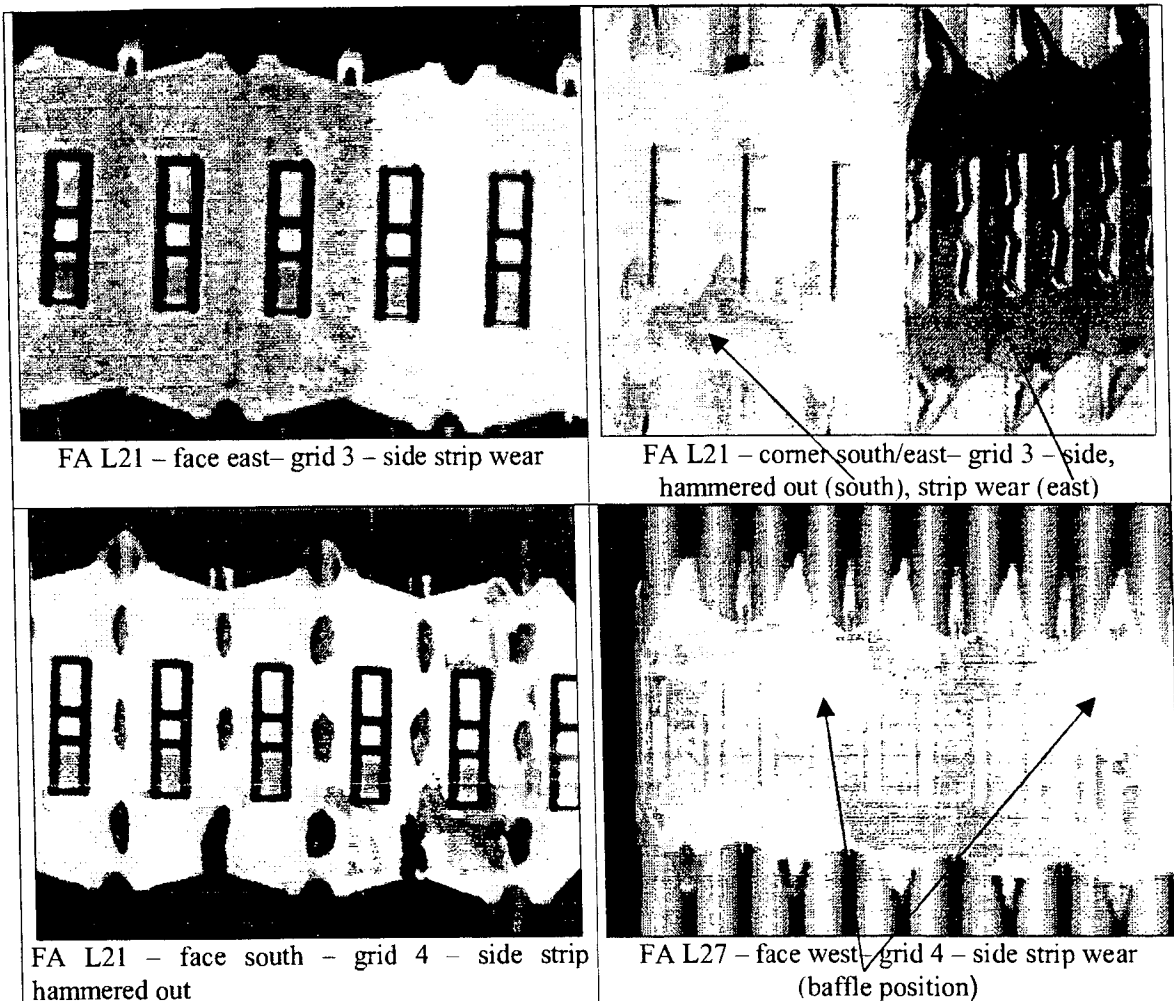


FIG.10. Angra 1, batch L, wear marks at spacer grids side strips.

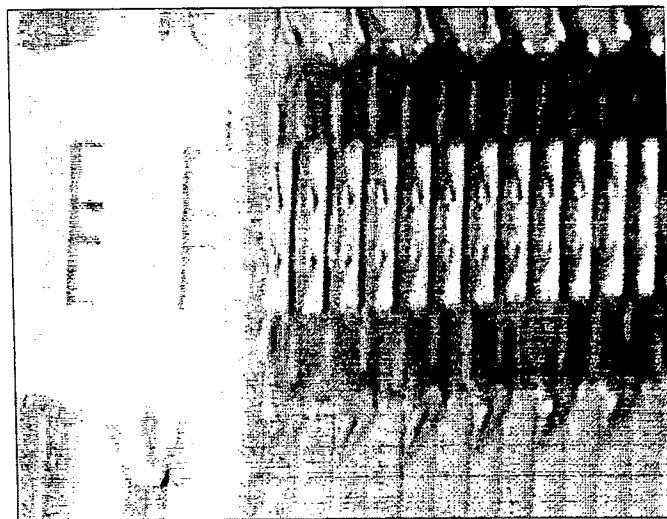


FIG.11. Angra 1 batch L - FA L04, face south, grid 4, damaged strip by wear.

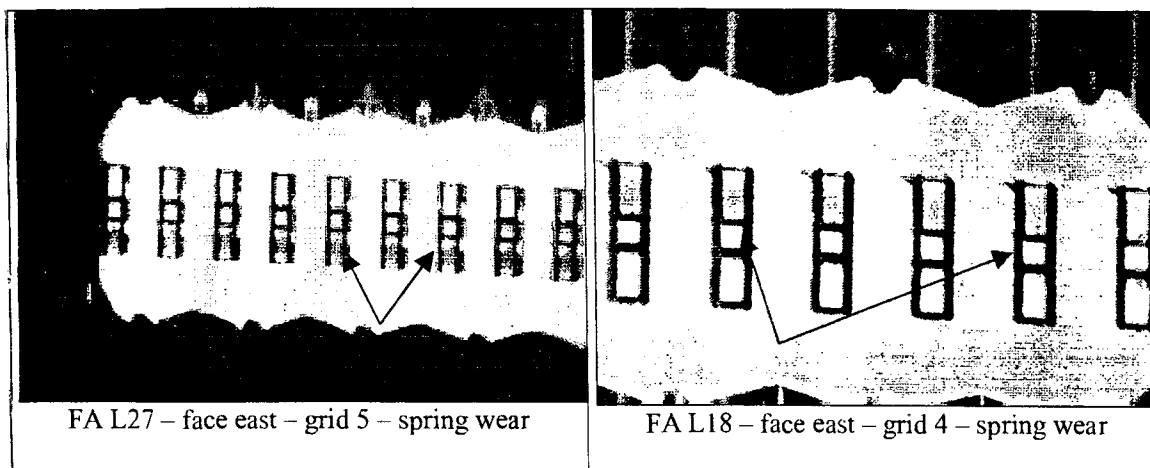


FIG.12. Angra 1 batch L spacer grid strip and spring wear.

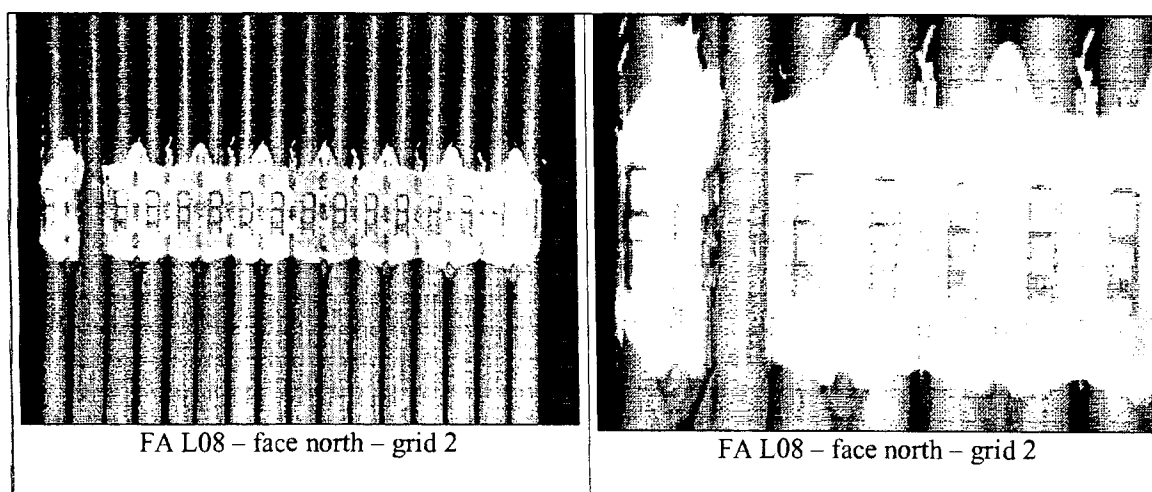


FIG.13. Angra 1 batch L, grid damaged by handling.

9. FAILURE ANALYSIS - DISCUSSION

The structure of a PWR fuel assembly is formed by a support structure (skeleton) composed by end nozzles, guide tubes and spacer grids. The guide tubes are rigidly fixed to the end nozzles and the spacer grids. The spacer grids support the fuel rods through fixing devices that allows the differential movement between the fuel rod and the spacer grids (or the fuel rod and the skeleton). The fuel assembly mechanical stiffness depends mainly on the stiffness of the fuel rod-spacer grid fixing device. This fixing device stiffness (in each of the three directions of displacement and the three directions of rotation) depends on the spacer grid spring and dimple stiffness, and on the geometry characteristics of the pair spring-dimple in each spacer grid cell. It is important to realize that the forces acting on a fuel rod "flow" from the rod to the spacer grid, then to the guide tubes and then to the end nozzles which receives the reaction of the core support plate structure. The forces acting on the fuel rod are the hydraulic ones and those from differential displacements due to thermal gradients and to irradiation growth. The fuel assembly displacements and rotations result from all forces acting in all fuel rods. An important force acting on the fuel rod is that due to the coolant flow. The force acts mainly perpendicular to the axis of the fuel rod and it is due to the parallel flow of the water and due to cross-flow originated from mixing vanes in the spacer spring or from thermal gradients and flow gradients along the fuel assembly. It is well known among fuel designers that the fuel rod is mainly excited in its lower mode of vibration by the coolant flow, Ref.[16]. This is an important point

in the behavior of FAs in the reactor and to identify fuel rod failure by fretting.

Perrotta, Ref.[17], developed, using a matrix method, the computer code ELCOM for PWR fuel assembly static structural analysis. The method description helps the understanding of the fuel assembly structural behavior. The main assumption of the method is that the spacer grid behaves like a rigid body, so each of its cells node displacement or rotation can be related to the displacement and rotation of the grid center of gravity. The method takes into account all fuel rods, guide tubes, spacer grids and end nozzles and constructs an equivalent beam to the fuel assembly where the beam nodes are at the center of gravity of each spacer grid and end nozzles. Each fuel rod or guide tube is considered as a local system and the equivalent beam as the global system in the matrix method. The method considers up to three displacement and three rotation directions (three-dimensional problem). The method considers linear behavior for small displacements.

The fuel rod local system can be described by:

$$\{R_{vi}\} + \{R_{Mi}\} = [K_{vi}] \{r_{vi}\} \quad (1)$$

$\{R_{vi}\}$ – vector of the equivalent nodal external forces acting on the i^{th} fuel rod (this could be from thermal gradients, mechanical forces, irradiation growth, and hydraulic forces);

$\{R_{Mi}\}$ – vector of the reaction forces from the fixing device in the spacer grid (due to the spring-dimple system in the grid cell);

$[K_{vi}]$ – stiffness matrix of the i^{th} fuel rod;

$\{r_{vi}\}$ – vector of the nodal displacement of the i^{th} fuel rod.

The equation (1) can be set for all fuel rods taking the subscript i out, and the size of the vectors will be $6m$, being m the number of fuel rods.

The guide tube local system can be described by:

$$\{R_{vj}\} + \{R_{sj}\} = [K_{vj}] \{r_{vj}\} \quad (2)$$

$\{R_{vj}\}$ – vector of the equivalent nodal external forces acting on the j^{th} guide tube;

$\{R_{sj}\}$ – vector of the reaction forces from the fixing device in the spacer grid (considered to be a rigid joint);

$[K_{vj}]$ – stiffness matrix of the j^{th} guide tube;

$\{r_{vj}\}$ – vector of the nodal displacement of the j^{th} guide tube.

The equation (2) can be set for all guide tubes taking the subscript j out, and the size of the vectors will be $6n$, being n the number of guide tubes.

The displacement vector of the local system of the fuel rod - grid joint (spring or dimple) is given by:

$$\{R_{Mi}\} = \{r_{gi}\} - \{r_{vi}\} \quad (3)$$

$\{r_{gi}\}$ – displacement vector of the i^{th} node at the spacer-grid cell (external node);

The reacting force in the fuel rod-spacer grid-fixing device is given by:

$$\{R_{Mi}\} = [K_M] \{r_{Mi}\} = [K_M] (\{r_{gi}\} - \{r_{vi}\}) \quad (\text{before fuel rod sliding}) \quad (4)$$

$$\{R_{Mi}\} = \{R_o\} \quad (\text{after fuel rod sliding}) \quad (4a)$$

$[K_M]$ is the stiffness matrix (assumed linear) of the joint device (spring-dimple).

$\{R_o\}$ is the vector of the limiting forces for fuel rod sliding in the spacer grid.

The equation (4) can be set for all fuel rods – spacer grid system taking the subscript i out. The size of the vectors will be $6m$, being m the number of fuel rods.

Assuming rigid body movement for the spacer grid, the following relations are obtained:

$$\{r_g\} = [A_M]\{r_G\} \quad (5)$$

$$\{r_i\} = [A_i]\{r_G\} \quad (6)$$

$\{r_G\}$ – displacement vector for the grid center of gravity;
 $[A_M]$ – transformation matrix for the fuel rods;
 $[A_i]$ – transformation matrix for the guide tubes.

The equilibrium equation for the spacer grids and end nozzles (global system) is given by:

$$\{R_G\} = [A_M]^T\{R_M\} + [A_i]^T\{R_s\} + [A_f]^T\{R_f\} \quad (7)$$

$\{R_G\}$ – vector of the external forces acting in the grids and nozzles;
 $[A_f]^T \cdot \{R_f\}$ – this term represents the vector of reacting forces of the fuel assembly fixing spring at the top nozzle, and this term can be written as:

$$[A_f]^T\{R_f\} = [A_f]^T(-[K_f]\{r_{f0}\} - [K_f][A_f]\{r_G\}) \quad (8)$$

$[A_f]$ – transformation matrix for the fuel assembly fixing spring;
 $[K_f]$ – stiffness matrix (assumed linear) of the fuel assembly fixing spring;
 $\{r_{f0}\}$ – initial displacement vector of the fuel assembly fixing spring;

The following system of equations can be written:

$$\{R_v\} + [K_M]([A_M]\{r_G\} - \{r_v\}) - [K_v]\{r_v\} = \{0\} \quad (9)$$

$$\{R_G\} - [A_M]^T[K_M]([A_M]\{r_G\} - \{r_v\}) + [A_i]^T\{R_s\} - [A_i]^T[K_i][A_i]\{r_G\} + [A_f]^T[K_f]\{r_{f0}\} + [A_f]^T[K_f][A_f]\{r_G\} = \{0\} \quad (10)$$

Taking the value of $\{r_v\}$ in (9) and replacing it in (10) gives the equilibrium equation for the equivalent beam to the fuel assembly:

$$\{R_G\} + [A_i]^T\{R_s\} + [A_f]^T[K_f]\{r_{f0}\} + [A_M]^T[K_M]([K_M] + [K_v])^{-1}\{R_v\} = ([A_M]^T[K_M][A_M] - [A_M]^T[K_M]([K_M] + [K_v])^{-1}[K_M][A_M] - [A_i]^T[K_i][A_i] + [A_f]^T[K_f][A_f])\{r_G\} \quad (11)$$

Equation (11) can be written as:

$$\{F_G\} = [K_G]\{r_G\} \quad (12)$$

Where:

$$\{F_G\} = \{R_G\} + [A_i]^T\{R_s\} + [A_f]^T[K_f]\{r_{f0}\} + [A_M]^T[K_M]([K_M] + [K_v])^{-1}\{R_v\} \quad (13)$$

$$[K_G] = [A_M]^T[K_M][A_M] - [A_M]^T[K_M]([K_M] + [K_v])^{-1}[K_M][A_M] + [A_i]^T[K_i][A_i] + [A_f]^T[K_f][A_f] \quad (14)$$

It can be seen from equation (14) that the stiffness of the equivalent beam of the fuel assembly takes into account the stiffness of all components: fuel rods, guide tubes, fuel rod-spacer grid fixing device, fuel assembly fixing spring. As the value of the stiffness of the fuel rod fixing device increases, the stiffness of the fuel assembly increases. The opposite is true, that means, as the stiffness (or the fixing

force) of the fuel rod in the spacer grid decreases, the stiffness of the fuel assembly decreases. As the fixing force of the fuel rod decreases along burn-up (mainly by creep), the stiffness of the fuel rod (local system) and the stiffness of fuel assembly (global system) decrease along burn-up either.

It can be seen from equation (13) that the forces acting in the equivalent beam of the fuel assembly come from forces acting directly on the spacer grids, the compression of the fuel assembly fixing spring, the forces acting on the guides tubes and the forces acting on the fuel rods. These last ones are transmitted to the fuel assembly by the fuel rod – spacer grid fixing device. As the fixing force of the fuel rod decreases along burn-up (mainly by creep), the forces transmitted from the fuel rod (local system) to the fuel assembly not necessarily decreases, but the differential displacement between the fuel rod and the grid (fuel rod sliding in the grid) certainly increases, which may increase fretting in the fuel rod along irradiation.

It is interesting to compare the values of stiffness for the fuel rod – spacer grid fixing device and the fuel rod stiffness (terms of $[K_M]$ and $[K_V]$). Table III presents these values. From this table is seen that the shear stiffness of the fixing device is much bigger than the fuel rod value. This means that for the term $([K_M] + [K_V])$ $[K_M]$ is the most important for beginning of live and also for end of live. For rotation there is a higher importance of the term $[K_M]$ for beginning of live, but $[K_V]$ gets important for end of live.

Table III. Comparison between stiffness values

Spacer Grid Device Stiffness Value for Beginning of Live		Fuel Rod		
		Stiffness Value (*)	Between 1 st and 2 nd spacer grid (620.5mm)	Other segments (522 mm)
Shear (Spring)	~60 N/mm	12 EJ/l ³	0.69 N/mm	1.16 N/mm
Shear (Dimple)	~ 600 N/mm	12 EJ/l ³	0.69 N/mm	1.16 N/mm
Rotation	~ 400000 Nmm/rad	4EJ/l	88345 Nmm/rad	105016 Nmm/rad

(*) $E = 7,8 \times 10^4 \text{ N/mm}^2$; $J = 175,7 \text{ mm}^4$

From the static equilibrium system shown before, one can estimate the natural frequencies of the local system (fuel rod) and the fuel assembly equivalent beam. The complete time dependent equation may be written:

$$[m_{vi}]\{\ddot{r}_{vi}\} + [c]\{\dot{r}_{vi}\} + ([K_M] + [K_V])\{r_{vi}\} = \{R_{vi}(t)\} \quad (15)$$

$$[M]\{\ddot{r}_G\} + [C]\{\dot{r}_G\} + [K_G]\{r_G\} = \{F_G(t)\} \quad (16)$$

$[m_{vi}]$, $[M]$, $[c]$, and $[C]$ are the mass and damper matrix at the local system (fuel rod) and fuel assembly equivalent beam. $\{R_{vi}(t)\}$, and $\{F_G(t)\}$ are the forces, same definition as Eq.(13), but time dependent. The damping behavior for the fuel rods depends on the structural damping, the pellet cladding interaction (burn-up dependent), friction between the fuel rod and the grid spring and the viscosity damping (temperature dependant). The damping behavior of the fuel assembly depends on the damping of all fuel rods plus the interaction of the guide tubes with the grids and the rods inserted (control rods or burnable poison rods).

As in the case of the system stiffness, the fuel rod and the fuel assembly natural frequencies will increase or decrease as a function of the stiffness (or fixing force) of the fuel rod fixing device. As the fixing force of the fuel rod decreases along burn-up (mainly by creep), the natural frequencies of the fuel rod (local system) and of the fuel assembly decrease. Fig.14 shows the modes of vibration of the

fuel assembly and fuel rod in the plane along the axial direction (dry condition, without added mass). Table IV presents the variation of the natural frequencies with the stiffness values of the spacer grid spring device.

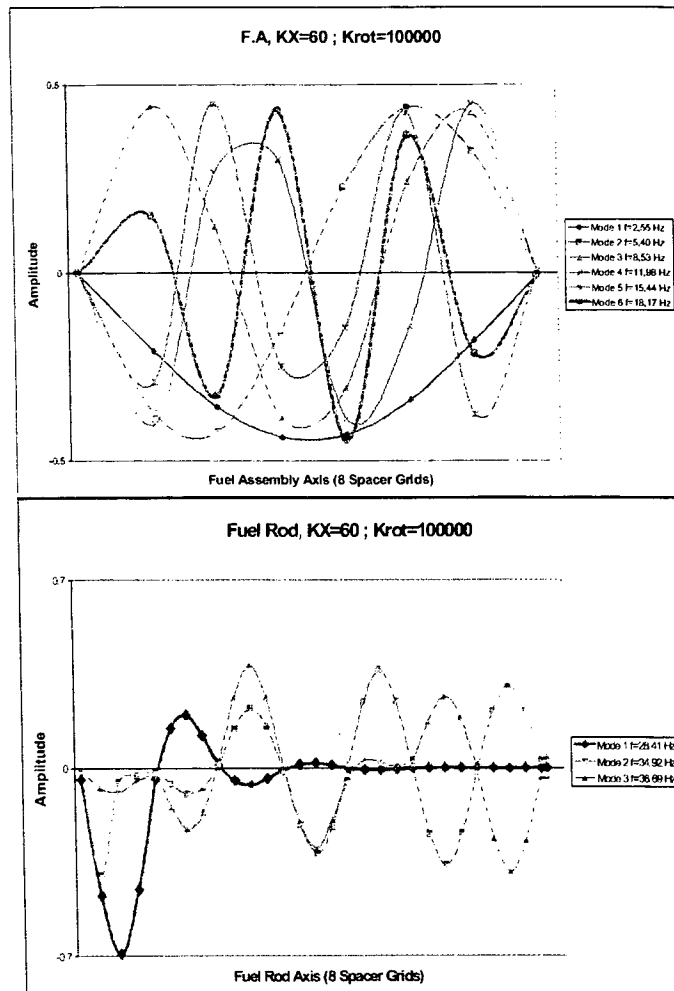


FIG.14. Fuel Assembly and Fuel Rod Natural Frequencies and Modes of Vibration (BOL).

Table IV– Comparative values of frequencies for Angra 1 fuel assembly.

Fixing Device Shear Stiffness (N/mm)	Fixing Device Rotation Stiffness (Nmm/rad)	FA Flexure Equivalent Stiffness (N/mm)	FA First Natural Frequency (Hz)	FR First Natural Frequency (Hz)
60	10^7	$5621/22.12=254.1$	3.72	38.9
60	10^5	$5621/47=119.6$	2.55	28.4
60	0	$5621/112=50.2$	1.66	21.7
30	10^7	$5621/22.2=253.2$	3.71	35.4
30	10^5	$5621/47=119.6$	2.55	27.4
30	0	$5621/112=50.2$	1.66	21.2
5	10^7	$5621/23.6=238.2$	3.57	19.0
5	10^5	$5621/47.8=117.6$	2.52	18.3
5	0	$5621/112=50.2$	1.65	16.4
1	10^7	$5621/29.19=192.6$	3.12	8.9
1	10^5	$5621/50.87=110.5$	2.41	8.8
1	0	$5621/112=50.2$	1.65	8.6

The main cause of Angra 1 fuel failure in cycles 4,6 and 7 was related to rod to grid fretting due to fuel rod and fuel assembly vibration. Cycle 4 (batch D) fuel failures showed a pattern related to fuel rod vibration. Fuel assembly burn-up were higher than 20 MWD/kgU, and were related to the third cycle of the fuel assembly inside the core. Ultrasonic tests performed showed that the majority of failed fuel rods were located in the peripheral rows of the failed fuel assemblies and there were a higher concentration of failed rods at the north and south sides, which gave an indication of preferential direction of flow induced forces acting on the fuel rods (perpendicular to the mixing vane direction). The grid position where fretting and loosed rods were observed in visual inspection can be seen in Fig.15. The axial position of fretting in the fuel rod matches very well with the highest amplitude of the first natural mode of vibration of the fuel rod. The grids 3 and 4 (from bottom to top of the F.A) would be the ones where spring relaxation along burn-up would be the highest. Although for some assemblies (D14 is a good example, see Fig.16) fretting was observed also in the first grid (F.A bottom). These fuel assemblies should have had problems during assembling (procedure or equipment) and the first grid spring forces should be very small. Again, in these cases, there is a good match of the highest amplitude of vibration for the first natural mode of the fuel rod with the fretting position. The root cause of the cycle 4 (batch D) failure is related to the cross-flow generated by the mixing vane pattern that leads to a force acting on the fuel rod much higher than that assumed by design.

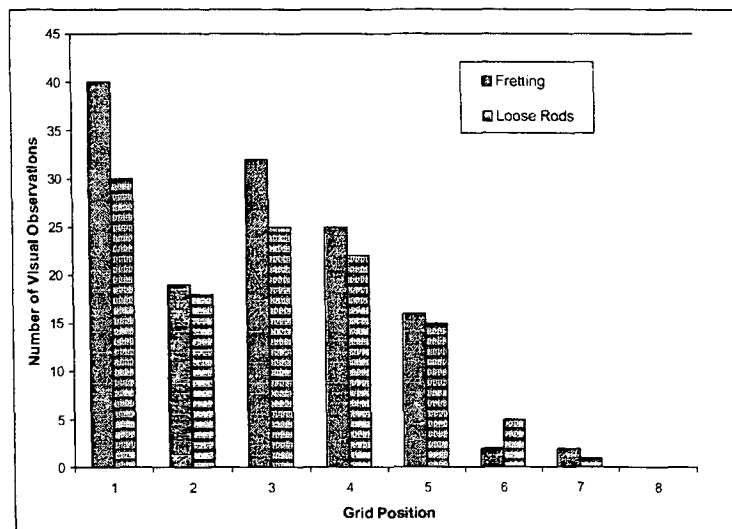


FIG.15. Angra 1 – cycle 4: fretting and loose FRs observed during visual inspection in all failed FAs.

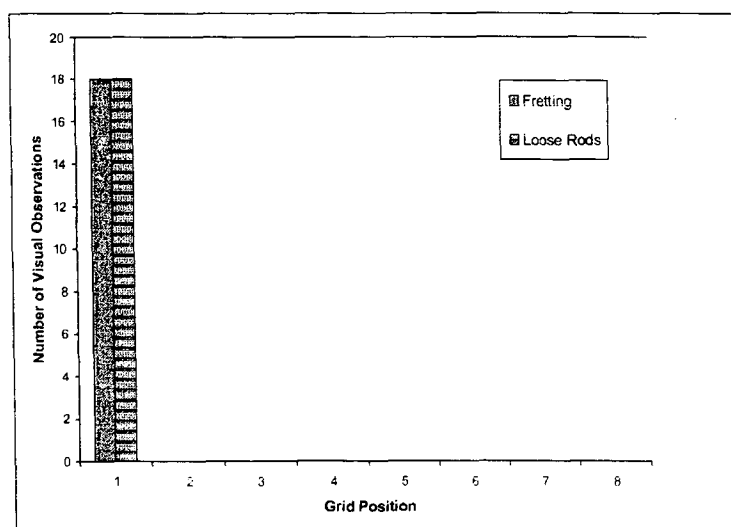


FIG.16. Angra 1 – cycle 4: fretting and loose FRs observed during visual inspection in FA D14.

After cycle 4 failure, the fuel designer issued a report, Ref.[2], evaluating the root-cause of the failures. According to it the failures were caused by grid spring force losses occurred when the fuel rods were inserted in the skeleton, possibly in combination with the loads sustained during transport to the site. The designer developed then a new grid spring design with a new shape and higher initial fuel rod fixing force (batch G fuel assembly). Neither flow experiments in hydraulic loops nor any change in the grid mixing vane were done, this means, the exciting force in fuel rods coming from the water flow through the fuel assembly was not evaluated or changed. Looking to the equations (9) to (16) one can conclude that the designer increased the stiffness of the grid spring $[K_M]$ and the fuel rod sliding force $\{R_o\}$, and consequently increased the fuel assembly equivalent beam stiffness $[K_G]$. However there was no change in the forces acting on fuel rods $\{R_v\}$ and, consequently, in the forces acting on the fuel assembly equivalent beam $\{F_G\}$. Then the problem of excessive fuel rod vibration or fuel rod fretting might not be solved.

Cycle 6 (batch G) showed a pattern related to fuel assembly vibration. Grid wear (east-west side), due to fretting between adjacent fuel assemblies, was located at fuel assembly position where the highest amplitude of higher (7th/8th) modes of fuel assembly vibration would appear. Visual inspection of batch L (same design as batch G) used in cycle 7, but just once burned, showed the same pattern of grid wears as batch G. Fig.17 presents the numbers of observation of wears in the fuel assemblies grids, and shows similarity to the amplitude of vibration of higher modes of the fuel assembly equivalent beam. As discussed in item 6, the designer performed flow experiments in a hydraulic loop with the batch G fuel assembly design. It was verified that the fuel assembly vibrates perpendicular to the spacer grid mixing vane direction in a sharp resonance at the range of 25-27 Hz for beginning of life mechanical condition. This resonance was not observed for end of life mechanical condition. It was concluded that the spacer grid mixing vane pattern design was responsible for the excitation mechanism. Looking to equation (15), one can assume that the fuel rod excitation force $\{R_v(t)\}$ is a consequence of the coolant flow and cross-flow generated by the mixing vane. As has been observed that the first mode is predominant for the fuel rod vibration under flow condition, it can be also assumed that the frequency of this excitation force is in the range of the first natural frequency of the fuel rod. So, looking to equation (16), one can assume that the fuel assembly equivalent beam will also receive an excitation in the range of the first natural frequency of the fuel rods (taking into account the phase angle among them). The resonance observed in the laboratory flow experiment, similar that one observed inside the reactor, is explained by this assumption presented before. 25 Hz represents the first natural frequency of the fuel rod (excitation) for BOL condition, and resonance occurs at the 25 Hz frequency of the higher mode of vibration of the fuel assembly equivalent beam. For EOL condition there is a decrease of the natural frequency (smaller stiffness) and an increase in the damping factor for the fuel rod and also to the fuel assembly equivalent beam, which may decrease in a sharp way the amplitude of vibration for a resonance condition.

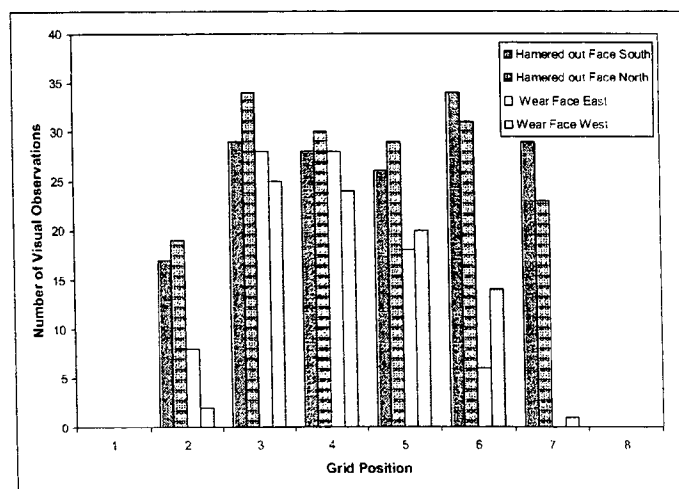


FIG.17. Angra 1, batch L, number of visual observations - wear marks at spacer grids side strips.

Laboratory flow tests with batch G fuel assembly design showed that the use of dampers would lower the amplitude of vibration observed at the resonance. The use of dampers (zircaloy rods inside guide tubes) was decided to be used to the batch L, low burn-up fuel assembly. Looking to equation (16) one can verify that the damping factor [C] will increase due to change in the damping factor of the guide tubes. This damper device does not change the damping factor of the fuel rods. Assuming the previous experience of cycle 4, 6, and 7, rod fretting may occur after 19 MWD/kgU. This is assumed because the forces due to the mixing vane are still acting on the fuel rod and are higher than that predicted by design, Ref.[18]. Twelve fuel assemblies of batch L are being used (with dampers) in cycle 10 with a maximum planned discharge burn-up of 25 MWD/kgU.

INB received from the designer an alternative fuel assembly design that uses split mixing vanes at the spacer grids. Four fuel assemblies (batch Q) were manufactured by INB with this new design and used (in an experimental basis) since cycle 9. This design with split mixing vane would certainly mitigate the fuel assembly vibration and the fuel rod fretting due to the smaller forces acting on the fuel rods compared to that of directional mixing vane. Visual inspections will be carried out on this fuel, after each reactor cycle, in order to verify its performance.

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REFERENCES

- [1] Chapot, J.L.C. and Freire, J.S., Tracing Fuel Failures at Angra 1, Nuclear Engineering International, p32-34, September 1994.
- [2] Report KWU BT52/BT51/94/E079: 21 February 1994.
- [3] Cheng, B., (EPRI/USA), Angra 1 Cycle 6 Fuel Performance Evaluation Report, October 31, 1997.
- [4] Remote Visual Inspection of Fuel Assemblies, TECNATOM, November 1997.
- [5] Fuel Failures: ANGRA 1 / 6th cycle, SIEMENS, NBTM/11.97/St
- [6] Perrotta, J.A., Silva, J.E.R., Relatório de Acompanhamento dos Testes de Elementos Combustíveis no Descarregamento do Ciclo 6 de Angra 1, Convênio IPEN/CNEN-SP-ELETRONUCLEAR, 30 Setembro, 1997 (in Portuguese)
- [7] Perrotta, J.A., Terremoto, L.A.A., Relatório de Análise dos Testes de Sipping dos Elementos Combustíveis no Descarregamento do Ciclo 6 de Angra 1, Convênio IPEN/CNEN-SP-ELETRONUCLEAR, 15 Outubro, 1997 (in Portuguese)
- [8] Perrotta, J.A., Terremoto, L.A.A., Relatório de Análise dos Espectros gama de Amostras Líquidas do SRR para Identificação de Np-239 no Ciclo 6 de Angra 1, Convênio IPEN/CNEN-SP-ELETRONUCLEAR, 19 Outubro, 1997 (in Portuguese)
- [9] Chapot, J.L.C., Freire, J.S., Sousa, U.C.S., Fuel Failures in the Sixth Cycle of Angra 1 (1998 OECD/NEA/IAEA Joint Meeting to Exchange Information on Recent Nuclear Power Plants Events and Annual Meeting of IRS National Coordinators, Paris, May/1998).
- [10] Perrotta, J.A. Relatório de Análise do Ensaio de Compressão de Grade Espaçadora do E.C de Angra 1 para Verificação de Resistência e Função de Segurança com Existência de Trinca na Tira Externa, Convênio IPEN/CNEN-SP-ELETRONUCLEAR, 22 Novembro, 1997 (in Portuguese)
- [11] Koebke, K., Stabel, J. Flow Experiments with Siemens Fuel Assemblies for Angra 1- Part 1: Description of the flow experimental device – KWU Report A1C-1305570-0, 17.12.98.
- [12] Koebke, K., Stabel, J., Neumann, H. Flow Experiments with Siemens Fuel Assemblies for Angra 1- Part 2: Description of the flow experiments – KWU Report A1C-1305570-1, 29.1.99.
- [13] Koebke, K., Stabel, J. Flow Experiments with Siemens Fuel Assemblies for Angra 1- Part 3: Conclusion – KWU Report A1C-1305570-2, 1.2.99.

- [14] Koebke, K., Stabel, J., Stephens, L.G. Simulation of PWR Fuel Vibration Response due to Different In-reactor Flow Conditions (ANS-International Topical Meeting on Light Water Reactor Fuel Performance) Park City, Utah, USA, April 10-13, 2000.
- [15] Perrotta, J.A., Silva, J.E.R., Terremoto, L.A.A. Inspeção Visual dos Elementos Combustíveis da Série L Estocados na PCU de Angra 1, Convênio IPEN/CNEN-SP-ELETRONUCLEAR , 24 Março, 2000 (in Portuguese)
- [16] Padoussis, M.P. A Review of Flow-Induced Vibration in Reactors and Reactors Components, Nuclear Engineering Design 74(1982) 31-60.
- [17] Perrotta, J.A., Macedo, L.V.S. Structural Analysis of PWR Fuel Assemblies, 13th SMIRT, Porto Alegre, Brazil, August 13-18, 1995.
- [18] Perrotta, J.A. Utilização de Elementos Combustíveis Irrradiados de Fabricação INB em Recargas de Angra 1, Convênio IPEN/CNEN-SP-ELETRONUCLEAR , 16 Novembro, 1999 (in Portuguese)



CENTRO DE ENGENHARIA NUCLEAR

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Angra 1 Fuel Failures: Cause and Mitigation

Trabalho apresentado no IAEA Technical Meeting on Fuel Failures in Water Reactor : Causes and Mitigation. Realizado de 17 a 21 de Junho de 2002 em Bratislava, República Eslovaca.

Alcides

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