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FUEL PERFORMANCE DURING AN LBLOCA IN ANGRA 1 NUCLEAR POWER PLANT

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ABSTRACT

This paper presents a comparison between the models and correlation sets used by Eletronuclear and IPEN/CNEN/SP in the thermal-mechanical analysis of the fuel of Angra 1 Nuclear Power Plant - NPP, during LBLOCA. RELAP4/MOD5 and FRAP-T6 coupled codes are used in this analysis. This methodology showed to be very much reliable compared to the one used by the regulatory body. These codes were used for the licensing process of Angra 1 NPP and now for Angra 2 the best estimate codes are used. Although this methodology could be applied to Angra 2, in this case adapting the model and using RELAP5 and the new version of FRAP-T, the license of FRAP-T is still under negotiation.

Key Words: RELAP, FRAP-T, Simulation, Angra 1, Reactor Safety, Accident Analysis, LBLOCA

1. INTRODUCTION

The objective of this work is to perform an integrated analysis for a Loss of Coolant Accident for a Large Break (LBOCA), focusing the effects in the fuel rod of Angra 1 Nuclear Power Plant. The fuel rod cooling and power data during the accident are generated by the thermal-hydraulic analysis code, RELAP4 [1], and then they are transferred to the fuel performance analysis code, FRAP-T6, [2] through a homemade code [3,4] interconnecting RELAP4 and FRAP-T6.

The results obtained with the code FRAP-T6 are compared with the ones supplied by the code TOODEE-2 [5] and, by FSAR (Final Safety Analysis Report) of Angra 1 [6].

2. CHARACTERISTICS OF THE CODES

This section presents the characteristics of the codes used in this paper:

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RELAP4: Computational codes as RELAP4 [1] are quite versatile and simulate the thermal-hydraulic behavior of light water reactors in the analysis of transients and accidents. They consider the thermal-hydraulic system to be analyzed as a series of control volumes connected by junctions and the heat transfer through the heat structures located among the volumes.

These codes solve the mass, momentum and energy equations for each one of the control volumes, assuming homogeneous fluid, one-dimensional flow and thermal equilibrium [1] for the liquid and vapor phases.

FRAP-T: Fuel performance FRAP-T [2] code series analyze the behavior of a fuel rod in hypothetical conditions of transients and LBLOCA, and reactivity accidents. They are restricted to the analysis of Uranium dioxide and Plutonium/zircalloy fuel.

RELAP4 and FRAP-T Coupling Code: In order to using FRAP-T6 [2] code, it is necessary rod data in cold zero power conditions, which are supplied by codes of the FRAPCON [7] series which generate the conditions for the fuel rod steady state. Finally data concerning the thermal-hydraulic channel during the transient are supplied by the RELAP4 [1] code.

Considering the input data size, which describes the thermal-hydraulic behavior for FRAP-T6, generated by RELAP4, a coupling program was developed in order to optimize this inputting process. Is presents a great advantage since the data is not typed by the user any longer, but read from a file.

Depending on the selected option, two different thermal-hydraulic data groups can be supplied to FRAP-T6:

- option 1 - Pressure, enthalpy, temperature and flow in the upper and lower plenum and in each axial zone previously defined in the fuel rod; and
- option 2 – Heat transfer coefficient, pressure and cooling fluid temperature in each axial zone previously defined in the fuel rod.

TOODEE-2: It is a program for the thermal analysis of the fuel element, dependent of time, developed from the code TOODEE-1 by Regulatory Nuclear Committee - RNC. TOODEE-2 calculates the temperature distribution in the fuel rod, determines the maximum temperature reached by the cladding and also determines the heat transfer coefficient and heat flux for the channel.

This program is a tool for evaluation of the thermal response of the fuel element and reflood of the reactor core during an LBLOCA.

3. METHODOLOGY

The methodology consists in the simulation of the primary side of the plant, Figure 1, including pressure vessel and its associated internals.

It is included in nodalization: the reactor primary cooling system (cold and hot legs, steam generator and pumps) and the secondary cooling system is modeled through boundary conditions. The objective of the RELAP4 model is to supply the boundary conditions to the hot channel and fuel rod performance analyses, to be accomplished with FRAP-T6.

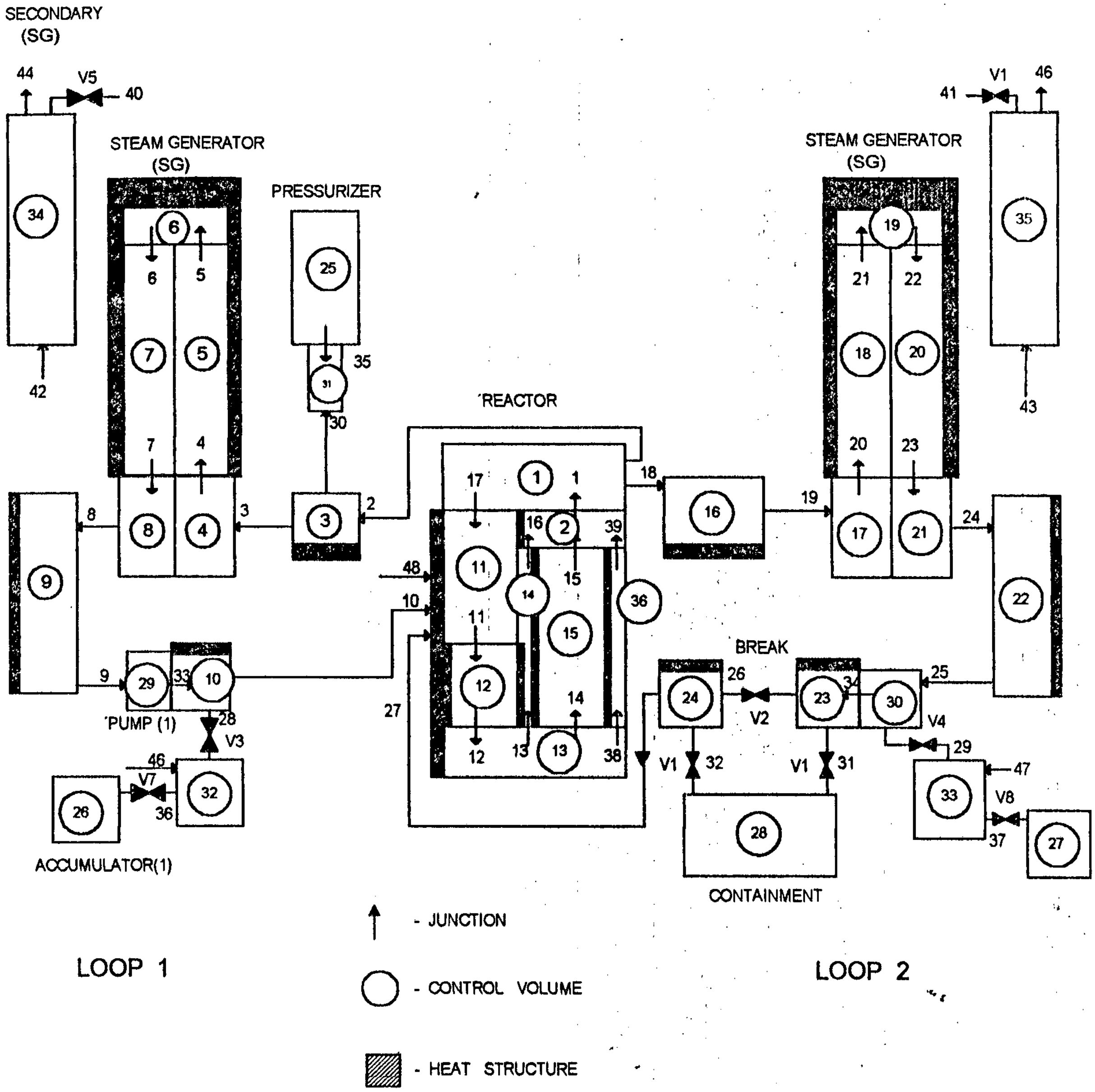

Figure 1- Nodalization of Angra 1 for RELAP4/MOD5.

The hot channel model, Figure 2, simulated by RELAP4, is constituted of 14 control volumes and boundary conditions generated during the simulation of the plant.

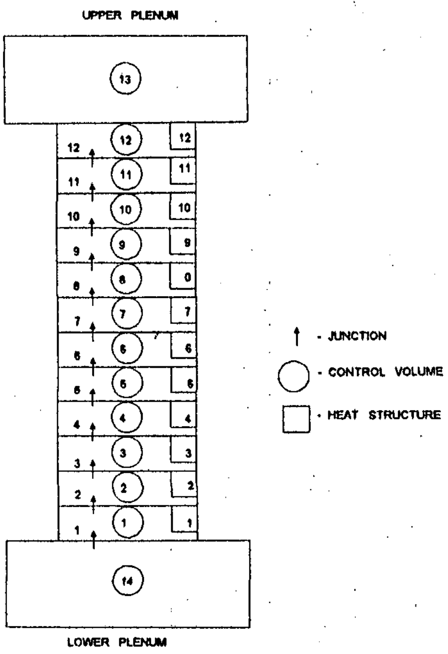

Figure 2- Nodalization of the Hot Channel

Figure 3 shows the model for the simulation of the accident during the reflood phase, with RELAP4, and Figures 4 and 5 show the models for the fuel performance analysis during the LBLOCA with TOODEE-2 and FRAP-T6 codes, respectively.

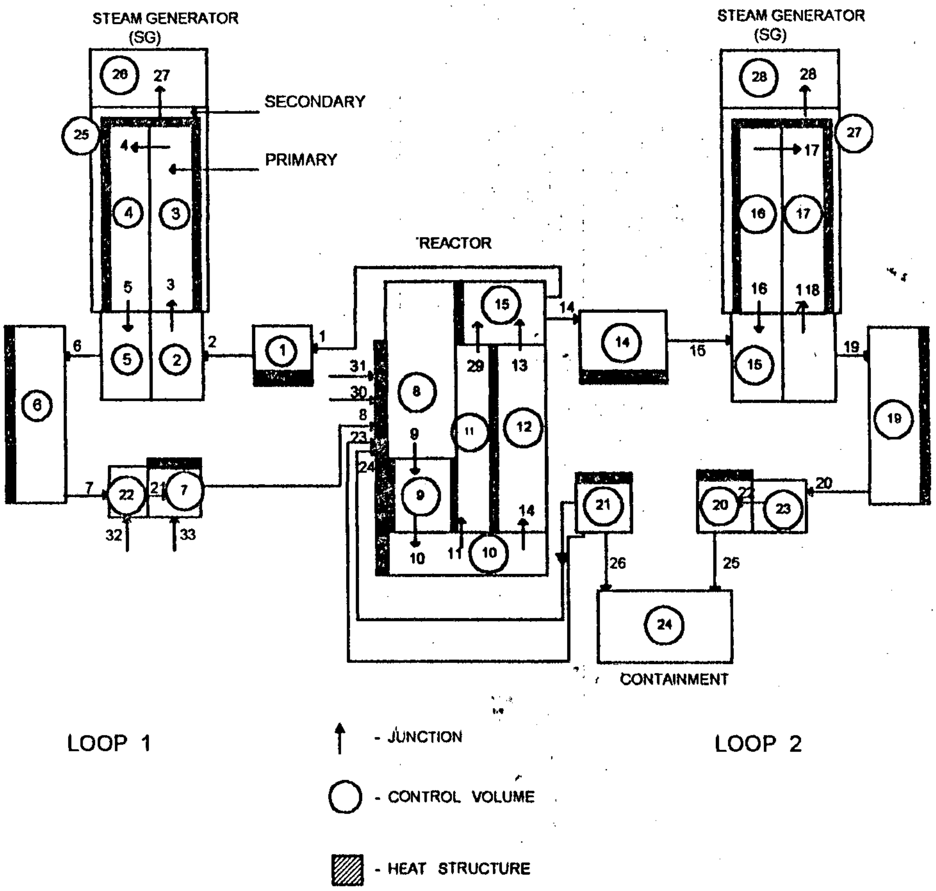

Figure 3- Nodalization of Angra 1 for FLOOD

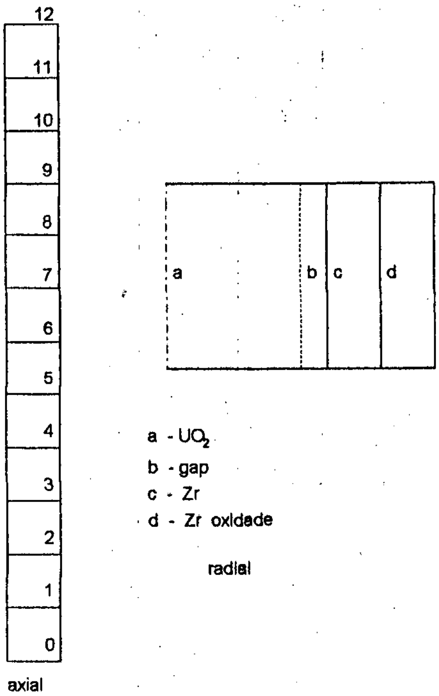

Figure 4- Axial and Radial division of Hot Rod using TOODEE-02

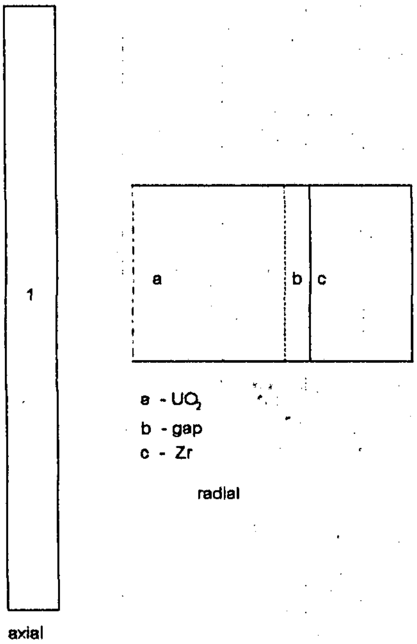

Figure 5- Axial and Radial division of Hot Rod using FRAP-T6

The following stages were adopted in this analysis:

1) Analysis of the thermal-hydraulic behavior of Angra 1 NPP for the blowdown and refill phases (LBLOCA), with RELAP4 (EM option - Evaluation Model), Figure 1. This study supplies boundary conditions (power, pressure, temperature, quality and mass flow) to the hot channel analysis;

2) The analysis of the hot channel behavior gives the boundary conditions to two phases of the accident for FRAP-T6;
3) from data generated in the 1rst stage, the reflood phase is simulated with RELAP4 (option FLOOD), giving the boundary conditions to TOODEE-2 and FRAP-T6; and
4) the fuel performance is done with RELAP4 (blowdown and refill phases) and TOODEE-2 (reflood phase), and with FRAP-T6 for the three phases of the LBLOCA.

Results obtained with RELAP4, TOODEE-2 and FRAP-T6 are compared with FSAR (Final Safety Analysis Report) of Angra 1.

4. LBLOCA SIMULATION HYPOTHESES

a) Blowdown and refill phases:
- Initial reactor power - 102% of the nominal power;
- LBLOCA starts at t = 0 s;
- Reactor shutdown at t = 0 s;
- Pumps shutdown at t = 0 s;
- Shutdown of the steam generators feeding water at t = 3.6 s; and
- Actuation of the accumulators through the injection emergency system for P = 48.5 bar.

b) Reflood phase:
- Simulation of the reflood phase with RELAP4 (option FLOOD) is done with the boundary conditions generated in blowdown and refill phases; and
- The reflood phase started after 25 s of the accident.

5. FUEL RODS RESULTS ANALYSIS

It is presented in this section a comparison and analysis of the fuel rod performance parameters for an LBLOCA accident.

The fuel rod presents a dependent thermal and mechanical behavior. However, the rod temperature response is a measure that characterizes the rod performance. So that, the cladding and central pellet temperature graphs are analyzed in first place. The rod internal pressure response depends on the parameters, such as void volumes inside the rod and the gap/pellet average temperature, with predominance of the last. The circumferential tension is consequence of the internal and external pressure balance and it is important that the tension doesn't rise as to provoke high plastic deformation, with possible channel obstruction, or even rod failure due to rupture of the cladding. The gap size alters the use of models for open or closed gap and its definition is consequence of all the previous parameters. Each performance parameter is analyzed independently.

External temperature of the Cladding. Figure 6 presents the behavior of the cladding temperature obtained through three different sources: from the results of TOODEE-2 and FRAP-T6 codes, and the graph obtained from FSAR. TOODEE doesn't simulate the blowdown phase, as mentioned before, and therefore in this phase RELAP4 temperature response comes in its place.

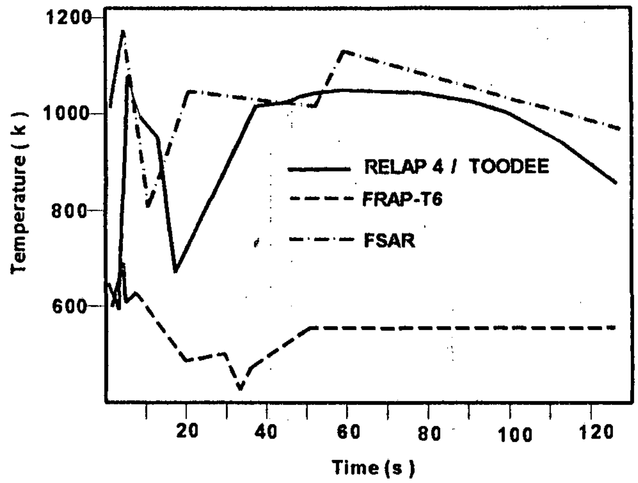

Figure 6- External Temperature of the Cladding

It is observed a clear proximity between the curves of TOODEE and FSAR, and below them with the same type of behavior, FRAP-T6 correspondent curve. It was expected that the curve of FSAR was above the other two, because the curves of FSAR represent a conservative parameters estimate, so that, codes which possess a more complete modeling, and therefore nearer to the real performance, tend to simulate values below the FSAR values.

FRAP-T6 is a best estimate code type and therefore its temperature response should be smaller than the one of TOODEE. Besides, FRAP-T6 used, in the rod simulation, just an axial part for the whole active length of the rod, and therefore its temperature response represents an average of the rod. The temperature response of TOODEE, although it is the temperature in the central region of the rod, contains the distribution axial factors of power so its values are larger than the average of the rod.

The comparison of the temperature evolution with time in the three graphs demonstrates a tendency of similar behavior. It is good to emphasize that the cladding temperature is a quite significant data, because external and internal conditions influence directly in its determination. External conditions: cooling condition during the accident and Internal conditions: power evolution and the energy stored in the rod before the accident. Thus, the characteristic of cladding temperature evolution is a typical result of an LBLOCA. Therefore in the beginning of the transient there is a small temperature drop, observed in the response curves of the simulation codes. This drop is due to the fast decrease of the cooling temperature due to pressure drop. On the other hand, there is a degradation relatively slower in the cooling conditions in terms of the rod heat removal capacity, because the mass flow is subjected to a fast oscillation and the cooling fluid is still in contact with the cladding. After this first impact, the heat transfer from the rod to the cooling fluid decreases and although the power of the rod decreases quickly in the beginning of the accident, there is a great amount of energy stored in the rod which tends to an equilibrium between the pellet and cladding. This equilibrium provokes an increase of the cladding temperature and a decrease of the pellet temperature. This phenomenon is typical of LBLOCA, and it is responsible for the temperature peaks observed in the blowdown phase of the three cladding temperature graphs, as shown in Figure 6. After this transfer of stored energy there is a temperature drop, because there isn't enough power in the rod to sustain this temperature. However, while time goes on, with the actuation of the decay power, although low, it provokes increase of the temperature and with the permanence of the condition of degraded refrigeration, the temperature increases again. This tendency of gradual temperature increase is only controlled with the actuation of the cooling systems, which inject water in the core during its reflooding with stabilization or cladding temperature drop, as it is observed in the final parts of the Figure 6 graphs.

Central pellet temperature. The pellet temperature was determined by TOODEE-2 and FRAP-T6, and for the blowdown phase to the TOODEE-2, RELAP4 is used. The graphs are presented in Figure 7.

Once again FRAP-T6 curve comes below TOODEE curve and this is due to the same causes presented before concerning cladding temperature item. For both codes the largest temperature value is the initial, so that LBLOCA tends to cooling the fuel.

Temperature evolution is the same in both codes, just in the beginning of the transient there is temperature drop, due to fast power drop, which is the main factor that sustains the pellet temperature. This would be the first temperature drop, which takes about 3 seconds of accident. Then, the equilibrium between the pellet and the cladding temperature tends to decrease the pellet temperature, with larger influence on the pellet from the center to the periphery. This would be the second temperature drop, longer and at the same time more gradual. After the drop, the temperature tends to re-establish due to the decay power. With the cooling condition re-establishment in the reflood phase, the cladding removes heat from the pellet, so the pellet temperature tends to stabilize, due to the equilibrium between production and energy removal in the pellet.

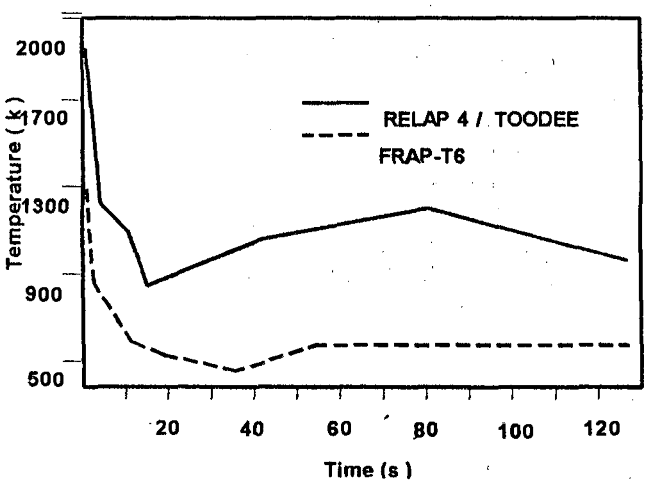

Figure 7- Central Temperature of the Pelent

Internal rod pressure. The internal pressure is totally determined by the temperature distribution, by the void volumes inside the rod and also by the amount of gas inside it. The amount of gas practically doesn't vary during the effective time of an accident. From the other two effects, the sensitivity concerning the temperature is more influential, and it is expected a pressure behavior similar to the temperature's, which really takes place.

The internal pressure was simulated by FRAP-T6, according to Figure 8.

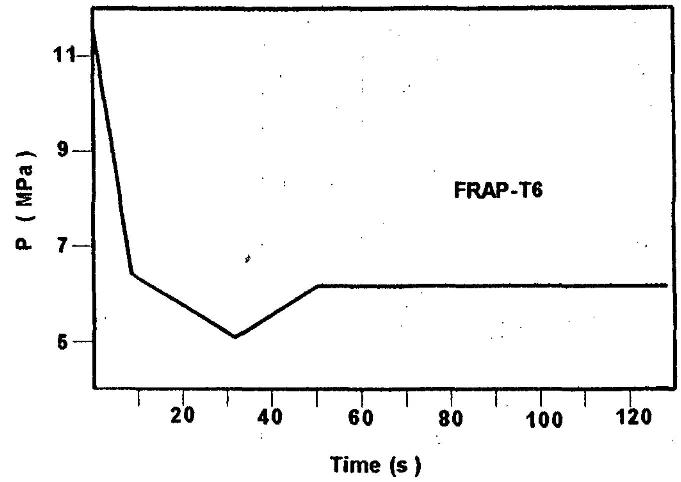

Figure 8 - Internal Pressure in the Rod

There is an initial pressure drop, not so accentuated as the one of the central pellet temperature. what is influencing in the rod pressure is the radial temperature distribution, from the gap until the center of the pellet, where the average temperature drop is less accentuated than the central temperature drop. Then, the drop continues, with a smaller gradient, similar to the graph of FRAP-T6 central temperature, and later it increases and finally it stabilizes in an intermediary value.

Circumferential tension. The superficial tension in the cladding was simulated by FRAP-T6, Figure 9. This tension depends basically on the difference between external and internal pressure of the cladding. In the beginning of its evolution, the tension passes quickly from a compression condition, with negative value, to a traction condition, with positive value. This is due to the initial external pressure drop of the cooling in the blowdown phase. After this inversion, tension still increases, although more gradually, since the external pressure drop is still in course.

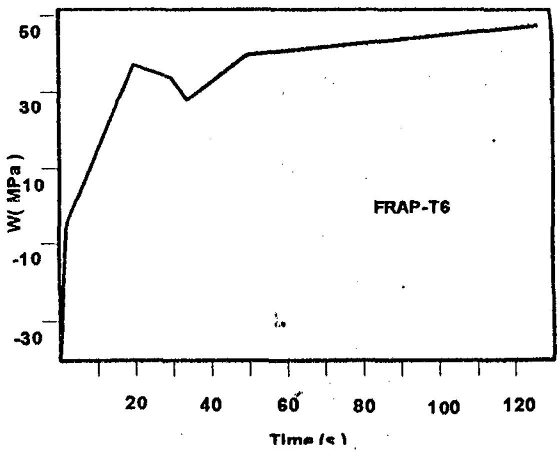

Figure 9- Circumferencial Tension in the Cladding

However, there is an instant in which tension change its behavior due to the internal pressure drop and decreases its value in traction. It happens during some seconds, then the internal pressure recovers and as the external pressure in this instant is practically stabilized the tension increases again. At a certain point the internal pressure stabilizes and then tension practically reaches a constant value.

Structural and thermal gap size. The gap size is a measure in hundredth of millimeter, which gives the distance between the internal surface of the cladding and the external surface of the pellet. The difference between structural and thermal gap is that in the calculation of the thermal gap the effect of the fuel pellet repositioning is taken in consideration. This repositioning consists of circumferential cracks which are formed in the material and produce an extra radial deformation of the pellet. For that reason the thermal gap is always smaller than the structural. As to the effect of the mechanical contact between the pellet and cladding, these cracks should not be considered and therefore what determines the gap closing in this case, is the structural gap. As to the effect of temperature calculation, the real position of the pellet surface is important, with repositioning, and therefore the thermal gap should be used. The same is valid for internal pressure calculation. The gap size is shown in Figure 10.

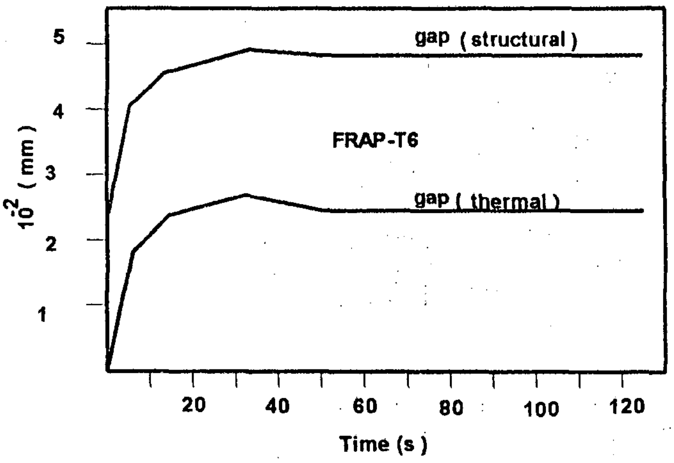

Figure 10 - Structural and Thermal gap size

Several factors influence directly in the gap size: the thermal and mechanical deformation of the cladding, the permanent and thermal deformation of the pellet that depends on the gap temperature, which depends on its size. Therefore, the calculation of the gap size is iterative and has several influences. However, considering the graph behavior it can be inferred that the preponderant effect is the decrease of the pellet thermal deformation, due to its temperature decrease, with consequent increase of the gap size. The increase of the gap size corresponds basically to the decrease of the pellet central temperature as observed in the comparison of Figures 7 and 10. After 50 s the gap size stabilizes together with the other parameters of the rod behavior.

6. CONCLUSIONS

The methodology exposed in this paper, considering the analysis of an LBLOCA accident, is satisfactory. Data were generated and passed correctly between the programs and the results are coherent within the expected behavior to this kind of accident. As to the rod performance, it is noticed the great importance of the temperature response on the other performance parameters. The cladding external temperature presented two maximum regions: one in the blowdown phase due to the energy stored in the rod and another during the reflooding phase by the decay power. The values of the performance parameters are always inside of acceptable limits for the safety of the core.

The methodology using RELAP4 and FRAP-T codes, for the analysis of the fuel performance, has shown very much reliable when compared with the methodology proposed by CNEN. Besides, the use of best estimate codes as FRAP-T, for the fuel performance analysis, is in accordance with the new RNC guidelines, i. e., and accident analysis of nuclear power plants in the most possible realistic methodology.

Although this methodology could be applied to Angra 2, in this case adapting the model and using RELAP5 and the new version of FRAP-T, the license of FRAP-T is still under negotiation.

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