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An Analysis of Natural Circulation Cooling of a Reactor Vessel during Severe Accidents by RELAP5/MOD3 Computer Code

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ABSTRACT

One of the proposed accident management strategies for severe accidents is the In-Vessel Retention (IVR) of molten fuel. As a means of IVR strategy, the reactor cavity is flooded with cold water. In the present paper, the feasibility of ex-vessel cooling by natural circulation during a severe accident is analyzed by RELAP5/MOD3 computer code. We considered the case where a reactor vessel is enclosed by an insulation structure. The flow channel is modeled by a series of nodes with variable flow area and inclination angle. Cases with a constant wall temperature and constant heat flux are considered. The general trends of these two cases are similar in the sense that the system shows cyclic boiling behavior, after the fluid in the upper portion of the flow channel reaches the saturated condition. Cyclic behaviors are observed for the void fraction, mass flow rate, and fluid temperature in the flow channel, and the steam flow rate to the atmosphere. The period of cycle becomes shorter as the heat flux increases. Also, a regular micro-scale oscillation is observed for the case with a constant wall temperature. The results of Fast Fourier Transform of the void fraction and mass flow rate indicate a dominant frequency of 0.5Hz. The behavior is closely related to the cyclic generation and collapse of a bubble in the sub-cooled liquid in the heated channel.

The results of the analyses for the case representing the Korea Standard Nuclear Power Plant show that decay heat can be effectively removed by natural circulation. In the case of the Korea Next Generation Reactor the temperature of the reactor vessel wall is found to exceed the melting temperature of the vessel wall. As the RELAP5 predicts the overall system behavior and the local CHF correlation based on the AECL look-up table employed in RELAP5 is a good first order approximation, the results of the present analyses can be utilized in judging the feasibility of ex-vessel cooling.

1. Background

One of the proposed accident management strategies for a severe accident is In-Vessel Retention (IVR) of molten fuel. The reactor vessel can maintain its structural integrity, if the heat flux generated from the molten fuel pool can be effectively removed. As a means of the IVR strategy, the reactor cavity is flooded by cold water. The reactor vessel cooling is then performed by a passive natural circulation flow in a cavity. This passive cooing mechanism is desirable, as it would not call for operator action.

The maximum heat removal capability is determined by both the local phenomena of the critical heat flux on the downward facing walls and the overall boiling characteristic of the system. The local maximum heat load is limited by the Critical Heat Flux (CHF) to avoid film boiling. If the heat transfer mechanism becomes film boiling, the reactor vessel wall temperature will increase above the melting temperature, which would jeopardize the IVR strategy. There has been research on the critical heat flux on downward facing walls [1,2,3]. They claimed that the critical heat flux is minimum at the bottom of the reactor vessel and it increase as the inclination angle of the wall increases. However, as the local hydrodynamic and thermodynamic condition along the heated channel is determined by the overall system behavior, the system behavior needs to be considered. The overall system behavior of the boiling phenomena outside the full-scale reactor vessel[4] and in a simplified geometry[5] were experimentally investigated. This gave qualitative insight to the physical phenomena.

The feasibility of this concept in a prototypic reactor is determined by the interaction among the heat load along the heated vessel wall due to decay heat from the molten fuel pool, the heat removal capability provided by the natural circulation, and the geometry of the flow channel. As the prototypic condition is not easily achieved in an experimental facility, it is beneficial to analyze the phenomena by using analytical tools. In this study we use the state-of-the-art thermal-hydraulic computer code RELAP5/MOD3[5] to simulate the natural circulation cooling of the reactor vessel from outside and to perform parametric studies. This approach can be justified, as the various heat transfer and hydrodynamic correlations would provide a good first order approximation of the situation under consideration.

2. Analytical Models

The RELAP5 computer code employs a one-dimensional, transient, two-fluid model for the flow of a two-phase steam-water mixture. The two-fluid equations of motion are formulated in terms of volume and the time averaged parameters of the flow. The heat transfer model employs a heat transfer correlation in the whole range of the heat transfer regime, including boiling heat transfer. As it is basically a one-dimensional model, it has a limitation in simulating multi-dimensional natural circulation in a pool. However, when the insulation structure enclosing the reactor vessel is present, the overall system behavior can be approximated in a one-dimensional model. Therefore, the present analysis is limited to the case with an insulation enclosure.

The RELAP5/MOD3 model is constructed for ex-vessel cooling. The pool water is modeled as a big pool. The pool water is either sub-cooled or saturated. The flow channel consists of a heated wall, an unheated wall and the insulation enclosure along the reactor vessel wall. The heated wall is a portion of the reactor vessel, which encloses the molten fuel pool. The flow channel is modeled as 21 nodes. The height of the flow channel is 7.7 m. The gap size is 0.2 m. The length of the heated wall is 3.7m. The node flow path net work is the same as one employed in reference 6.

If we assume that all the fuel assemblies are melted and relocated to the bottom of the pool, the decay heat generated from the molten fuel pool induces a natural convection flow inside the pool. The outside of the pool is maintained at a constant temperature of the melting point of the molten fuel. Both the natural convection pattern and the hydrodynamic condition outside the reactor vessel wall determine the amount of heat transfer. Previous research indicated that the heat flux in the upper part of the steel layer is much bigger than the lower part due to the focusing effect [1]. For simplicity, we assumed a uniform heat flux from the reactor vessel wall or constant inner wall temperature. The uniform heat flux of 760 KW/m^2 is calculated from the decay heat of 40MW, which corresponds to the decay heat of the Korean Next Generation Reactor (KNGR) at 10000 seconds. The value corresponding to that of the Korean Standard Nuclear Power Plant (KSNPP) is 600 KW/m^2.

Depending on the natural circulation flow rate and wall heat generated from the molten fuel pool, the heat transfer mode is determined. The reactor vessel wall temperature can be maintained below the melting temperature when the heat transfer mode does not evolve to transition boiling or film-boiling regime. Therefore, the heat load should be maintained below the critical heat flux to enable IVR strategy.

As the geometry of the reactor vessel wall is multi-dimensional and curved in shape, the existing correlation of the CHF in a simple geometry cannot be directly applied. Therefore, there was a lot of effort to investigate the CHF mechanism for downward facing curved walls [1,2,3,4]. The CHF is dependent on the local thermodynamic and hydrodynamic conditions. However, as the local condition is determined by the overall system behavior, the overall system behavior should be appropriately evaluated. Though the CHF mechanisms are quite different from the AECL look-up table suitable for the vertical pipes of a fuel bundle implemented in RELAP5/MOD3, the RELAP5 correlation would provide a good first order approximation.

As RELAP5 enables parametric studies, it would provide valuable insight on the sensitivity of various system parameters. It will be very beneficial in determining the success criteria of the IVR strategy and the major scaling parameters for the experimental facility.

3. Analysis Results

If we assume that all the decay heat is transferred to the outside of the vessel, the heat flux of KNGR and KSNP ranges from 570 KW-770 KW. We selected a case with constant inner wall temperature of 400 ^{o}K as a base case. Depending on the heat transfer mode, the decay heat generated in the molten fuel pool is partitioned between the molten fuel pool and the water in the heated channel.

3.1 The case with constant inner wall temperature

Figure 1 shows the fluid temperature in the heated channel. The heated channel has 13 volumes. The temperatures in the first, ninth, and the last volume are shown. Initially, the water in the heated channel and cavity pool is at 50 ^{o}C and atmospheric pressure. The fluid temperature at the exit of the channel reaches the saturation condition at about 15 minutes and starts to oscillate with a frequency of 500 seconds. The fluid temperature of the fluid volume near the top of the channel stays at the saturation temperature. Fig.2 shows the void fractions in the heated channel. The flow regime changes from bubbly flow at the bottom and slug flow at the upper portion of the channel. The sudden void is generated from the channel at 15 minutes. This sudden void generation in the heated channel results in a sudden hydrostatic head unbalance between the heated channel and the pool, it induces a large amount of cold water flow from the pool. The water in the heated channel then becomes sub-cooled, which is heated up to the saturation condition again. This takes about 500 seconds. This phenomenon repeats its cycle as shown in Figures1 and 2.

The mass flow rate to the inside of the enclosure is shown in Figure 3. The flow rate shows a cyclic peak of high inflow. This phenomenon is closely related to the behavior of the fluid temperature and void fraction in the heated channel inside the insulation. As shown in Fig. 2, the abrupt increase in the void fraction occurs repeatedly. In the Figures, 200-01, 200-03, and 200-9 denotes the first, third, and ninth sub-node in the node 200.

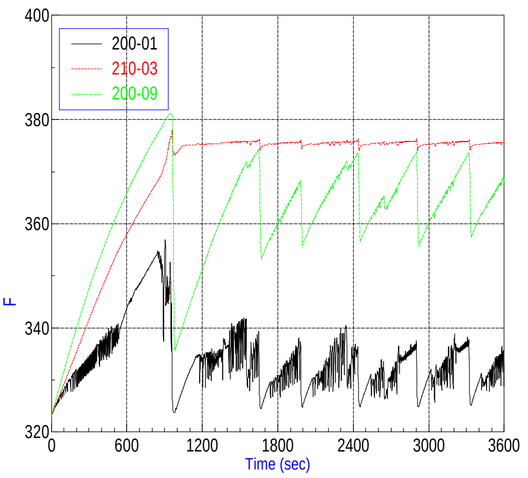


Fig. 1 Fluid temperature in the flow channel

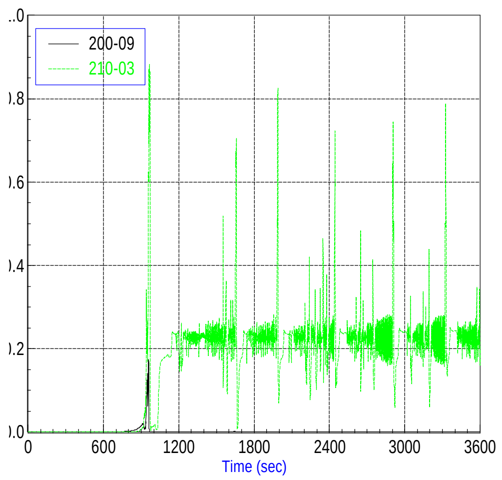


Fig. 2 Void fraction in the flow channel

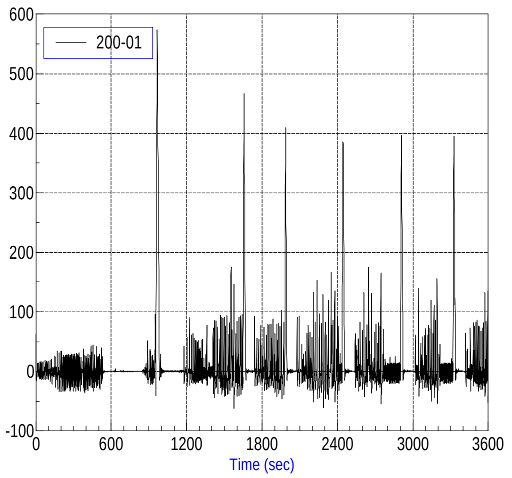


Fig. 3 Mass flow rate in the flow channel

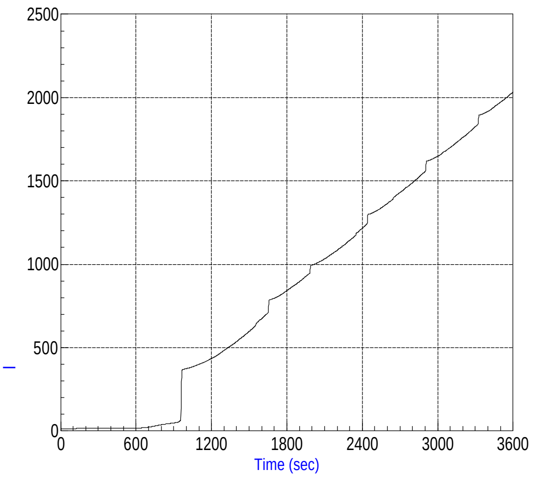


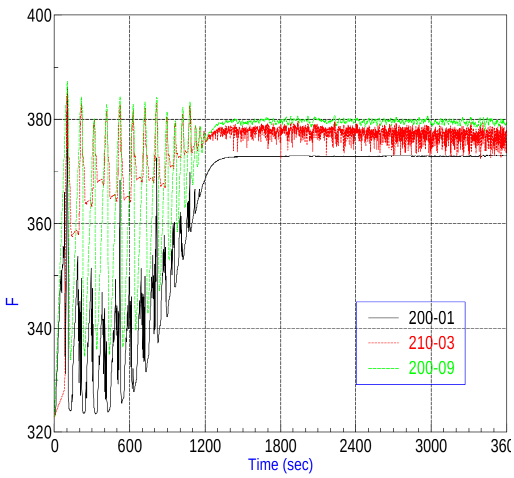
Fig. 4 Steam flow rate to the atmosphere

The sudden increase in the void fraction results in an abrupt inflow from the cold water pool, which results in the collapse of voids and an increase in the hydrostatic head. The fluid temperature and void at the bottom of the cavity pool increases when there is a net reverse flow from the volume near the bottom of the heated wall. As the fluid is heated, the heat-transfer rate decreases. When there is an abrupt increase in the inlet flow, the heat-transfer rate also increases abruptly. This cyclic behavior heat transfer rate and the cyclic behavior of the void fraction results in the cyclic behavior of steam flow to the atmosphere, as shown in Fig. 4. Until the 15 minute point, the heat transfer from the heated channel is used to heat up the fluid in the heated channel and part of the fluid in the lower cavity. The periodic jump in the steam mass flow rate is due to the rapid cyclic steam generation discussed above. The calculated heat transfer rate from the heated wall is about 80 KW/m^2 and the heat transfer mode was either sub-cooled nucleate boiling or saturated nucleate boiling. The integrated steam flow between 1000 seconds to 3600 seconds is about 1400 kg. It corresponds to about 1 kg/s.

The RELAP5 model has a big intermediate volume between the atmosphere and the flow channel and cavity pool. The role of this is such that the two-phase mixture coming out of the heated channel is separated in this volume. Though it does not model the condensation phenomena at the cavity wall and/or heat structure, as it returns saturated liquid to the outer pool, it represents the actual situation in a reasonable manner.

3.2 The case with a constant heat flux

The case with a constant wall heat flux of 600 KW/m^2 is analyzed to consider the feasibility of natural circulation cooling for a KSNP type nuclear reactor. The results of the analyses are shown below. The general trends of the system behavior are similar to those of a constant wall temperature. The frequency of the cyclic oscillations increased due to higher heat input from the reactor vessel wall to the heated channel.



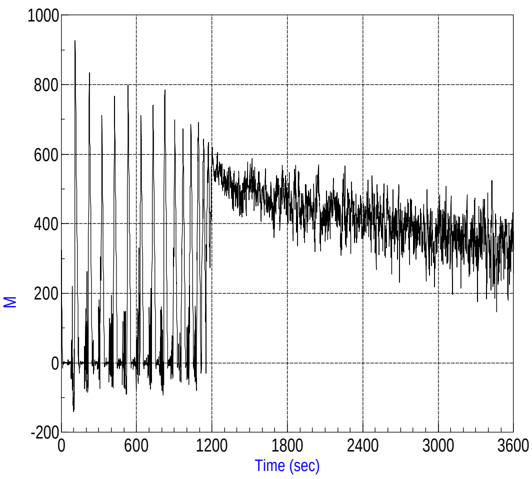
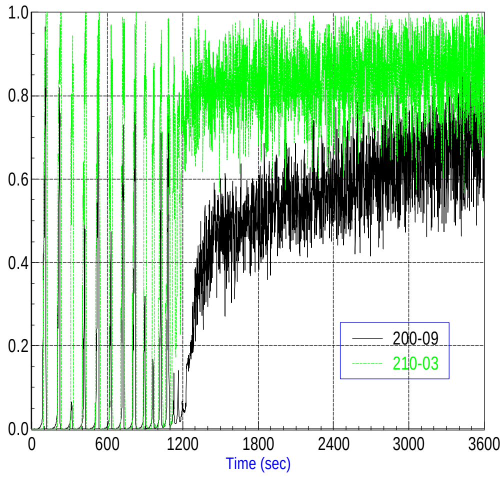


Fig. 5 Fluid temperature in the flow channel   Fig. 6 mass flow rate in the flow channel



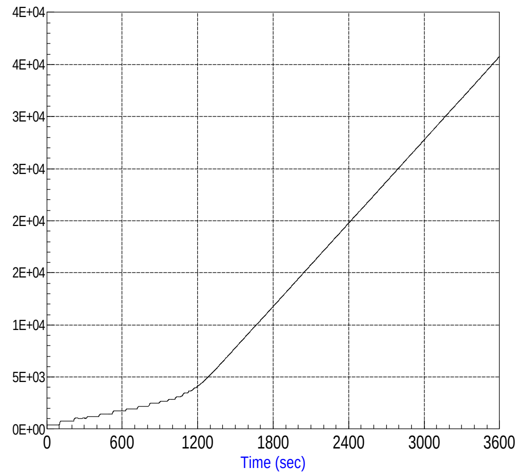


Fig. 7 Void fraction in the flow channel

Fig. 8 Steam flow rate to the atmosphere

Fig. 5 shows that the fluid temperature at the top of the channel reaches the saturated condition at 200 seconds and the fluid temperature oscillates in the same manner as that observed in the constant wall temperature case. The period of oscillation decreases due to increased heat input from the reactor vessel. As the heated water coming out of the heated channel is returned to the pool, the pool water reaches the saturation condition at atmospheric pressure at about 1400 seconds. This phenomenon is different from the previous case. After the pool water reaches saturated condition, the pool water is depleted due to continuous boil off from the heated channel. As it reduces the hydrostatic head, the mass flow rate slowly decreases as indicated in Figure 6. The oscillatory behavior in the mass flow rate is due to the same reason as that of the previous case.

Figure 7 shows the void fraction in the flow channel. It shows that after the inlet flow became saturated, the channel became voided and the channel reached a steady state void distribution. The hydrostatic balance between the voided flow channel and saturated pool then drives the mass flow rate, which also reached a steady state value. As the pool water decreases due to boil off, the mass flow rate decreases. The steam flow to the atmosphere is depicted in Figure 8. After the inlet flow becomes saturated, the steam flow rate increases.

The results of the analyses indicate that natural circulation cooling is feasible for a KSNP type reactor, where the average heat flux from the heated wall is about 600 KW/m^2. As RELAP5 employs a CHF correlation of AECL look-up table, the present analyses may not predict CHF condition at the channel precisely. However, the RELAP5 prediction is a good first order approximation. Therefore, our judgement that the IVR strategy for a KSNP type reactor is feasible by the natural circulation flow in the reactor cavity pool can be justified.

The case with a constant heat flux of 770 KW/m^2 is analyzed to consider the feasibility of natural circulation cooling for a KNGR type of reactor. The wall temperature increases above the melting point of the reactor vessel material, which is carbon steel. The heat transfer regime at the wall became film boiling. This indicates that natural circulation cooling may not effectively remove decay heat in the KNGR type reactor, when the molten pool is totally relocated to the bottom of the reactor vessel. The heat transfer capability needs to be augmented by an engineered safety feature, such as external cooling or the use of heat transfer effective coolant.

3.3 Micro-scale oscillations

The void generated from the heated wall is condensed in cold water. As there is a characteristic time for the void drift velocity and void collapse, there is a micro-scale oscillation in the various parameters. A snap shot on the behavior is investigated for the base case and the case with 600 KW/m^2. The snap shot is taken between 1800 seconds and 1805 seconds. Figiures 9 and 10 show the mass flow rate in the flow channel and void fraction in the flow channel, respectively.

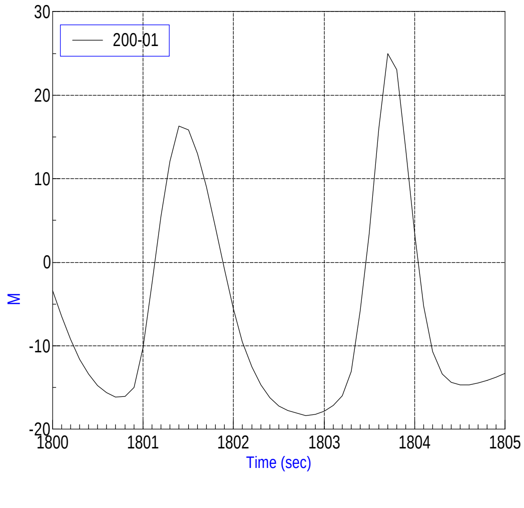


Fig. 9 Mass flow rate in the flow channel

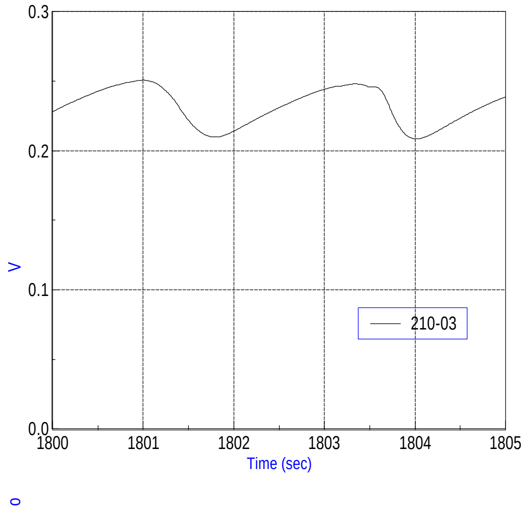


Fig. 10 Void fraction in the flow channel

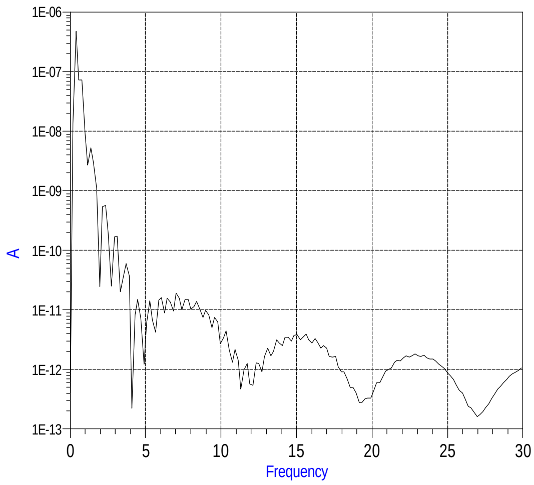


Fig. 11 Results of Fast Fourier Transform

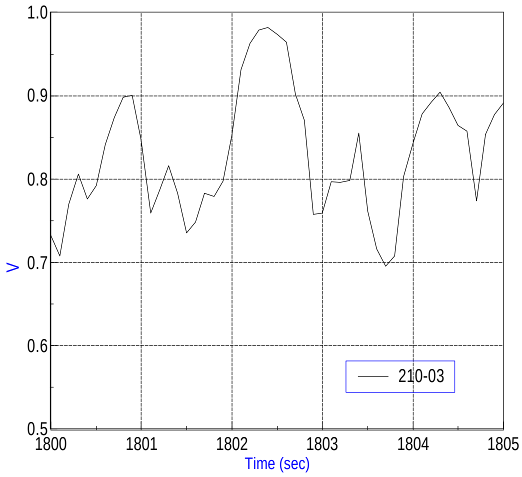


Fig. 12 Void fraction in the flow channel

In the base case, the heat transfer mode in the heated channel is sub-cooled nucleate boiling during the period of the snap shot. The cyclic behavior of the void fraction represents void generation and collapse of the bubble in the sub-cooled liquid in the heated channel. The period is about 2 seconds, which is judged to be independent of the system scale. The amplitude-frequency results of the Fast Fourier Transform of the void fraction is provided in Figure 11. The base case shows a dominant frequency of 0.5 Hz. In the second case with a constant heat flux of 600 KW/m^2, the heat transfer mode in the snap shot period is saturated pool boiling. Therefore, this kind of bubble generation and collapsing cycle does not appear. Rather, random oscillations in the channel rate and void fraction are observed. The void fraction is shown in Figure 12.

4. Summary and conclusion

The feasibility of ex-vessel cooling by natural circulation during a severe accident, in which molten fuel is relocated to the bottom of the reactor vessel, is analyzed by RELAP5/MOD3 computer code. The natural circulation of the reactor vessel from the outside is modeled by a node flow-path network. The model consists of a heated channel, unheated channel, atmospheric boundary condition, reactor cavity pool, the upper region of reactor cavity, and the bottom portion of the reactor cavity. The cases with constant wall temperature and constant heat flux are analyzed. The general trends of both cases are similar in the sense that the system shows cyclic boiling behavior after the fluid in the upper portion of the flow channel reaches the saturation condition.

The results of the analyses for the case representing the KSNP type reactor show that the decay heat can be effectively removed from the outside of the reactor vessel by natural circulation. The heat transfer regime stayed within either sub-cooled nucleate boiling or saturated nucleate boiling. The results of the analyses for the KNGR type nuclear reactor indicate that the temperature of the reactor vessel wall may exceed the melting temperature of the vessel wall. The heat transfer regime moves to either transition boiling or film boiling. Due to the fact that the RELAP5 employs a CHF correlation of the AECL look-up table the present analyses may not predict the CHF condition at the channel precisely, but the results of the present analyses can be utilized as a good first order approximation. Also a regular micro-scale oscillation is observed for the case with constant wall temperature. The results of the Fast Fourier Transform indicate that the dominant frequency is 0.5Hz. This behavior is closely related to the cyclic generation and collapse of a bubble in the sub-cooled liquid in the heated channel. It is not found for the case with saturated nucleate boiling.

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