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Loss of Coolant Accidents in Pool Type Research Reactors – Lessons Learned with IEA-R1 Upgrade

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ABSTRACT: This paper presents the results obtained in a set of experiments using electrically heated plates simulating the heat fluxes corresponding to the decay curve after full power operation at 5 MW of the IEA-R1 research reactor. These experiments were performed to demonstrate the effectiveness of the Emergency Core Cooling System (ECCS) designed for IEA-R1 to remove the decay heat after a loss of coolant accident with core uncovering. The results showed a peculiar behavior in the temperature field due to the flow pattern that occurs in the plates. The water flow,in the form of water fillets, indicate the complexity of modeling this problem in such accident conditions. This emphasizes the importance of this kind of experiments.

1.INTRODUCTION

IEA-R1 is a pool type research reactor that uses MTR fuel elements and was designed by Babcok & Wilcox. Since its first criticality in 1957, it has been operated at 2 MW power level, although its nominal design power is 5 MW. In order to increase its production capability, an upgrading program was implemented to assure the safe operation at 5 MW.

According to experimental studies by Webster [1], pool type research reactors with MTR type fuels operating up to 3 MW does not need ECCS to mitigate the consequences of LOCA (Loss Of Coolant Accident) with core uncovering. However, for higher power levels, additional systems and modifications in existing systems are needed to assure core integrity during a LOCA event. The most usual systems and modifications adopted were: ECCS with spray header (Omega West Reactor [2], Rossendorf Research Reactors [3], RAS Research Reactor [4], and RP10 Research Reactor [5]), siphon breakers [2], double walled piping (FRG-1 Research Reactor [6]) and replacement of the primary pipes by more robust pipes.

In the IEA-R1 Research Reactor, the following systems were added to the original project: an ECCS, two motorized isolation valves installed at inlet and outlet of the primary piping, near the pool, and isolation devices for the Beam Hole ports.

To design such an ECCS, the following basic design parameters are necessary: a) the system total flow rate required to effectively remove the residual heat by using sprays; b) spray flow rate distribution in the core in order to assure that every fuel element including the control fuel element are adequately cooled; c) the minimum operational time required to remove the residual decay heat during the initial period of the loss of coolant accident until the heat flux is low enough that the core can be cooled by natural air convection. This last data together with the total system flow rate are used for dimensioning the reservoirs capacity. These parameters were determined or verified experimentally. This work describes the design, experimental validation, construction and commissioning of the ECCS for IEA-R1 research reactor.

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2. ECCS – EMERGENCY CORE COOLING SYSTEM

Calculations performed by Maprelian [7] had shown that in occurrence of a full scale LOCA, the core begins to uncover after 300s. Maprelian also demonstrate that after operating at 5 MW during infinite time, the core needs emergency water cooling during a minimum period of 13.5 hours. Preliminary calculations indicated that a flow rate of 3.5 m^3/h would be sufficient to cool the core. The confirmation that this value would be adequate was done through experiments to determine the spray flow rate distribution over the core and by experiment with heated plates cooling. For a flow rate of 3.5 m^3/h and a minimum operating time of 13.5 hours, the minimum water volume capacity required was calculated to be around 50 m^3.

An ECCS must have redundancy in its water supply and the feeding should be preferably driven by passive means, e.g., by gravity. This leads to the requirement of having two independent feedwater reservoir with a total capacity of 100 m^3. Fortunately, near the reactor building, two reservoirs with 75 m^3 capacity each, constructed for other purposes were not being used, being available for the ECCS. The reservoirs pressure head was enough to provide the necessary drive. Each reservoir when full and without make-up has the capability to supply the system at nominal flow rate for more than 20 hours. The use of these reservoirs reduced significantly the cost and time for ECCS implementation, being only necessary to perform some maintenance and adaptations.

The ECCS [8], Fig. 1, is equipped with two independent branches and physically separated to avoid that a common event could damage both of them simultaneously. These branches are conducted above the ground up, to facilitate inspection and maintenance, to the reactor building. The branch A enters directly into the reactor hall while the branch B pass through the Emergency Room before entering the reactor hall. Inside the reactor hall both branches merge together into one feedwater line to feed both the spray header over the core and the periodical testing spray header. Each branch is equipped with two solenoid valves in parallel which are actuated automatically by signals coming from three level switches located in the pool. These valves can also be actuated manually from a control panel in the Emergency Room.

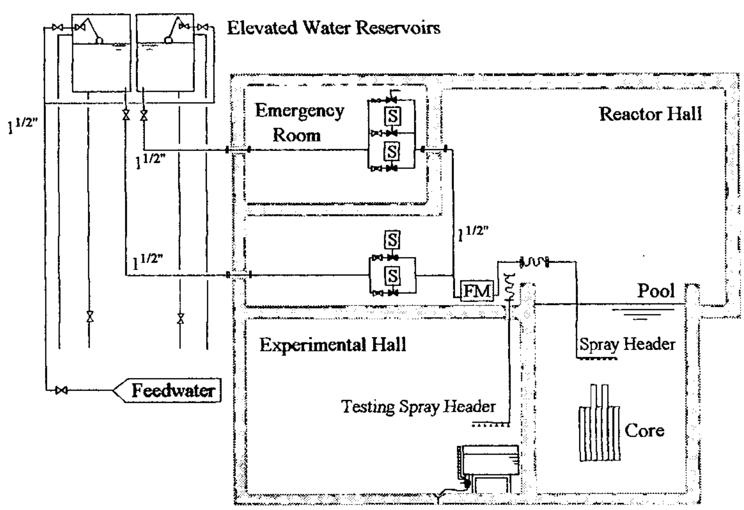

Figure 1 - Schematic Diagram of IEA-R1 Emergency Core Cooling System

The development of the ECCS was divided into the following subsequent phases: a) Spray Header Flow Rate Distribution Experiment; b) Heated Plates Cooling Experiment; c) ECCS - Manufacturing, Construction and Installation and d) ECCS – Commissioning.

3. SPRAY HEADER FLOW RATE DISTRIBUTION EXPERIMENT

The spray header flow rate distribution experiment main objective was to define the characteristics necessary to provide an adequate flow distribution over the core, assuring that every core fuel element will receive the needed amount of water. A full mock-up in natural scale of the core and the U shaped spray header were constructed for this purpose. Among other studies, this mock-up allowed the study of the shadowing effects caused by the control elements and neutron detectors housing over the other fuel elements. The experimental data and results were used to define the spray header and its spray nozzles specifications. Fig. 2 shows the test section and experimental circuit, and Fig. 3 shows the normalized flow rate distribution results for the chosen header configuration actually used for the ECCS. These results shown flow values over specified ones [4] (30 cm^3/min/plate) to total flow rates over 3 m^3/h.

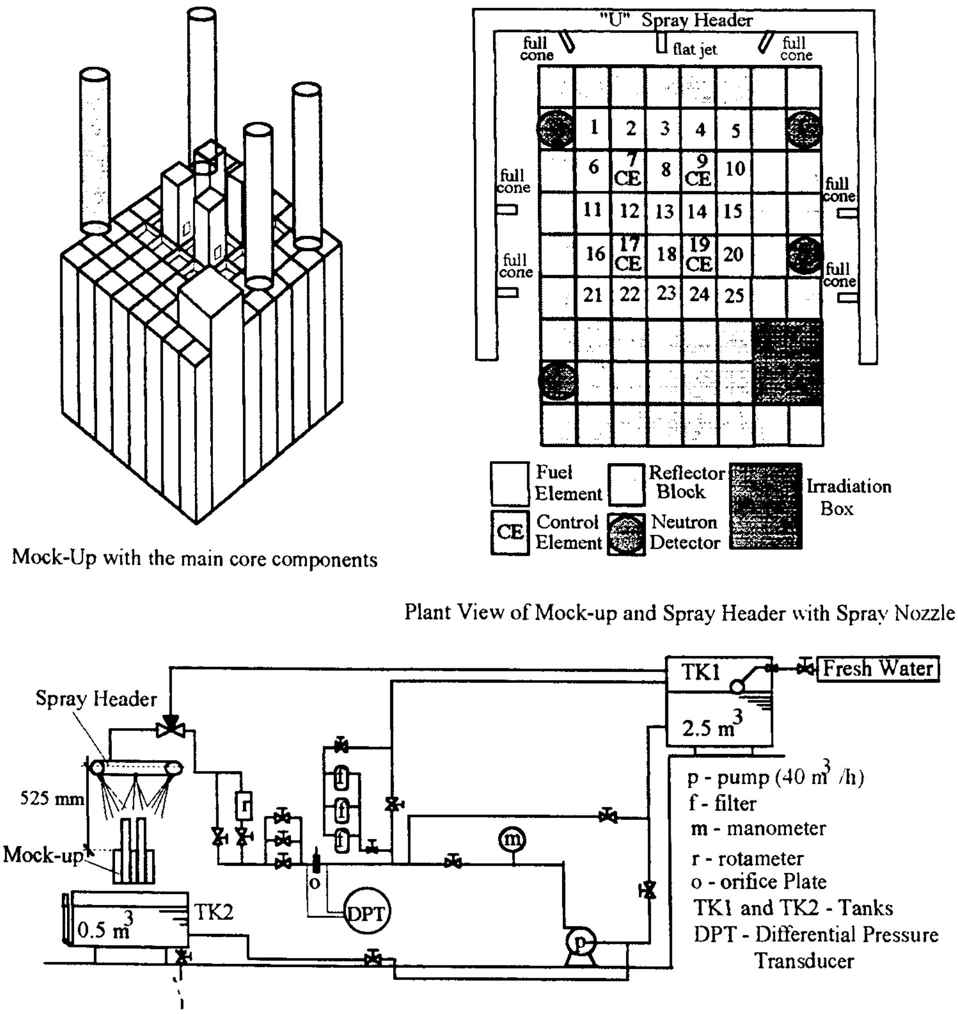

Figure 2 - Experimental Circuit and Mock-up.

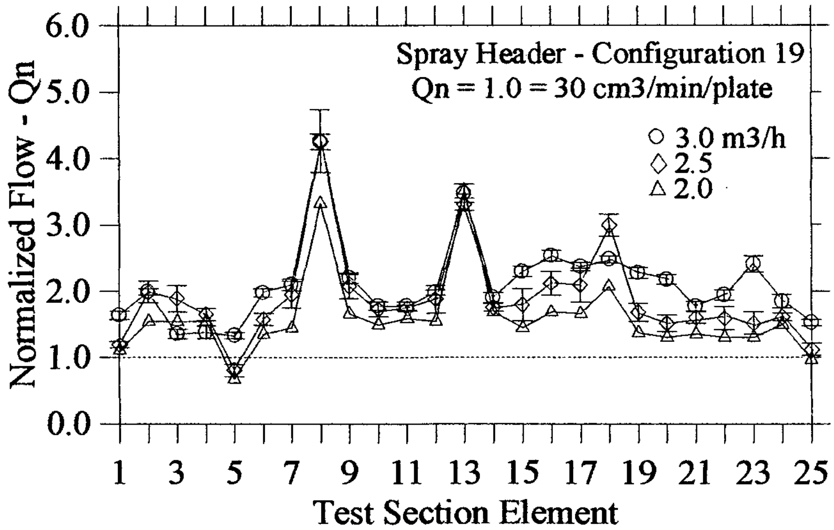

Figure 3 - Normalized Spray Flow Distribution

4. HEATED PLATES COOLING EXPERIMENT - HPCE

The heated plates experiment main objective is to demonstrate the effectiveness of the ECCS spray system to cool the core and to keep the temperatures below the limiting value. For this experiment, the same mock-up of the spray header flow rate distribution was used with a test section (STAR) formed by four electrically heated plates made of Ni-Cr alloy and generating a heat flux equivalent to the residual heat in the core after shutdown, Fig. 4. The four plates connected in series and electrically fed by a current rectifier were placed at shadowed position of the fuel no. 12, as defined in the Fig. 2.

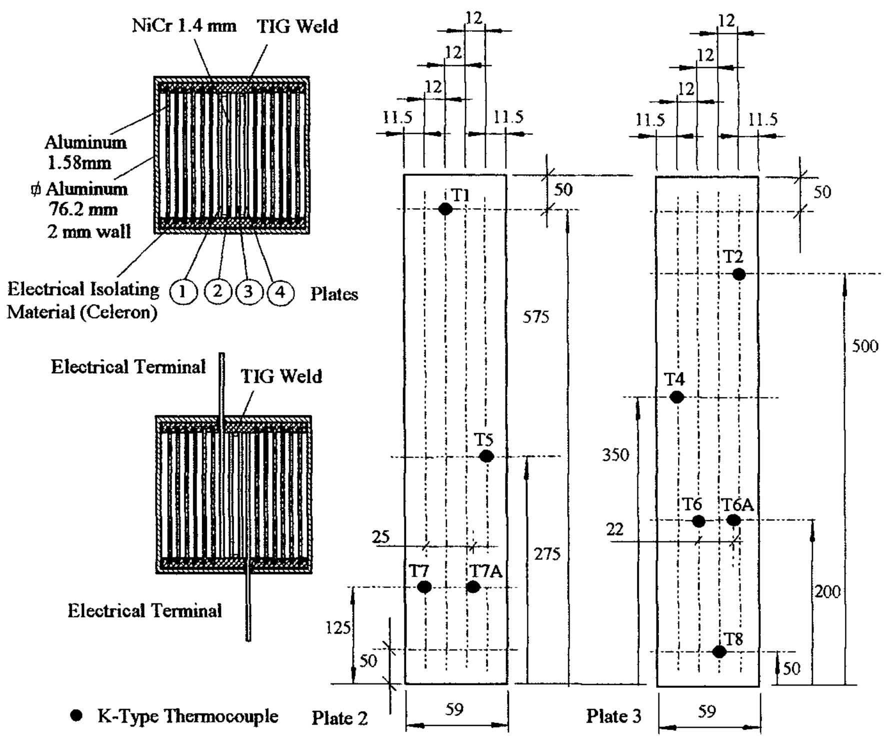

Figure 4 - Heated Plates Test Section – STAR

4.1. HPCE results

Figures 5 – 8 shows the experimental conditions and the results of two different tests performed with STAR Heated Plates Test Section. The tests were accompanied by licensing inspectors from responsible department of Nuclear Energy National Commission of Brazil. The results obtained in the tests show that the limiting value of 500°C to surface temperature is not reached even in most severe conditions and were used to obtain the ECCS certification.

In the STAR53 and STAR54 tests the uniform heat flux simulates the conservative conditions of the fuel channel in the core with the largest energy integral. The ECCS water flow rate in these two tests was 3.5 m^3/h.

In the STAR55 and STAR56 tests the uniform heat flux simulate an also conservative and hypothetical fuel channel with heat flux equal to peak heat flux. The same anterior water flow rate in ECCS was used in these tests.

Figures 5c and 5d (STAR53) shows that in despite of the same heat flux in the plates 2 and 3 the temperatures present different behavior and indicate the complexity of modeling this accident condition. The STAR54 test was performed at similar experimental conditions of STAR53 and the temperature results were different (Fig. 6c and 6d), showing the inability to repeat the phenomenon. The same conclusions can be obtained comparing the results of the STAR55 and STAR56 tests, shown in Fig. 7 and 8.

Although the thermocouples 6/6A and 7/7A were located at the same axial position but in different plates, they recorded very different temperature time history. This behavior can be explained by observing the water flow pattern in the channels. It was visually observed during the experiments that the cooling process is composed both by water evaporation as well as heat convection to flowing water. The flow pattern presents a peculiar behavior in the form of "fillets" running along the entire channel. The difference between the measured temperatures from two adjacent thermocouples is due to the particular position of this "fillet" in relation to the thermocouples position. It can be noticed that sometimes one thermocouple indicates a higher temperature than its adjacent pair and some times this relation is inverted indicating that the position of the water "fillet" is changing.

In order to explain how this peculiar cooling flow pattern can affect the resulting temperature distribution, a numerical 2D model was developed to solve the stationary conduction equation for the plate. The model also allows for comparison of the influence on temperature gradients caused by difference between the experimental plates and the actual fuel elements material properties.

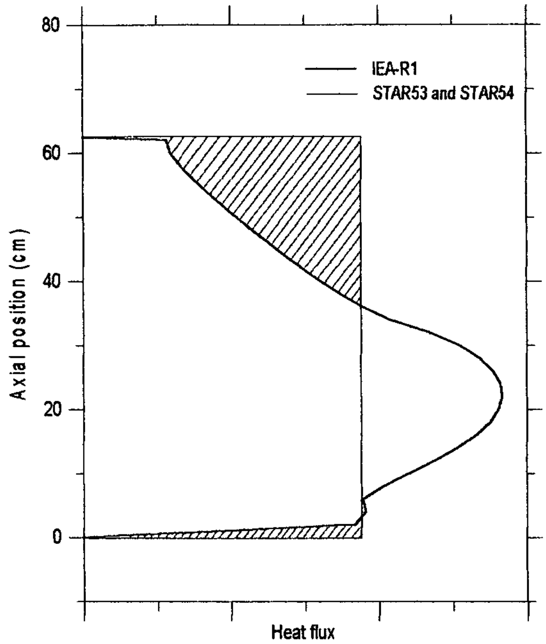

Figure 5a - Heat flux profile in STAR53 test.

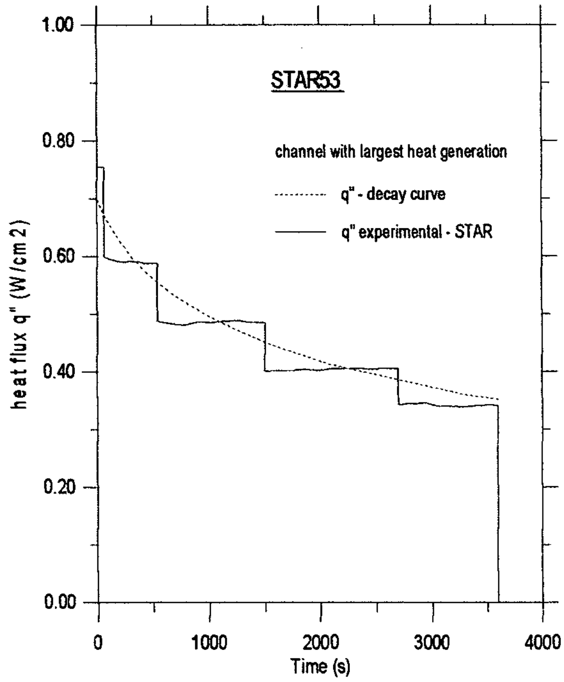

Figure 5b - Heat Flux time history STAR53 test

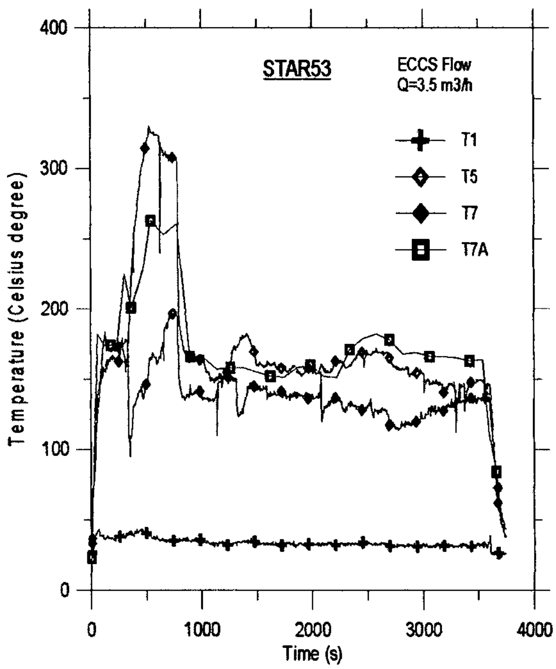

Figure 5c - Temperatures in plate 2 of STAR Test Section

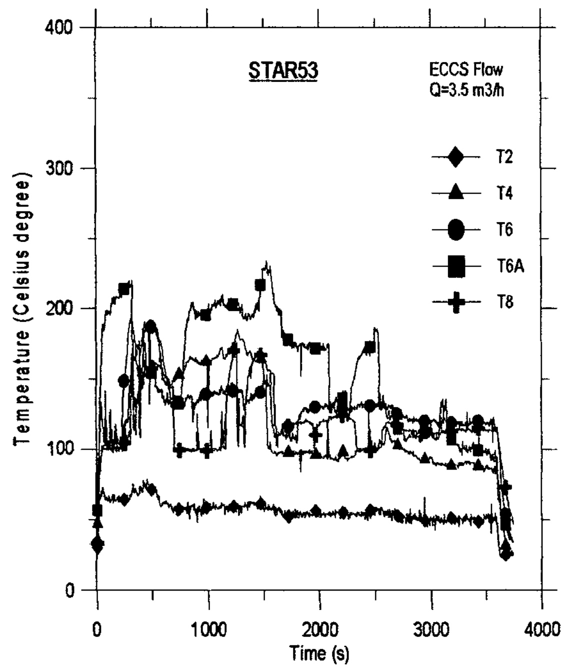

Figure 5d - Temperatures in plate 3 of STAR Test Section

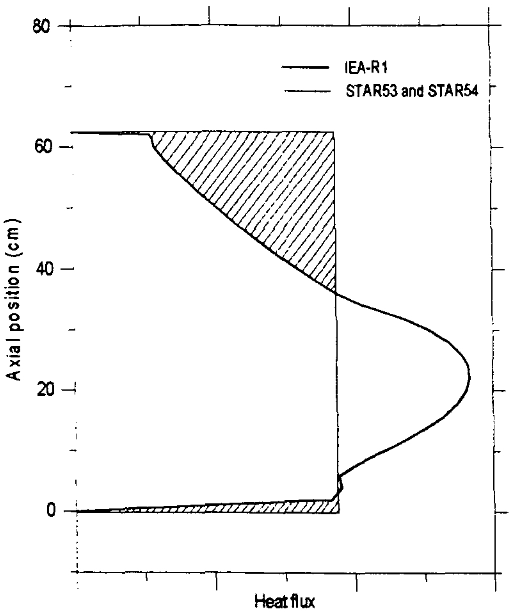

Figure 6a - Heat flux profile in STAR54 test.

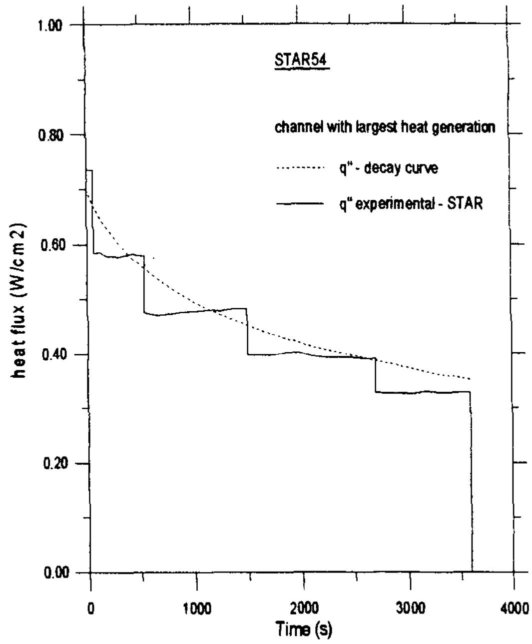

Figure 6b - Heat Flux time history STAR54 test.

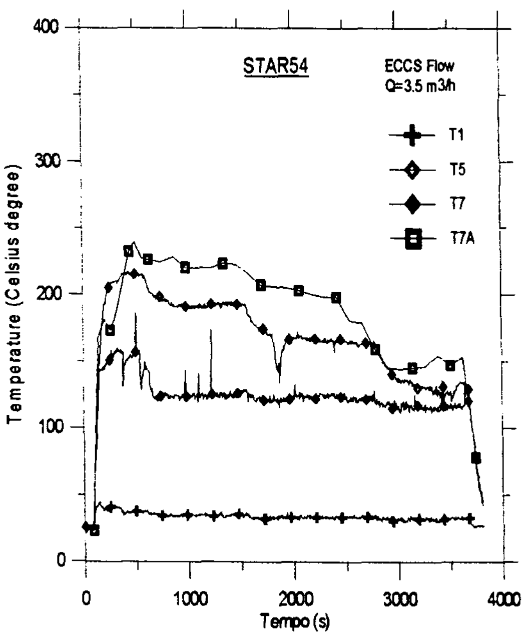

Figure 6c - Temperatures in plate 2 of STAR Test Section

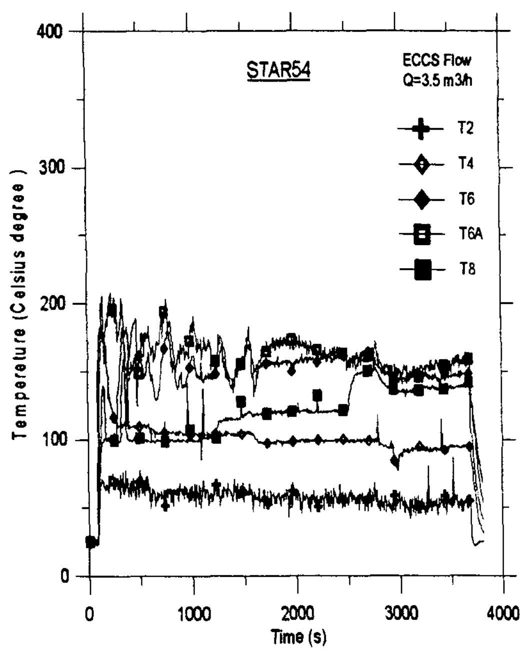

Figure 6d - Temperatures in plate 3 of STAR Test Section

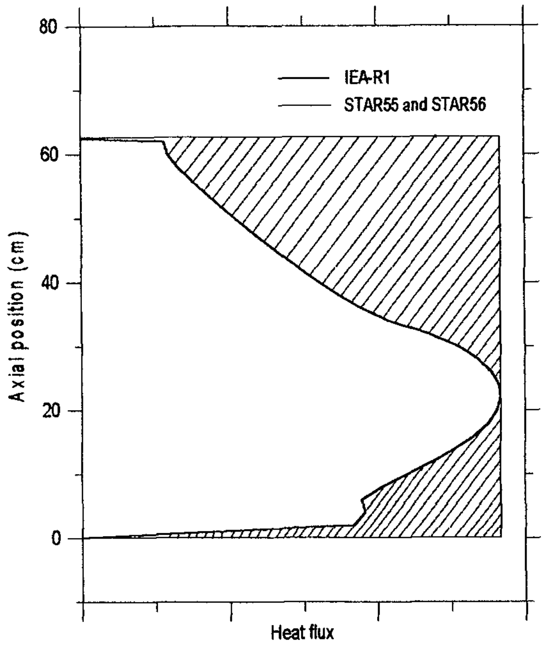

Figure 7a - Heat flux profile in STAR55 test.

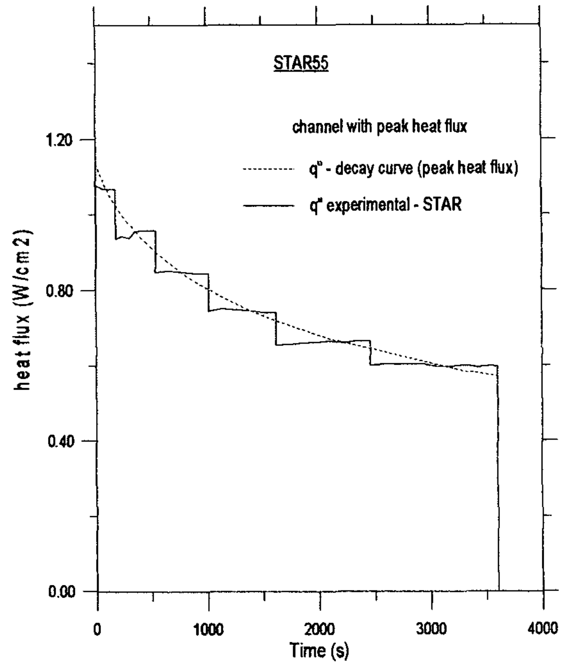

Figure 7b - Heat Flux time history STAR55 test

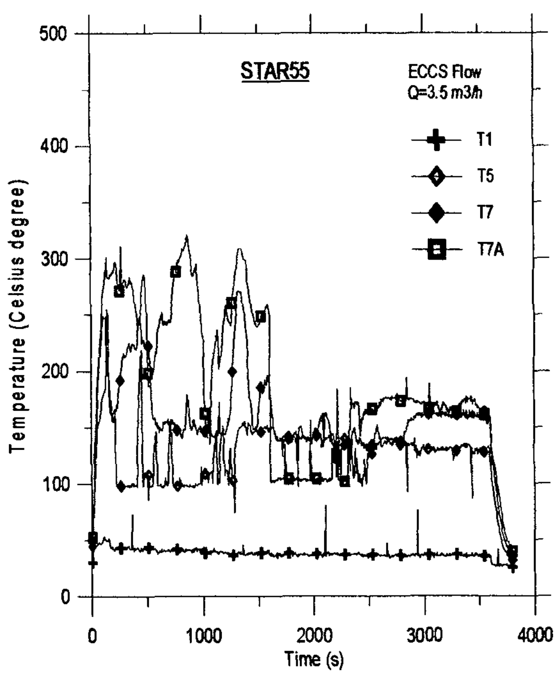

Figure 7c - Temperatures in plate 2 of STAR Test Section

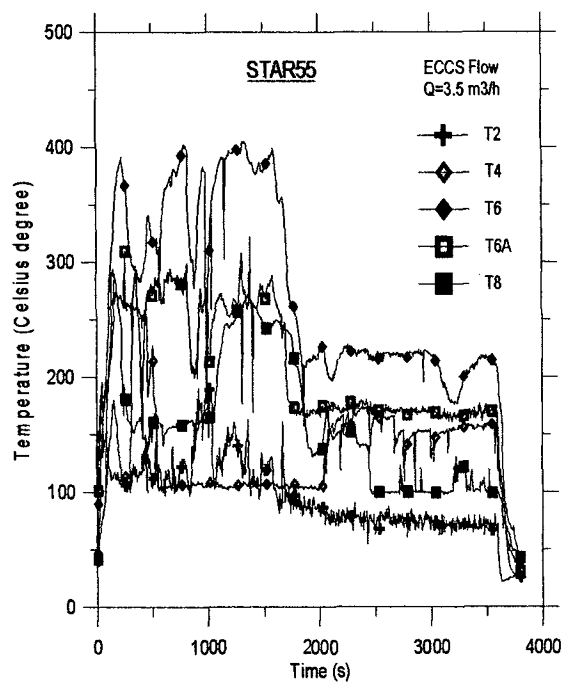

Figure 7d - Temperatures in plate 3 of STAR Test Section

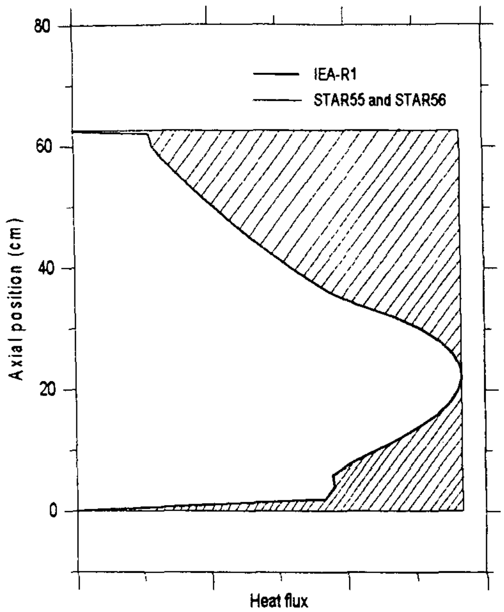

Figure 8a - Heat flux profile in STAR56 test.

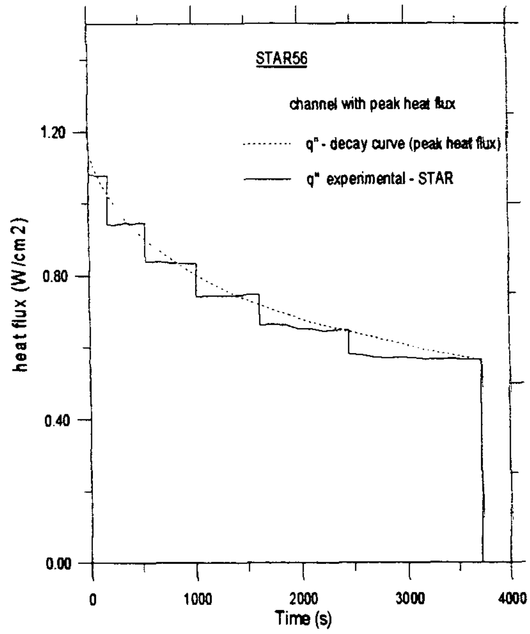

Figure 8b - Heat Flux time history STAR56 test

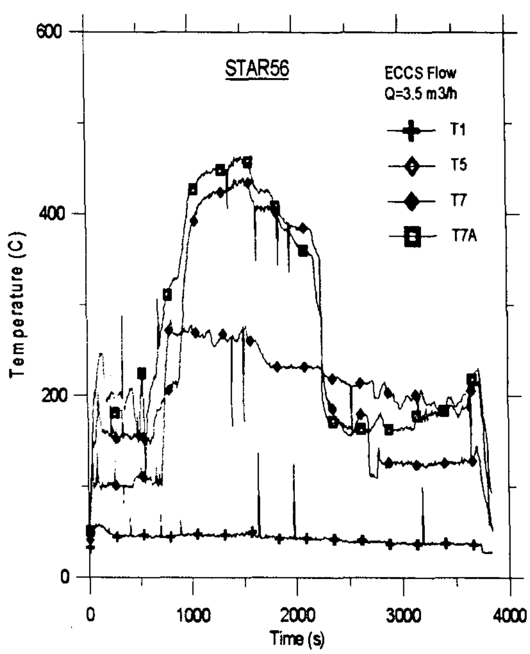

Figure 8c - Temperatures in plate 2 of STAR Test Section

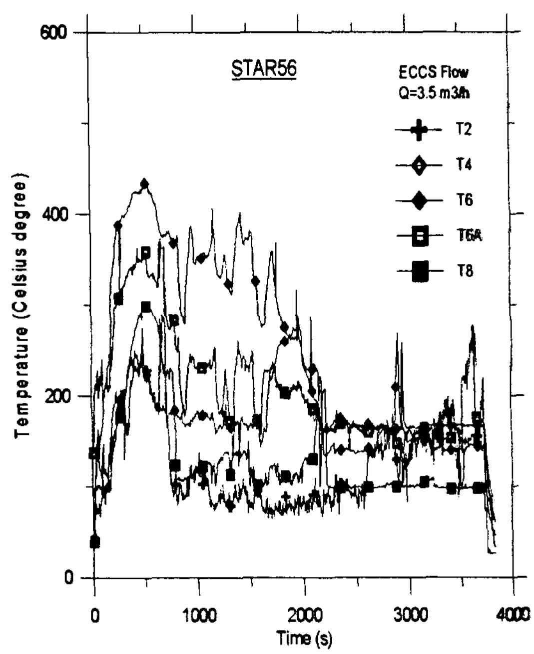

Figure 8d - Temperatures in plate 3 of STAR Test Section

5. HEAT CONDUCTION MODELLING

The differences in the results observed between tests performed under identical conditions and the difference in the temperature time history during the same experiment measured by adjacent thermocouples lead us to further investigate the heat transfer regime in the plates. In the first phase of the investigation, visual observation of the plates indicated that the flow pattern formed during the plates cooling has the form of "fillets" and the water evaporation with mineral salts cristalization leave a footprint on the plates allowing visual observation of the flow pattern as illustrated in Fig. 9.

Comparison between the results obtained in different tests showed that the flow pattern on the heated plates are not repeated, following different trajectories for each test. This behavior, i.e., changes in the position of the water "fillets" relative to the thermocouples, is responsible for the different temperature time history measured in each identical test. Due to this peculiar flow pattern behavior and also due to the impossibility of installing more thermocouples to give higher resolution in the experimental mapping of the temperature time history, a numerical model is necessary to complement the experimental data in order to reach a safe conclusion.

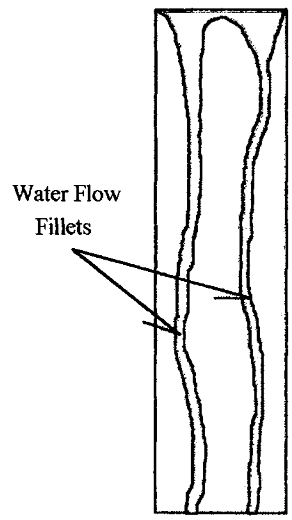

Figure 9. "Fillets" water flow on the plates.

In order to verify the effect of different possible positions of the "fillets" upon the maximum temperatures and also to extrapolate the results from the experiments where the heated plate material is a Ni-Cr alloy to that of the fuel elements where the material is an Al-UO_2 alloy, a 2D heat conduction model Eq. 1 was developed using finite difference techniques.

$$\rho\, c \frac{\partial T}{\partial t} = q''' + k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right), \qquad (1)$$

where ρ is the material density in kg/m^3, c is the material specific heat in J/kg.$^\circ$C, q''' is the volumetric thermal source in the plate in W/m^3, k is the material thermal condutivity in W/m.$^\circ$C and T is the temperature in $^\circ$C. The spatial domain discretization is shown in Fig. 10 with the plate width divided into ii=30 nodes and the thickness into jj=5 nodes. The heat transfer coefficient for the water "fillets" was calculated using Thom's correlation (Thom (1965)), given by Eq. 2, and for natural convection cooling by air, a constant value of 7.5 W/m^2 $^\circ$C was used.

$$T_W - T_{sat} = 22{,}65\, \phi^{0{,}5}\, e^{-P/87}, \qquad (2)$$

where T_W and T_{sat} are the plate surface and saturation temperatures in $^\circ$C, ϕ is the heat flux in MW/m^2 and P is the absolute pressure in Bar.

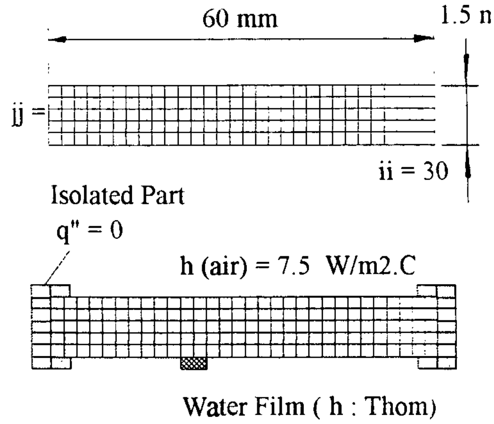

Figure 10- Heated Plate Cross Section - 2D discretization.

The measured experimental volumetric flow rate for each individual channel was always larger than 45 cm^3/min/channel, which is sufficient to cool the entire channel even for the most critical condition when the core maximum heat flux value of 1.133 W/cm^2 is used. Under this condition, an overall energy balance showed that the fraction of water evaporated is around 30% from the entrance of the channel down to the bottom. This fact indicates that a constant "fillet" width and thickness model will not introduce significant errors in the solution.

Figure 11 shows the steady-state surface temperature results from the numeric model where only one 4 mm width water "fillet" was considered at 22 mm from the heated plate border and 600 W power which is equivalent to a heat flux of 0.8 W/cm^2. Two solutions are shown: one using the thermal conductivity of the experimental heated plate material (Ni-Cr) which is 12 $W/m^{\circ}C$ and another using the thermal conductivity of the fuel elements ($AL\text{-}UO_2$) which is 144 $W/m^{\circ}C$. The smaller value of the thermal conductibility used in the experiments causes a correspondent difference in temperature gradients between the experimental heated plates and the actual fuel element. When in the experiments the maximum temperatures were above 250 $^{\circ}C$, under identical conditions, the actual fuel elements maximum temperatures should be around 150 $^{\circ}C$.

One can also notice that when in the Ni-Cr plate thermocouple T7 measures 150 $^{\circ}C$ and its adjacent thermocouple T7A registers 200 $^{\circ}C$, the correspondent temperatures in the actual fuel element would be 120 $^{\circ}C$ and 140 $^{\circ}C$, respectively. A similar behavior is observed at the T6 and T6A thermocouples positions. These numerical results explain the data obtained during the STAR53 and STAR55 experiments and offer a phenomenological insight for the temperature difference measured at two adjacent position.

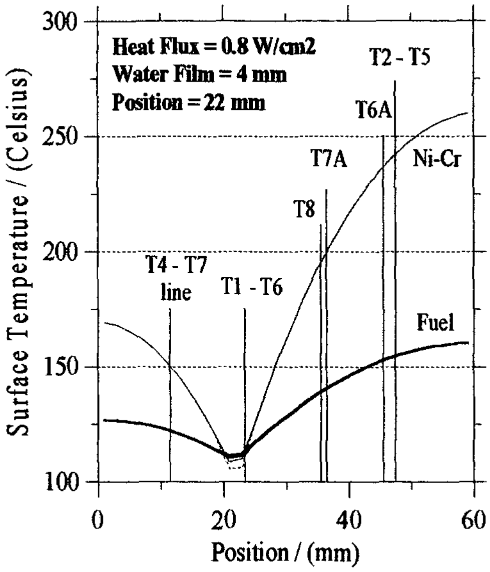

Figure 11. Temperature distribution (q"=0.8 W/cm2)

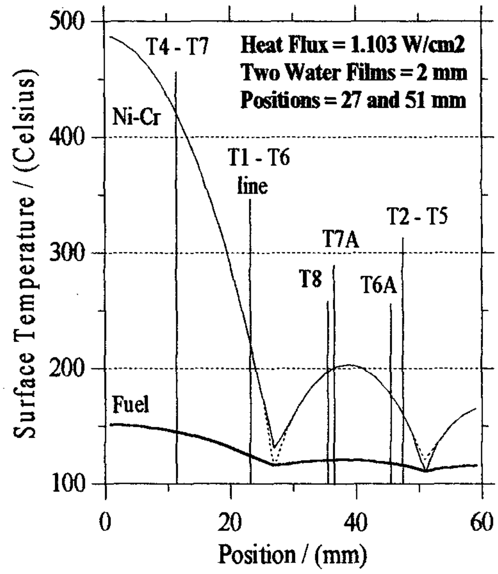

Figure 12. Temperature Distribution – (q" = 1,103 W/cm^2)

Figure 12 analyses the effect of more than one water "fillet" and of their widths. Two "fillets" with 2 mm width each positioned at 27 and 51 mm from the border were simulated, keeping the heat flux at 1.103 W/cm^2. Under these conditions the maximum calculated temperatures for the Ni-Cr heated plates were around 500 °C and the correspondent maximum temperature in the fuel is 150 °C. Fig. 11 and 12 also indicate the position of the installed thermocouples so that they can be used to interpret the experimental data and to extrapolate for the actual core condition.

6. - CONCLUSIONS

The design of the Emergency Core Cooling System of the IEA-R1m research reactor, upgraded to operate at 5 MW, used conservative parameters and redundancy criteria to assure that in the ocurrence of the postulated total loss of pool water the maximum fuel temperatures will be kept at safe levels. The Spray Flow Distribution Experiments defined the spray header specifications and demonstrated that every core component including the control elements are adequately irrigated by the spray system. The Heated Plates Experiments demonstrated that during the first 30 minutes critical period, even under very conservative conditions, the maximum temperatures were well bellow the 500 °C limit. These results also show the plate temperature behavior and indicate to the difficulties to mathematical modeling of these phenomena. The numerical modeling is able to demonstrate and to explain the peculiar water "fillets" flow pattern and cooling regime and also to calculate the actual fuel elements temperatures which are quite smaller than the temperatures measured experimentally due to different thermal conductibility of materials.

7. REFERENCES

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