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FLOW REGIMES AND HEAT TRANSFER MODES IDENTIFICATION IN ANGRA 2 CORE, DURING SMALL BREAK IN THE PRIMARY LOOP WITH AREA OF 100 cm^2, SIMULATED WITH RELAP5 CODE

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ABSTRACT

Identifying the flow regimes and the heat transfer modes is important for the analysis of accidents such as the Loss-of-Coolant Accident (LOCA). The aim of this paper is to identify the flow regimes, the heat transfer modes, and the correlations used in the RELAP5/MOD3.2.gama code in ANGRA 2 during the Small-Break Loss-of-Coolant Accident (SBLOCA) with a 100cm^2-rupture area in the cold leg of primary loop. The Chapter 15 of the Final Safety Analysis Report of ANGRA 2 (FSAR - A2) reports this specific kind of accident. The results from this work demonstrated the several flow regimes and heat transfer modes that can be present in the core of ANGRA 2 during the postulated accident.

1. INTRODUCTION

Identifying the flow regimes and the heat transfer modes is important for the analysis of accidents such as the Loss-of-Coolant Accident (LOCA). The LOCA has been studied since the Three Mile Island and Chernobyl accidents, because this kind of accident is considered a design basic accident in the nuclear power plants.

The aim of this paper is to identify the flow regimes, the heat transfer modes, and the correlations used in the RELAP5/MOD3.2.gama [1] code in ANGRA 2 during the Small-Break Loss-of-Coolant Accident (SBLOCA) with a 100cm^2-rupture area in the cold leg of primary loop – described in detail in the Chapter 15 of the Final Safety Analysis Report of ANGRA 2 (FSAR-A2) [2].

The accident consists of the partial break of the cold leg of the Angra 2 nuclear power plant. The rupture is the 100 cm^2 and the efficiency of the Emergency Core Coolant System (ECCS) is also verified for this accident.

2. THE NODALIZATION OF ANGRA 2 USING THE RELAP5 CODE

The RELAP5 was developed by the Idaho National Laboratory. This code was originally designed for the analysis of thermal hydraulic transients in Pressurized Water Reactors (PWR). The RELAP5 can model the primary and secondary cooling systems of experimental facilities and of Nuclear Reactors with geometric details. The program uses the non-homogeneous non-equilibrium two-fluid model, and considers the conservation equations of mass, momentum and energy for the liquid and gas phases. One-dimensional model is used to treat the fluid flow and the heat conduction in the structures; however, in some special cases such as the cross flow in the reactor core and the rewetting region in flooding model, the two-dimensional model is used [1].

For each postulated LOCA, the ECCS performance is different. The Chapter 15 of the Final Safety Analysis Report of Angra 2 (FSAR-A2) reports the ECCS actuation [2] for each accident.

The SBLOCA is characterized by a slow blowdown in the primary loop; until reaching the set point of the actuation of the high-pressure injection system, when the water is introduced in the circuit again. The thermal-hydraulic processes inherent the accident phenomena, such as primary loop vaporization and consequently an inappropriate fluid distribution in the reactor core. It can lead to a reduction in the core liquid level and the ECCS is capable to refill it.

In this case failure and repair criteria for the ECCS components were adopted as specified to this event in the FSAR-A2 in order to verify the system operation, preserving the integrity of the reactor core and to guarantee its cooling, as presented in Table 1.

Table 1: Injection by the ECCS for SBLOCA

ECCS Components	**Injection**							
	Loop 10		**Loop 20**		**Loop 30**		**Loop 40**	
	hot	cold	hot	cold	hot	cold	hot	cold
Safety Injection Pumps	1	_	1	_	SF	_	RC	_
Accumulators	1	1	1	1	1	1	1	1
Residual Heat Removal Pumps	1		1		SF		RC	

SF: Single failure of diesel engine, RC: Diesel engine down for repairs

Figure 1 shows the nodalization of the Angra 2 core. Although, the cooling primary loop was modeled in the simulation using RELAP5, it is not presented in the figure. The boundary conditions used were taken from FSAR-A2. The accident started after 100 seconds of the steady state simulation time.

The input file was based in the work performed by the Technical Cooperation among *Instituto de Pesquisas Energética e Nucleares* (IPEN), *Centro de Desenvolvimento Tecnológico Nuclear* (CDTN), and *Comissão Nacional de Energia Nuclear* (CNEN) [3]. Furthermore, the research published in the VIII Congress of Mechanical Engineer held in *Uberlândia* was used as reference to the work [4].

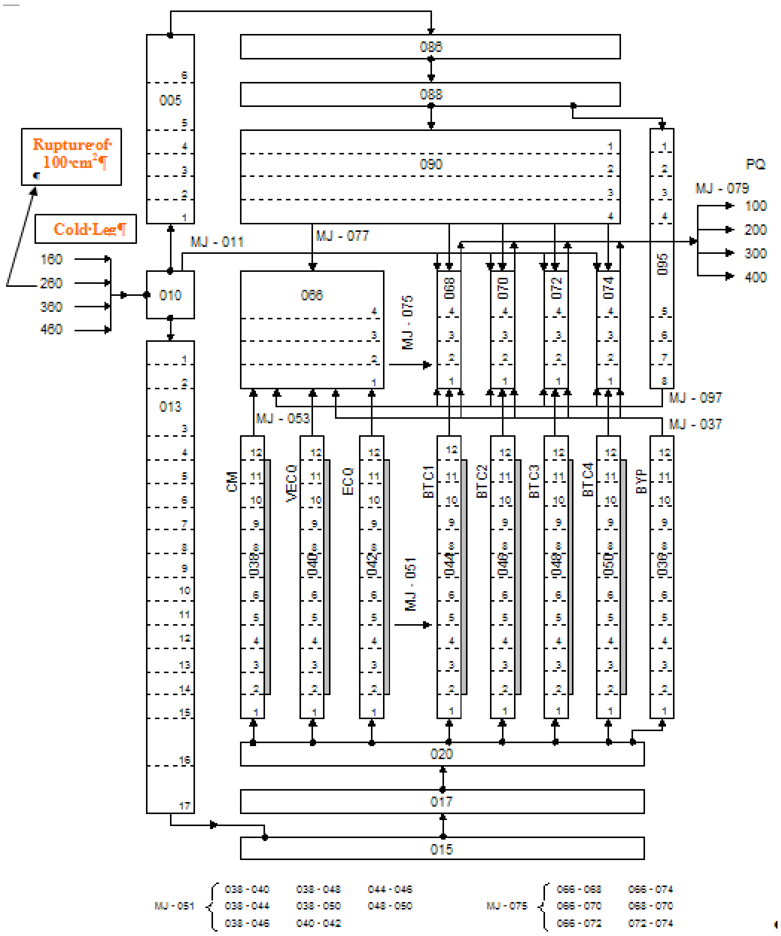

Figure 1: Angra 2 nuclear reactor core nodalization to RELAP5 code.

The RELAP5 code is capable to identify fifteen different flow regimes, which are presented in Table 2. Each one associated to an integer number. Those numbers are obtained from RELAP5 code output file to specify the fluid behavior for each control volume during the accident simulation

Table 2: Flow regime number (RELAP5)

Flow regime	Number
High mixing bubbly	1
High mixing bubbly/mist transition	2
High mixing mist	3
Bubbly	4
Slug	5
Annular mist	6
Mist pre-CHF	7
Inverted annular	8
Inverted slug	9
Mist	10
Mist post-CHF	11
Horizontal stratified	12
Vertical stratified	13
Level tracking	14
Jet junction	15

Table 3 shows the numbers that correspond to the heat transfer mode and the correlations used in the RELAP5 code. They were accessed during the execution of the program to this case, and the results are presented in item (3) of this work.

Table 3: Heat transfer mode numbers and correlations used by RELAP5

Number	Heat Transfer Mode	Correlation
0	Convection to noncondensable-water mixture	Kays, 1955; Dittus-Boelter, 1930; ESDU*; Shah, 1992; Churchill-Chu, 1975; McAdams, 1954
1	Single-phase liquid convection at supercritical pressure	Same as mode 0
2	Single-phase liquid convection, subcooled wall, low void fractions	Same as mode 0
3	Subcooled nucleate boiling	Chen, 1966 **For horizontal bundle**: Polley-Ralston-Grant, 1981; ESDU*; Forster-Zuber, 1955
4	Saturated nucleate boiling	Same as mode 3
5	Subcooled transition boiling	Chen-Sundaram-Ozkaynak, 1977
6	Saturated transition boiling	Same as mode 5
7	Saturated film boiling	Bromley, 1950; Sun-Gonzales-Tien, 1976; and mode 0 Correlations
8	Saturated film boiling	Same as mode 7
9	Single-phase vapor convection or supercritical pressure with the void fraction greater than zero	Same as mode 0
10	Condensation when the void is less than one	Nusselt, 1916; Shah, 1979; Colburn-Hougen, 1934
11	Condensation when the void equals one	Same as mode 10

* ESDU (Engineering Science Data Unit, 73031, Nov 1973; ESDU International Plc, 27, Corsham Street, London, N1 6UA)

3. RESULTS

The main boundary conditions used in this simulation were obtained from the FSAR-A2 [2] and are presented as the following:

- reactor power - 106% nominal power;
- reactor trip from Reactor Coolant System (RCS) pressure < 132 bar;
- 100 k/h secondary-side cooldown (P_{RCS} < 132 bar and containment pressure > 1.03 bar);
- ECC criteria met (P_{RCS} < 110 bar and containment pressure > 1.03 bar).

The accident started after 100 seconds of the steady state simulation time, when the valve 951 was opened. Valve 951 is connected to the branch 255 (primary cold leg), which is connected to the volume 960 (containment). The area of the valve opening is 100 cm^2. This is the size of the rupture considered in this case. Figures 2 to 10 show the results obtained from SBLOCA of Angra 2 analysis using RELAP5 code. Some of these results were compared with the results found in the FSAR-A2 [2].

Figure 2 shows the pressures in the primary and secondary loops to RELAP5 and FSAR-A2. The behavior of the results in both cases was very similar.

Figure 3 shows the mass flow in the rupture.

Figures 4 and 5 show a good agreement of the mass flow results obtained from RELAP5 and FSAR-A2 in the lines of ECCS.

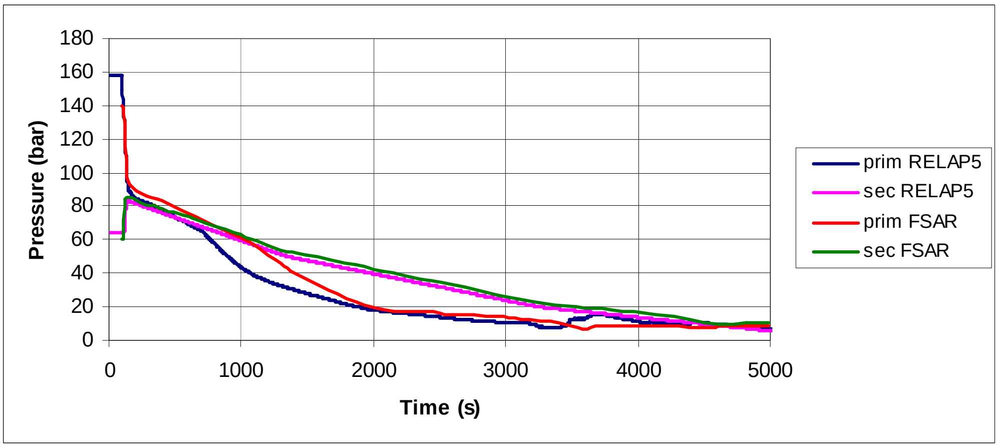

Figure 2: Pressure in the primary and secondary loops of Angra 2 (RELAP5 and FSAR-A2).

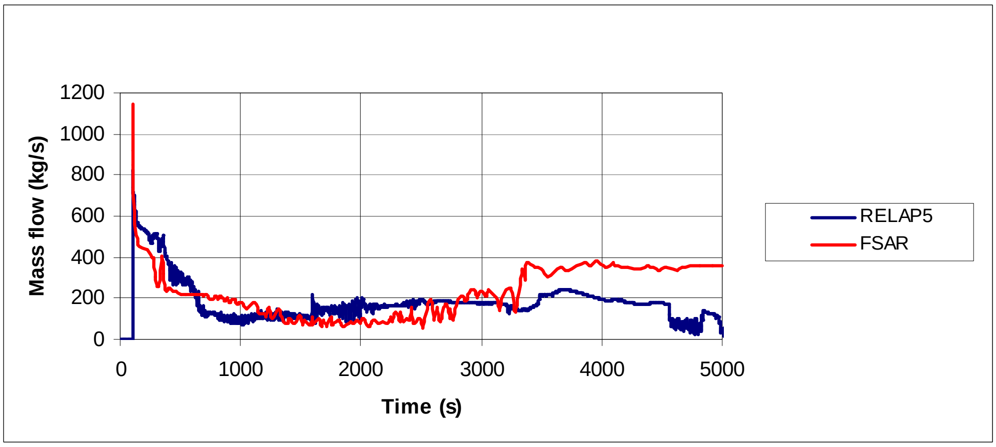

Figure 3: Mass flow in the break (RELAP5 and FSAR-A2).

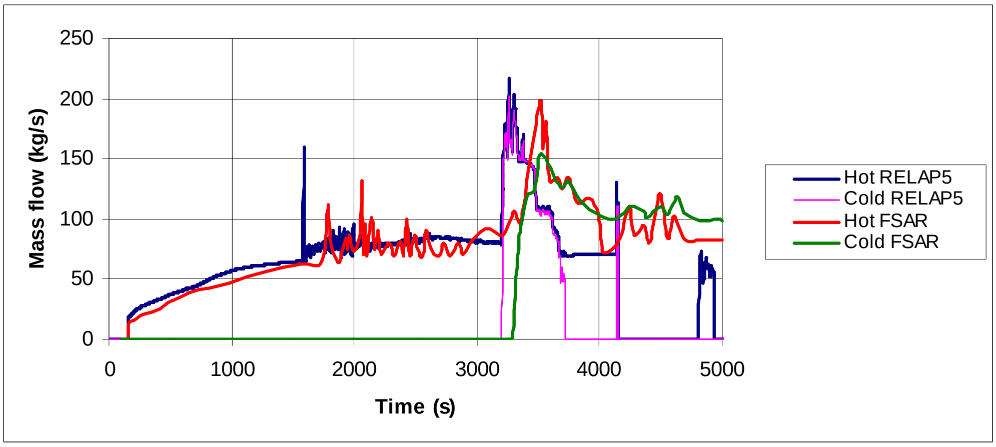

Figure 4: Mass flow in the lines of ECCS – Loop 10 (RELAP5 and FSAR-A2).

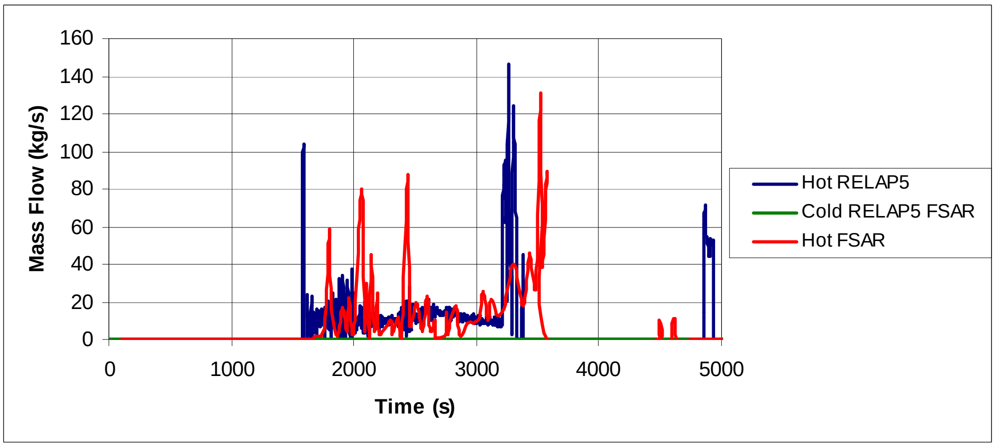

Figure 5: Mass flow in the lines of ECCS – Loop 30 (RELAP5 and FSAR-A2).

Figure 6 shows the cladding temperature of the hot rod in the lower part of the core of Angra 2. It showed to be in reasonable agreement with the FSAR-A2 [2].

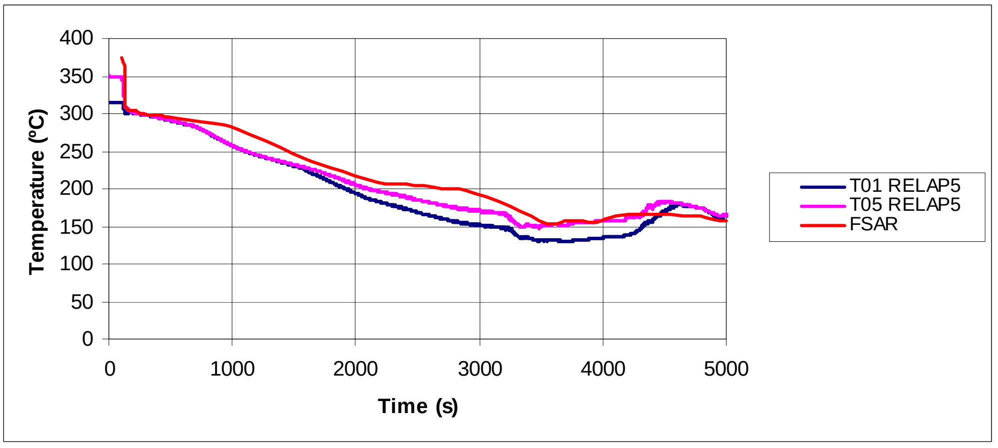

Figure 6: Hot rod cladding temperature in the lower part of the core of Angra 2 (RELAP5 and FSAR-A2).

Figures 7 to 10 show the following variables in the upper region of the hot channel of the core of Angra 2: the void fraction, hot rod cladding temperature, the flow regimes, and the heat transfer modes used by RELAP5.

Figure 7 shows an increase in the void fraction in the upper region of the hot channel of the core, between 400 and 550 seconds of simulation, when only vapor in the core was observed.

Figure 8 shows an increase of the temperature on the top region of the core, in this range of time, with maximum temperature of the hot rod cladding of 500 ºC.

Figures 9 and 10 show the flow regimes and the heat transfer modes on the top region of the hot channel of the core, respectively, during the simulation using RELAP5 code. These variables can be observed in the Tables 2 and 3.

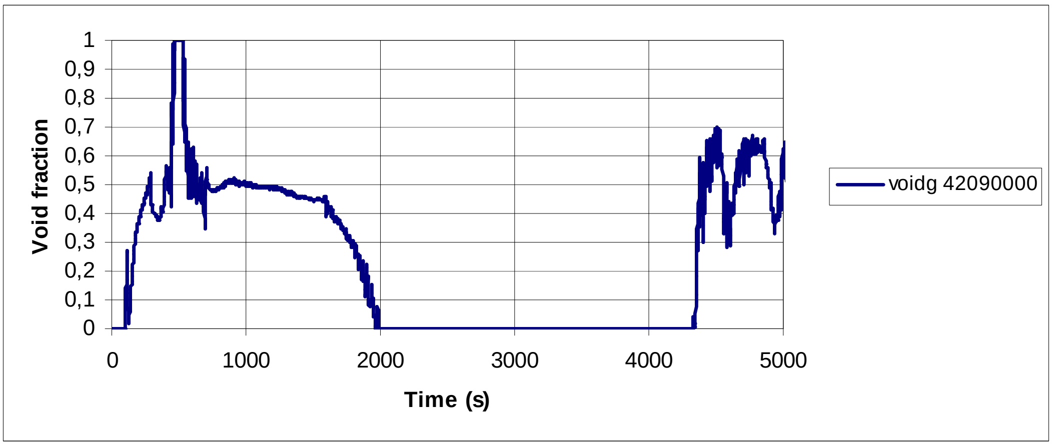

Figure 7: Void fraction on the top of the of the hot channel core of Angra 2 (RELAP5).

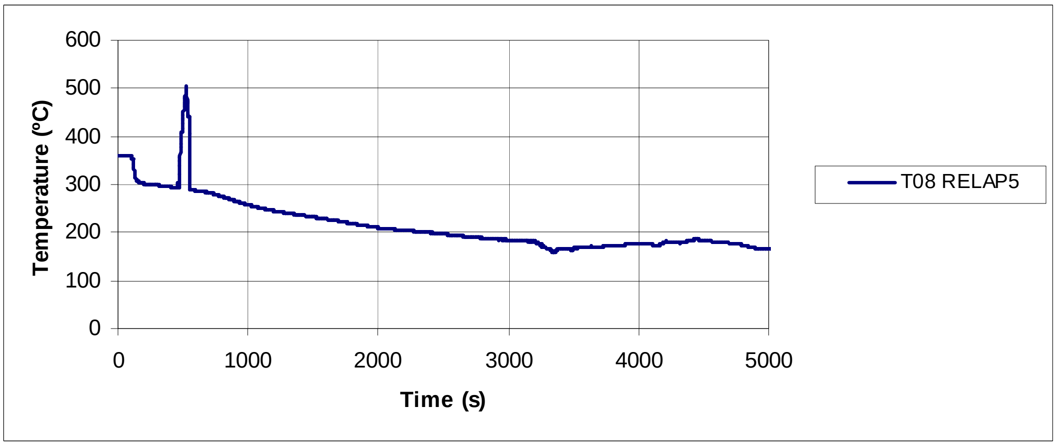

Figure 8: Hot rod cladding temperature on the top of the core of Angra 2 (RELAP5).

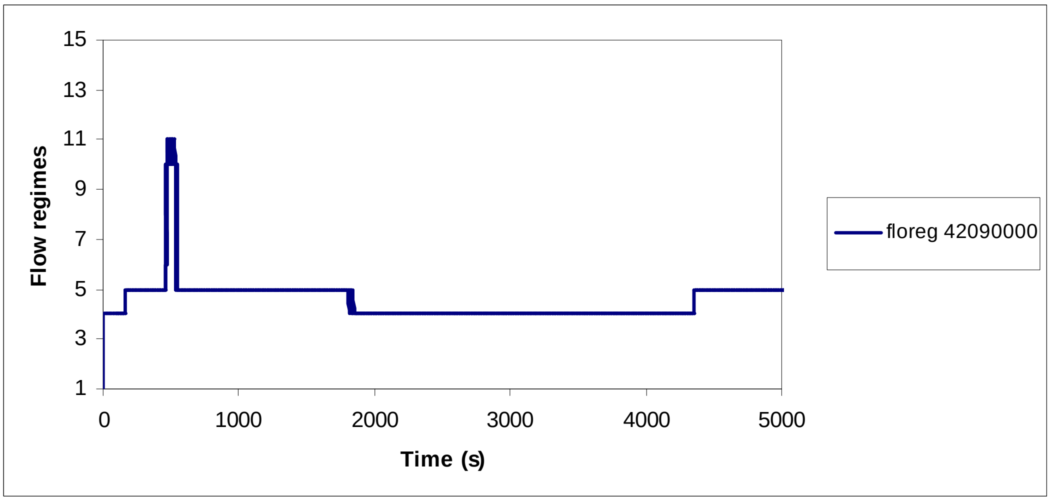

Figure 9: Flow regimes on top of the hot channel of the core of Angra 2 (RELAP5).

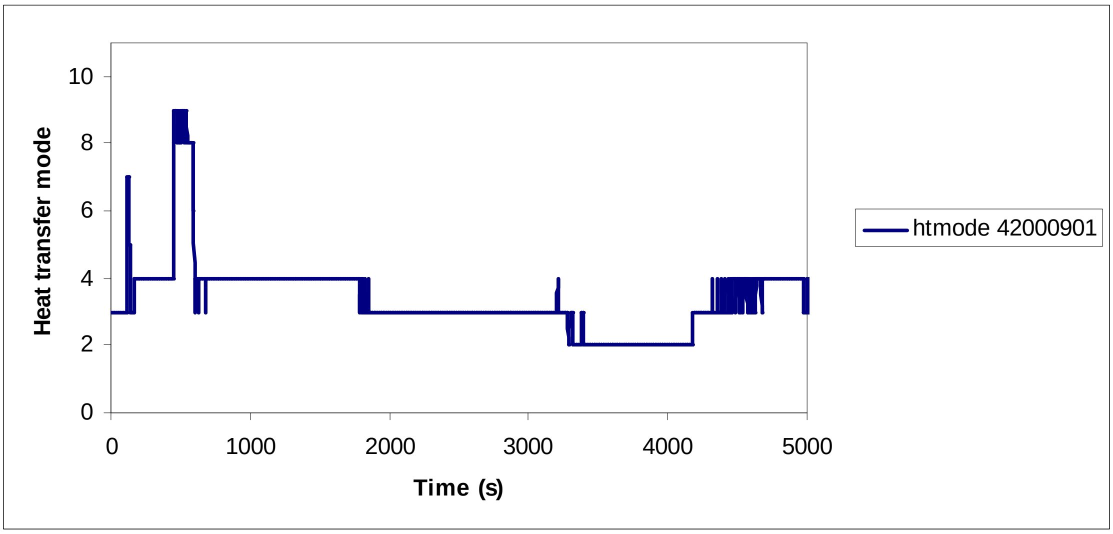

Figure 10: Hot cladding heat transfer modes on the top of the core of Angra 2 (RELAP5).

The results showed the expected behavior during the SBLOCA. The blowdown was very slow in this case.

4. CONCLUSIONS

In this work the flow regimes, the heat transfer modes, and the correlation used by RELAP5/MOD3.2.gama code, during the SBLOCA with 100cm^2 of rupture area in the cold leg of primary loop were identified. The results showed the correct actuation of the ECCS, guaranteeing the integrity of the reactor core. In addition, the results obtained using RELAP5 were similar to the results of the FSAR-A2.

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