The 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-14
Toronto, Ontario, Canada, September 25-30, 2011

NURETH14-471

# ANALYSIS OF THE PERFORMANCE OF THE KERENA$^{NT}$ EMERGENCY CONDENSER

**A. Manera[1], H.-M. Prasser[1,2] and S. Leyer[3]**
[1] Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[2] Institut f. Energietechnik, Sonneggstrasse 3, 8092 Zürich, Switzerland
[3] AREVA NP GmbH, 63067 Offenbach, Germany

## Abstract

With the aim of gaining experimental data on the behaviour and performances of the passive systems of the KERENA$^{NT}$ reactor design, AREVA NP has built the INKA large-scale test facility situated in Karlstein, Germany. In order to support the experimental campaign by establishing a test matrix and a suitable experimental procedure for the evaluation of the performances of the emergency condenser (EC), pre-test simulations have been carried out by means of the best-estimate thermal-hydraulic code RELAP5/mod3.3. The results have shown that, in stationary conditions, a single train of the EC can remove a power up to about 70 MW at the nominal reactor pressure of 70 bar. Only a limited region of the operational range of the EC can be investigated at the INKA test facility in stationary conditions, due to the limited power of the steam supply to the RPV (up to 24 MW). Therefore, a transient experimental procedure has been designed aimed at the “quasi-stationary” characterization of the EC over a wide range of power levels and pressures, which range far beyond the steady-state power supply available at the INKA facility. The transient procedure has been tested and verified by means of RELAP5/mod3.3, and a data evaluation methodology based on windows-averaging has been proposed and applied, aimed at deriving the field of quasi-stationary characteristics of the EC. The experimental procedure has been successfully employed by AREVA at the INKA test facility and the experimental results have been used to validate RELAP5 for the passive emergency condenser. The validated RELAP5 model will be used to perform an uncertainty analysis of the experimental results with regard to the dynamic measuring errors originating from the quasi-stationary approach. The physical insights on the EC behavior gained by the RELAP5 simulations are also presented in the paper.

## Introduction

Gen-III+ designs, the latest generation of nuclear power reactors currently available on the market, feature different types of innovative passive safety systems. Passive systems are considered to be a desirable method for increasing the reliability of the performance of safety functions [1], and many research efforts have been dedicated internationally to their study (see for example Ref. [2] and [3]).

KERENA$^{NT}$ [4] is a Gen-III+ Boiling Water Reactor (BWR) designed by AREVA NP. Among the passive features of the KERENA$^{NT}$ design (previously known as SWR-1000), four so-called emergency condensers (ECs) are employed for the passive heat removal from the reactor pressure vessel (RPV). Each EC consists of a horizontal tubes bundle connected to the RPV through a steam line (top connection, EC feed line) and a condensate line (lower connection, EC return line). The EC horizontal tubes bundle is submerged in the core flooding pool (CFP) present in the containment. The operation of the EC is illustrated in Figure 1. In normal operation conditions, the EC horizontal tubes are completely filled with water and the EC does not operate. If the water level in the RPV drops below a certain elevation, steam will reach the horizontal tubes of the EC bundle and condense. The resulting condensate will flow back into the RPV due to gravity, yielding a passive cooling of the primary system and therefore contributing also to the depressurization of the primary system.

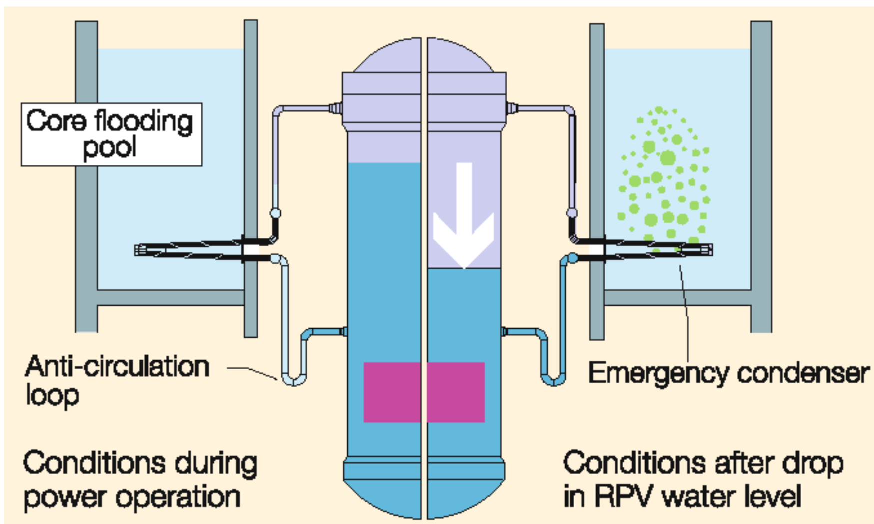


Figure 1 Working principle of the KERENA$^{NT}$ emergency condenser

## 1. The INKA test facility

With the aim of gaining experimental data on the behaviour and performances of the passive systems of the KERENA$^{NT}$ reactor design, AREVA NP has built the INKA large-scale test facility [5],[6], situated in Karlstein, Germany. A scheme of the facility is reported in Figure 2, together with a sketch of the KERENA$^{NT}$ reactor. The facility has been designed to keep a 1:1 scaling for the heights and a 1:24 scale for the volumes, with respect to the reactor design. Only one of the four redundancy trains of the KERENA$^{NT}$ passive systems are modelled in INKA. All passive systems of the modelled train (emergency condenser, containment condenser, etc.) are represented in original geometry (i.e. scale 1:1). The energy source in the RPV is modelled by means of a steam injection, the steam being produced in a 24 MW Benson boiler. A standpipe connected to the RPV represents the reactor downcomer. The emergency condenser is attached to the standpipe through a steam line (EC feed line) and a condensate line (EC return line). The EC is submerged in the flooding pool vessel (FPV). At the top of the FPV, the containment cooling condenser (CCC) allows heat removal from the FPV, by heat transfer to the shielding/storage pool vessel (SSPV). A drywell vessel, simulating the reactor drywell, and a pressure suppression pool vessel are also part of the INKA test facility.

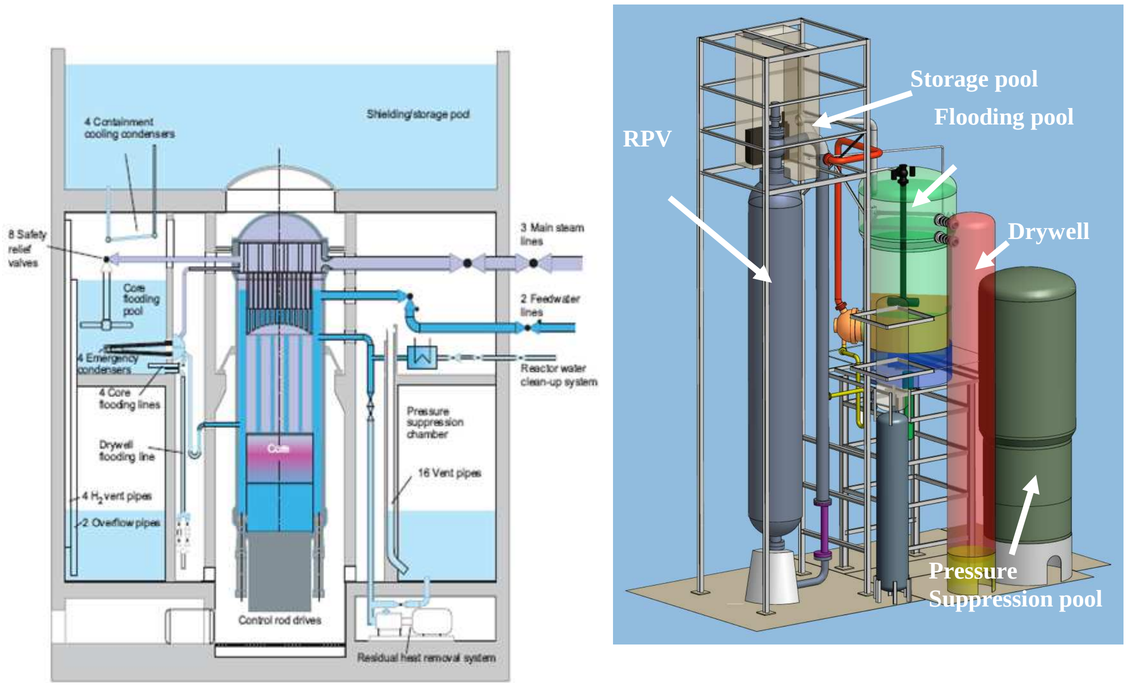


Figure 2 Scheme of the KERENA$^{NT}$ reactor (left) and of the INKA test facility (right)

## 2. The RELAP5 nodalization

In order to estimate the behaviour and the performances of the emergency condenser, the following components of the INKA test facility have been modelled with RELAP5/mod3.3 [7]: the pressure vessel; the standpipe, including the connecting piping to the pressure vessel; the horizontal U-tubes of the emergency condenser, mixing plena and connections to the standpipe, namely steam and condensate lines; the flooding pool vessel. A scheme of the RELAP5 nodalization is illustrated in Figure 3 (right), together with a sketch of the corresponding INKA components (Figure 3, left).

All components walls have been modelled in RELAP5 by means of heat structures, in order to correctly represent heat losses to the environment, the heat stored in the metallic structures, as well as the heat transferred between fluid and structures during transients.

The EC consists of 61 heat exchanger tubes which have the shape of U-tubes arranged in a horizontal tube bundle. The tubes are arranged in 7 separate rows (1a, 1b, 2 - 6) connected to the EC bundle plate at 6 different elevations (the two internal rows, 1a and 1b, are connected to the bundle plate at the same elevation, but have a slightly different horizontal length). Within each group, the geometry of the pipes is identical. The longest pipes are the one belonging to group 6. In the RELAP5 input deck, 6 groups of pipes are modelled: the EC bundle groups 1a and 1b have been modelled as a single group in RELAP5, with a length equal to the average tube length representative of these two groups of tubes. All other EC groups are modelled by an individual tube element. This simplification does not lead to significant modelling errors, since the characteristic heights of groups 1a and 1b are identical, i.e. their depletion is equally dependent from the water level in the reactor vessel. 26 axial nodes are employed in the RELAP5 nodalization of the EC tubes. The EC pipes are connected to the FVP nodalization by means of heat structures representing the EC pipes walls. The heat transfer correlations package, implemented in RELAP5/mod3.3 for horizontal bundles, has been selected to describe the convective boundary condition on the outer surface of the EC walls. The FVP pool is modelled by means of two vertical pipes, representing the downcomer and riser sections respectively. Baffle blades surrounding the EC bundle are located from node 3 to 6 (numbering from bottom to top). Therefore, each axial node of the two pipes is connected by means of cross-flows with the exceptions of nodes 3 to 6. This nodalization of the FVP allows reproducing the natural circulation that establishes in the pool when the EC enters in operation.

All friction factors have been determined on the basis of Ref. [8]. The valves, present in the EC outlet line and in the condensate line connecting the RPV with the downcomer, have been included in the RELAP5 nodalization as well. As described in chapter 4, the local friction factors associated with these two valves has been determined experimentally.

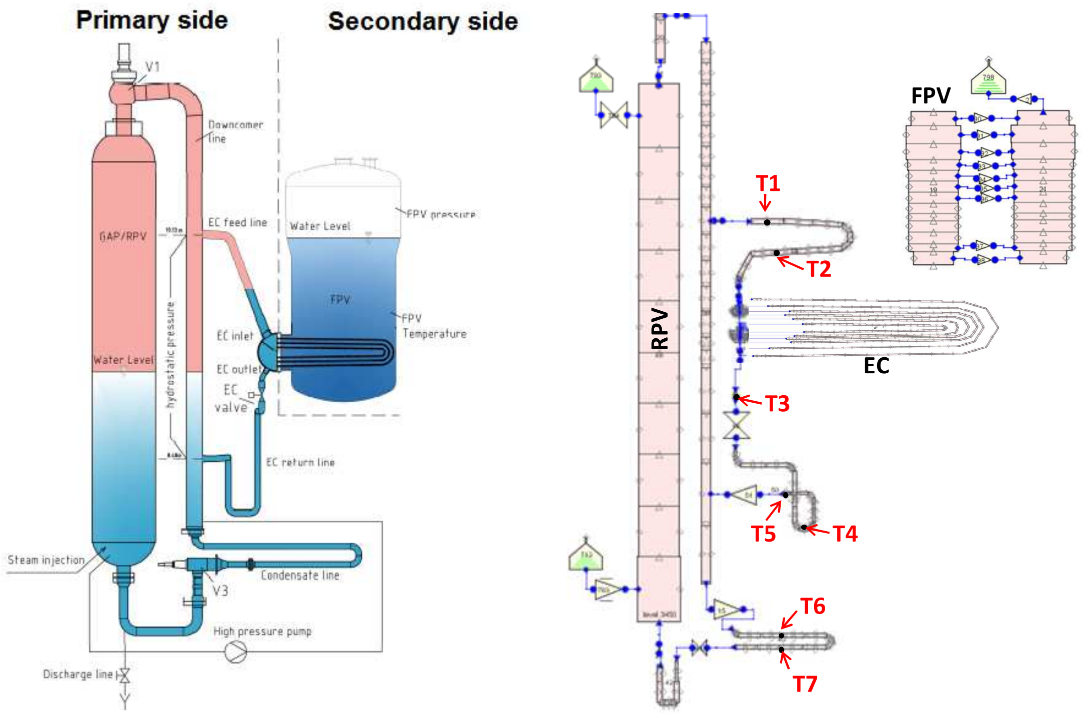


Figure 3 Scheme of the part of INKA facility included in the model (left) and RELAP5 model (right)

## 2.1 Determination of EC power

The power $P_{EC}$ transferred from the primary circuit to the FPV is estimated in three ways:

o By integrating the heat flux along the length of each tube row of the EC bundle:

$$P_{EC}(t)=\sum_{k=1}^{N}\sum_{j=1}^{M_k} N_k q''_{jk}(t)\pi D_o \Delta Z_{jk}$$

Note, that the power can be measured either at the inner or the outer surface of the EC tubes, which are not equal in transient cases due to the accumulation of energy in the wall. In the following comparisons, the power was calculated at the outer surface, e.g. the power transferred to the secondary side is given.

- o By multiplying the enthalpy change across the EC system with the condensate mass flow-rate $G_C$ in the EC return line:

$$P_C(t)=G_C(t)[h_S(t)-h_C(t)]$$

- o By multiplying the enthalpy change across the EC system with the steam mass flow-rate $G_S$ in the EC feed line

$$P_S(t)=G_S(t)[h_S(t)-h_C(t)]$$

Where $N$ is the total number of tube rows in the EC bundle (N = 7), $N_k$ is the number of tubes in the EC bundle k-th row, $M_k$ is the number of axial nodes in which the k-th bundle row is nodalized, $q''_{jk}$ is the outer surface heat flux in the j-th axial node of the k-th tubes row, $\Delta Z_{jk}$ is the length of the corresponding axial node, and $D_o$ is the outer tube diameter. $G_C$ and $G_S$ are the mass flow-rates in the EC return and feed lines respectively, while $h_S$ and $h_C$ are the steam and condensate enthalpies respectively. Note that, while $P_{EC}(t)$ is the exact time-dependent power exchanged through the EC bundle, $P_C(t)$ and $P_S(t)$ are only approximate values. The two latter estimations are however based on measurable quantities (flow-rates and temperatures at the inlet and outlet of the EC system) and are therefore of importance for the evaluation of the experimental results.

## 3. Behaviour of the emergency condenser

### 3.1 Stationary characterization

About 300 simulations have been carried out with RELAP5/mod3.3 by controlling the RPV water level, and the RPV and FPV pressures, in order to characterizing the power that the EC would transfer to the FPV pool in stationary conditions. Each code run was executed in transient mode for 5000 s process time, in order to allow the establishment of stationary conditions. The last 50 s of transient were run with a finer resolution (0.01 s) in order to ensure the possibility of analysing the occurrence of instabilities, if any. The results of the steady-state conditions are obtained by averaging the solution over the last 200 s of transient. A standard deviation around the average is computed as well.

The results are reported in Figure 4 and Figure 5, as function of the RPV water level and pressure drop across the EC system respectively, for different pressures in the RPV and in the FPV. The FPV is assumed to be filled with water at saturation conditions. It is found that the power might exhibit an oscillatory behaviour, due to the instability of the condensations within the horizontal bundle of U-tubes. The bars in the figures represent the standard deviation of the power fluctuations. As expected, the power increases with decreasing RPV water level, as more surface of the EC bundle tubes is involved in the heat exchange process through condensation. The maximum power is found at a primary pressure of 7.5 MPa and a secondary pressure of 0.1 MPa, i.e. in correspondence with the highest primary pressure and the lowest secondary pressure. With decreasing primary pressure or increasing secondary pressure, the emergency condenser power decreases. This result has to be expected, due to the decreasing temperature difference between the saturation temperatures on both sides of the EC pipes.

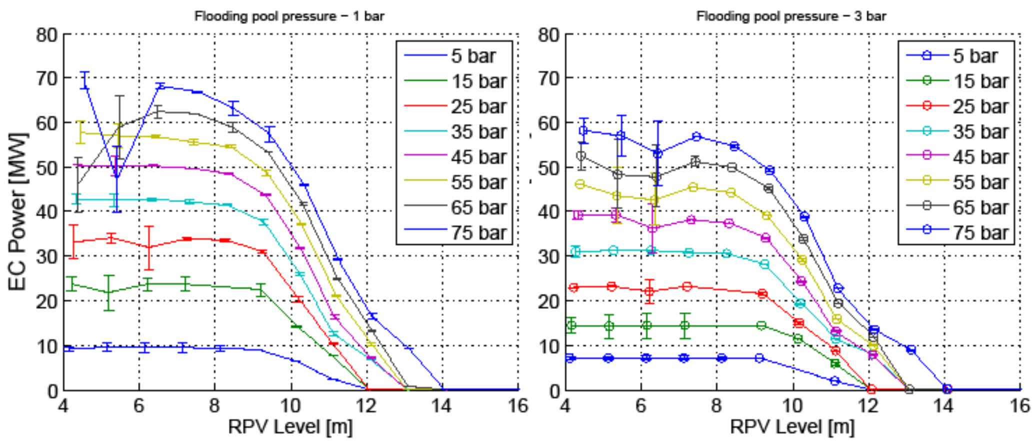


Figure 4 EC power as function of RPV water level, for different RPV pressures (5 to 75 bar), and a pressure in the FPV of 1 bar (left) and 3 bar (right) respectively.

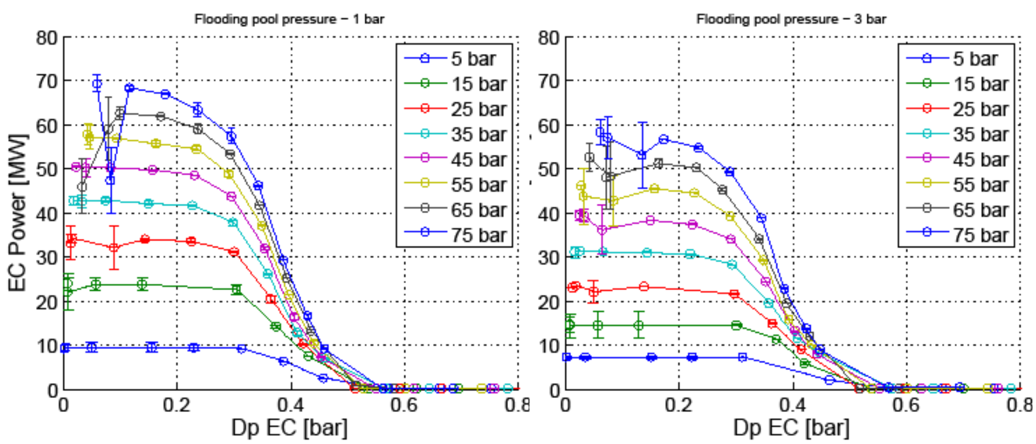


Figure 5 EC power as function of the pressure drop across the EC system, for different RPV pressures (5 to 75 bar), and a pressure in the FPV of 1 bar (left) and 3 bar (right) respectively.

There are two peculiarities observed in the power plots of Figure 4 and Figure 5: (a) in some of the operational conditions, the calculated EC power is significantly below the trend (e.g. in Figure 4 left, at a primary pressure of 7.5 MPa and a RPV water level below 6 m), (b) for some operational conditions, quite strong fluctuations of the EC power are observed (points with large bars). The power oscillations are probably caused by instability of the water level in the RPV downcomer coupled with the water inventory in the tubes of the EC. The nature of the abrupt decrease of the emergency condenser power, instead, was found to be a result of a departure from nucleate boiling (DNB) close to the inlet of the heat exchanger pipes, where the heat flux is at maximum. The heat transfer crisis at the outer surface of the EC heat exchanger tubes can be suppressed by decreasing the enthalpy of the fluid on the secondary side. The possibility of reaching DNB conditions cannot be completely excluded during transient processes for which the EC is designed. Unlike the DNB in fuel elements, the film boiling on the outer surface of EC heat exchanger pipes does not pose any risk to the integrity of the EC, since the maximum temperature is fixed by saturation temperature at the given reactor pressure. Therefore, the pipe material cannot heat up to harmful temperatures. The deterioration of the EC power due to DNB, if it should appear at all, is quite limited in effect and duration, since the reactor pressure, and together with it the EC power, rapidly decreases during the transient in case of an accident. In accidents, situations with high reactor pressures nearly always coincide with low temperatures in the flooding pool vessel, i.e. saturation at the EC secondary side is reached only after the pressure in the RPV has significantly decreased. For this reason, DNB at the EC heat exchanger tubes is very unlikely to occur in real accident scenarios.

It can also be noticed in Figure 4 that the operation of the emergency condenser does not terminate (null exchanged power) for the same RPV collapsed water level, for different primary and secondary pressures. This is because the RPV level is only an indirect measurement of the water level in the EC chambers, which is instead the determining parameter for the establishment of heat exchange with the secondary side. For a characterization of the EC power, therefore, the pressure drop across the EC system is a more significant parameter. As a matter of fact, a collapsing of all the power curves around a pressure drop of about 0.55 bar can be observed in Figure 5. At null power, the pressure drop across the EC corresponds approximately to the gravitational head of the liquid column present in the RPV standpipe between the connections with the EC feed and return lines.

The characteristics shown in Figure 5 can serve to setup a simplified lumped parameter model of the EC. The pressure difference between inlet and outlet is corresponding to a unique value of the EC power for given primary and secondary side pressures, and secondary side fluid temperature. The use of the pressure difference is more appropriate than the use of the RPV water level as independent variable, because in the latter case the performance of the EC is then additionally influenced by the axial density profile in the RPV.

## 3.2 Quasi-stationary characterization

### 3.2.1 Design of a transient operation procedure

In order to characterize the behaviour of the emergency condenser for power levels above 24 MW, a transient operational procedure has been envisaged at PSI for the INKA test facility [9]. In the conditioning phase of the experimental procedure, it is proposed to pressurize the facility at high pressure (e.g. 88 bar), to fill the downcomer with water at saturation conditions, with level above the connection of the EC feed line. The valve between RPV and downcomer (valve V3 in Figure 3, left) is closed, and the RPV is filled at the desired level. The RPV is then isolated. The transient is initiated by opening valve V3. Alternatively, the valve V3 could be kept open in the conditioning phase, while keeping the valve in the EC return line close (EC valve in Figure 3, left). In this case, the transient would be initiated by opening the EC valve. Once the transient is started, the water level in the downcomer will adjust to the level in the RPV. This will leave part or all of the EC tubes uncovered, bringing the EC in operation, and leading therefore to heat transfer to the FPV and to the primary system depressurization.

The typical evolution of collapsed water levels in RPV and downcomer, EC power, and RPV pressure, are reported in Figure 6 and Figure 7. As soon as the connection between downcomer and RPV is open (at 3000s in Figure 6), the water levels in the two components stabilize around an "equilibrium" value which depends mainly on the initial water levels in the two components (a small effect is given by the degree of subcooling at the exit of the EC bundle). Consequently to the rapid uncover of the EC tubes, a sudden increase in the power transferred by the EC bundle to the FPV is registered (Figure 6, right). The exchange of power with the secondary side leads to a fast depressurization of the reactor pressure vessel, as illustrated in Figure 7 (left). Due to the continuous system depressurization, the power released to the FPV through the EC bundle decreases with time.

It is worthwhile noticing that the steam entering the EC feed line, initially at saturation conditions, might get superheated with the progression of the transient, as shown in Figure 7 (right). This is due to the release of the heat accumulated in the walls of the RPV during the depressurization. Especially in the upper part of the RPV, where the RPV walls are in contact with steam only, the wall temperature remains well above the saturation temperature (see Figure 7, right).

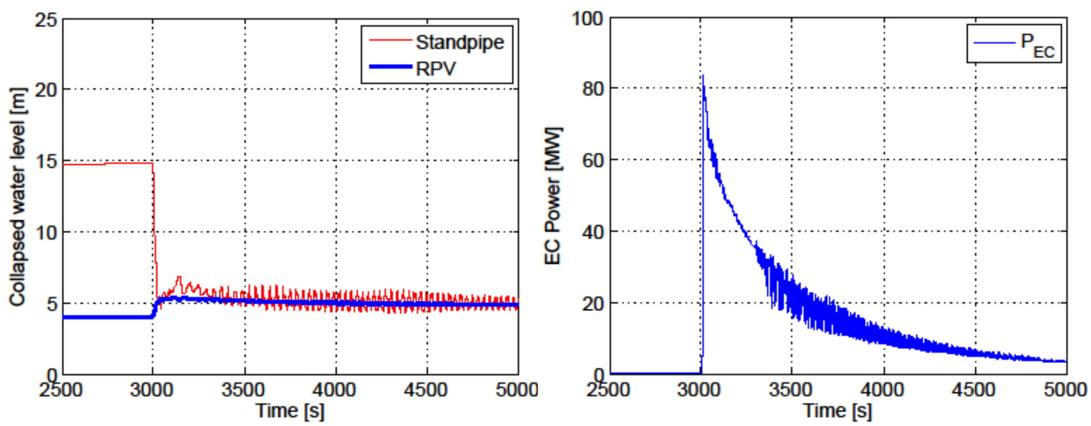


Figure 6 Collapsed water level in RPV and downcomer (left) and EC power (right), during the transient procedure. The transient is started by opening valve V3 after a conditioning phase of 3000s.

At the INKA facility, the EC power will be evaluated on the basis of the enthalpy change across the EC bundle. Therefore it is important to compare the different estimations of EC power as described in chapter 2.1, noticing that $P_{EC}$ is the correct estimator, while $P_S$ and $P_C$ are approximations. In the comparison reported in Figure 8, it is clear that estimating the experimental EC power on the basis of the mass flow-rate in the EC feed line should be the preferred solution. This in view of the strong fluctuations of liquid mass flow-rate in the EC return line, which are caused by the condensation process in the EC horizontal bundle.

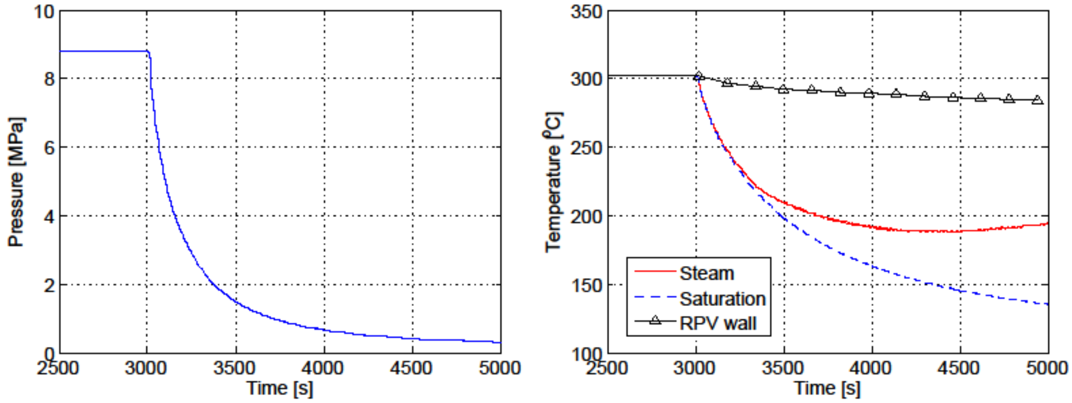


Figure 7 RPV pressure (left) and steam temperature in EC feed line vs saturation temperature and RPV wall temperature (right) during the transient procedure.

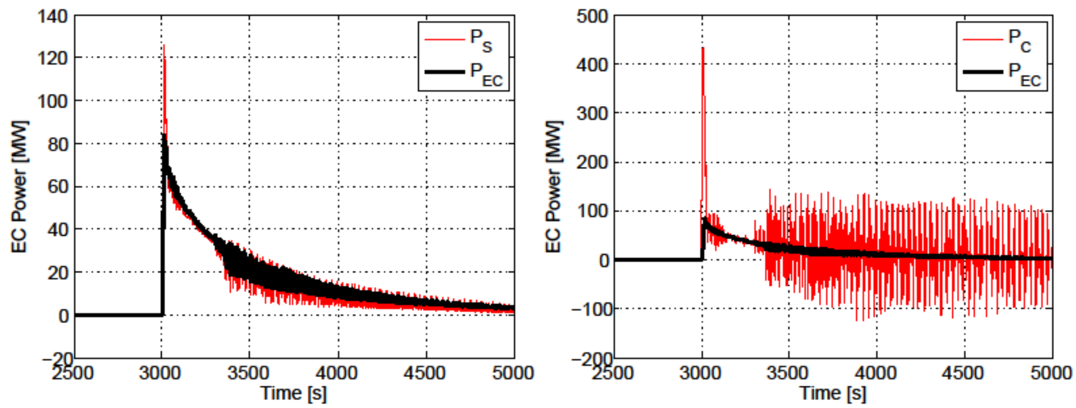


Figure 8 Comparison between the exact EC power estimator $P_{EC}$ and the approximate estimators based on the steam EC flow (left) and the condensate EC flow (right).

### 3.2.2 Data evaluation for the transient operation procedure

In order to estimate the quasi-stationary characteristics of the emergency condenser on the basis of the transient data, first the RPV pressures of interest have to be selected. Around those pressure, an averaging window is determined, having a certain pressure band (in the present work, a ± 1% amplitude is selected around 7.5 and 6.5 MPa, and ± 3% is selected around all other pressures; see Figure 9). For each interval [$p_i$-Δp; $p_i$+Δp], with $p_i$ the i-th pressure of interest, the corresponding time interval [$t_{i,in}$; $t_{i,end}$] of the transient can be identified. Within this time interval, the average value of each given quantity of relevance for the

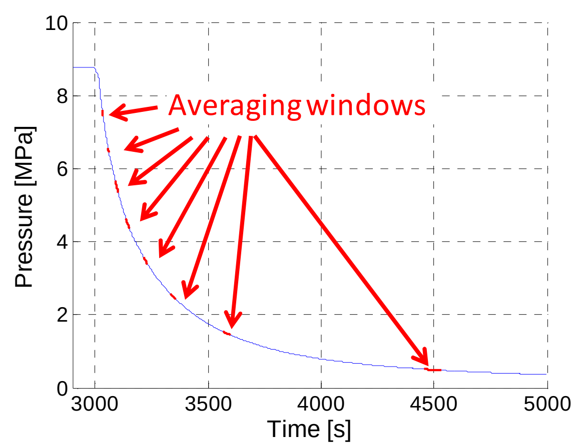


Figure 9 Selection of averaging windows around the pressures of interest. In red is the

quasi-steady state evaluation is performed.

extension of the averaging windows around the selected pressures.

The average value can be extracted by a simple averaging procedure within the time interval or by extracting the middle point of a linear fit of the data contained within the time interval. Both methods are identical, as long as a linear regression is used for fitting the experimental data.

### 3.2.3 Comparison with steady-state results

The transient procedure described in the previous chapter can be repeated for different collapsed water level in the RPV. By applying the averaging windows, as explained in chapter 3.2.2, the EC power can be characterized as function of a “quasi-stationary” operational condition. It has to be noted that the first few seconds during the transient procedure are needed to reach an equilibrium level in the RPV. In addition, in the initial phase of the transient the depressurization of the system is rather fast. As a consequence, the first part of the transient procedure is not suitable for the data evaluation. For this reason it is recommendable to start the transient from the highest possible primary pressure, so that the EC can be characterized over a widest pressure range.

In order to investigate the feasibility of the proposed transient procedure for a stationary characterization of the EC, in Figure 10 the results obtained with the transient procedure (Figure 10, circles) are presented together with the steady-state results already presented in 3.1 (Figure 10, lines). The bars indicate the standard deviation of the EC power fluctuations around the average value.

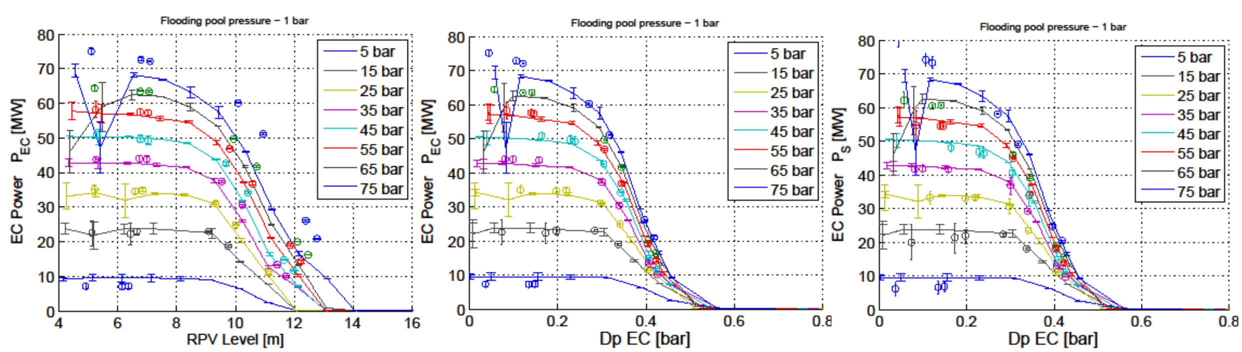


Figure 10 EC power as function of the pressure drop across the EC system, for different RPV pressures (5 to 75 bar), and a pressure in the FPV of 1 bar (left) and 3 bar (right) respectively.

It can be concluded that (a) the experimental procedure proposed in 3.2.1 is suitable for the determination of the quasi-steady-state characteristics of the emergency condenser; (b) in view of the initial transitory effect of the opening of the valve between RPV and downcomer and because of the large gradients (in time) of the averaged quantities (pressure, power, etc.), the higher deviations of the EC power estimated with the transient procedure with respect to the stationary values are found at the higher pressures; (c) a characterization of the EC power as function of the pressure drop across the EC system rather than the RPV water level is recommendable, as in this way it is possible to eliminate the influence of the axial temperature profiles in the RPV and in the downcomer. This is especially visible for high RPV water levels (i.e. low EC powers) for which a relative high subcooling at the exit of the EC bundle is observed, which leads to a large effect on the relative water level difference between RPV and downcomer. In this case, a large scatter in the EC power characteristic is observed (Figure 10, left). This scatter is practically eliminated when the pressure drop across the EC bundle is taken as independent variable (see Figure 10, center); (d) the approximate EC power estimator $P_S$ defined in chapter 2.1 can be employed for the evaluation of the EC power (see Figure 10, right), within the limit of the uncertainties of the experimental instrumentation.

In Figure 10 only the results obtained for a FPV pressure of 1 bar are shown. However, similar trends are observed in the entire range of FPV pressures investigated.

## 4. Comparison with experimental results

The transient experimental procedure described in chapter 3.2 was successfully applied by AREVA NP at the INKA test facility. Several tests were performed for different RPV collapsed water level, and different conditions in the FPV. In the following, one of such experimental tests is presented, together with the results of the corresponding RELAP5/mod3.3 simulation.

First, two tests were performed in single-phase conditions, aimed at measuring the pressure losses at the locations of the EC and V3 valves. In the first test (test 1), the EC valve was always open, and the V3 valve was open after completely filling the downcomer. The friction factor at the V3 location was adjusted in the RELAP5 nodalization in order to correctly reproduce the time-dependent rise of the RPV water level. A second test (test 2) was performed, where both the EC and the V3 valves were initially closed, with downcomer and EC bundle filled with water. At first the V3 valve is open, followed by the opening of the EC valve, once the RPV water level had reached equilibrium with the downcomer level. While the first rise of the RPV water level gives indication only on the friction losses of the V3 valve (and was therefore used only as a confirmation of the V3 loss adjusted on the basis of test 1), the second rise of the RPV water level is an indirect measure of the pressure loss introduced by the EC valve. The comparison between the experimental RPV water level and the RELAP5 results are presented in Figure 11 for test 1 (left) and test 2 (right) respectively.

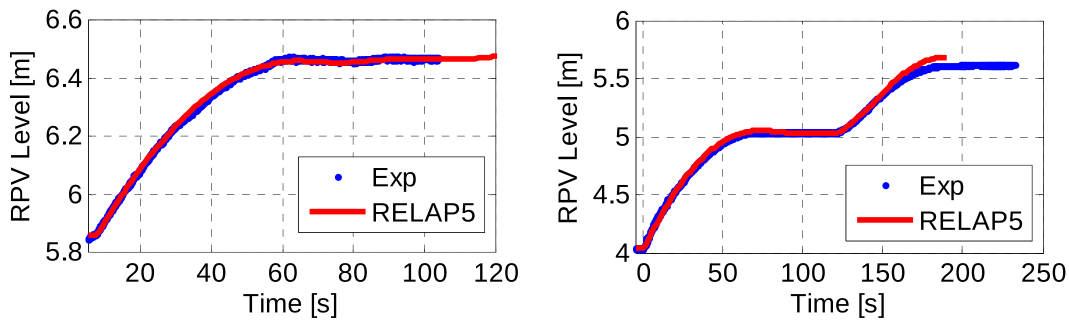


Figure 11 RELAP5 results vs experimental RPV water level

The friction factors at the locations of the EC and V3 valves are the only adjustments that have been made to the nodalization, before carrying out the post-test analyses for the INKA depressurization tests.

The depressurization test reported in the following is characterized by a conditioning phase in which the RPV is brought to a pressure of 85 bar, and the RPV water level is set to 7.55 m. The FPV is filled with water at 35 $^oC$ and is kept at atmospheric pressure. During the conditioning phase, the valve V3 (see Figure 3, left) is kept open and the EC valve is kept closed. The transient is initiated by opening the EC valve.

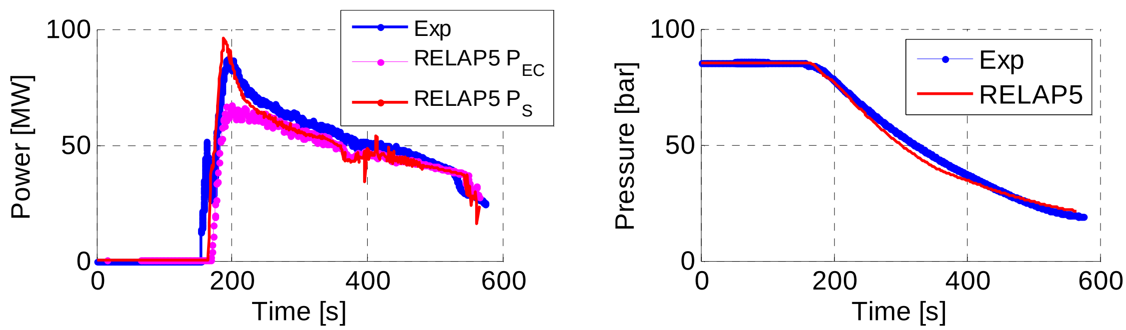


Figure 12 RELAP5 results vs experimental EC power (left) and RPV pressure (right)

Initially, the power exchanged by the EC to the secondary side (i.e. to the FPV) is null, since the bundle is completely filled with cold water, at the same temperature as the FPV water (35 $^oC$). As soon as the EC valve is open, the EC bundle remains partially uncovered and the EC power rises. This is clearly visible in Figure 12 (left) where the measured EC power is compared to the RELAP5/mod3.3 results. In the figure, both the RELAP5 $P_{EC}$ and $P_S$ estimators of the EC power are presented. Since the $P_S$ estimator is the one that can be directly compared to the measurements (the experimental EC power is measured based on the $P_S$ approximation), the good agreement with the experiment proves the high quality of the modelling. On the other hand, the comparison with the real EC power estimator $P_{EC}$ allows assessing the dynamic error of the balance method. A clear overestimation of the true EC power is observed especially in the first part of the transient, due to the energy accumulated by the heat-up of the structures. The corresponding RPV pressure decrease is shown in Figure 12 (right). In Figure 13 the comparison between experimental and RELAP5 results is presented for the EC feed line flow-rate (steam) and EC return line flow-rate (condensate).

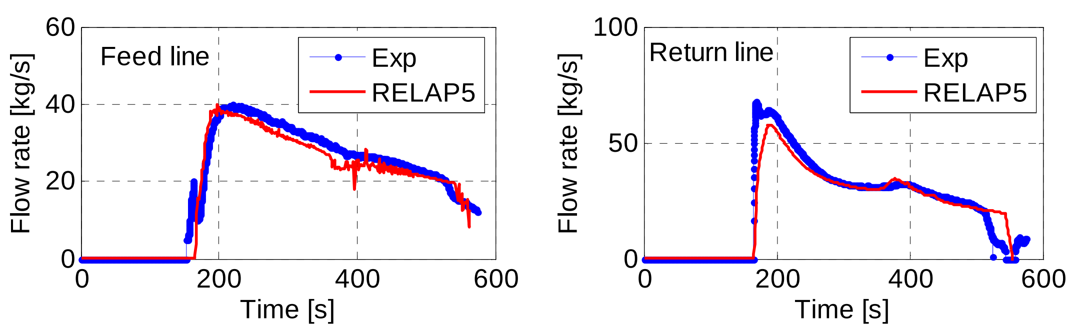


Figure 13 RELAP5 results compared to experimental flow-rates in EC feed line (left) and EC return line (right)

The prediction of the temperature in different location of the primary side is shown in Figure 14. Here, the measured temperatures are reported together with the values calculated by

RELAP5 and the corresponding saturation temperature. The thermocouple locations T1 to T7 are indicated in Figure 3 (right).

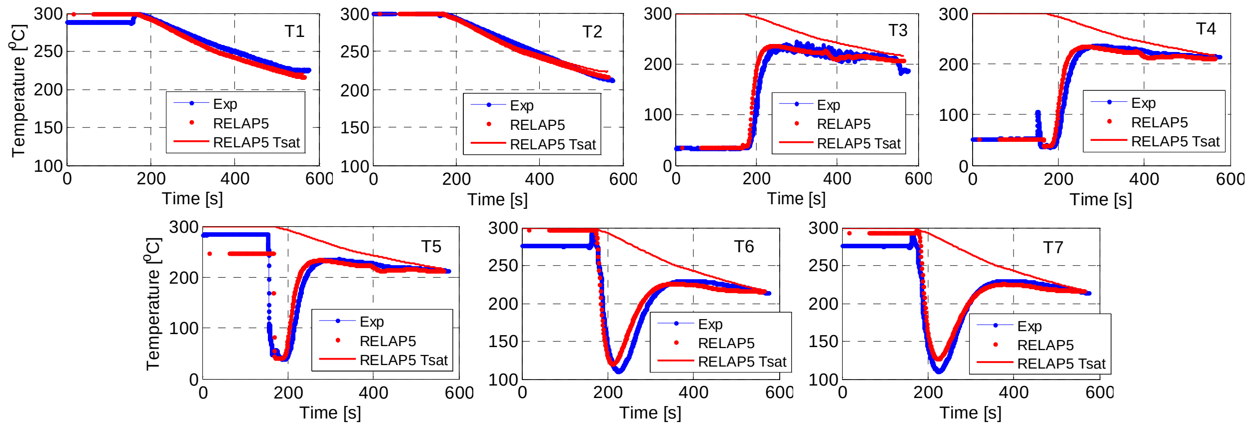


Figure 14 RELAP5 results compared to experimental temperature measured in the location T1 to T7 indicated in Figure 3.

The initial temperature values, before the EC valve is open and the following depressurization process is started, depends on the way the conditioning phase of the experimental test is carried out at the INKA facility. Therefore, some discrepancies between the experimental and RELAP5 temperature distributions might exist because of the difference between experimental conditioning phase and initialization of the RELAP5 model. Overall, the depressurization transient is well captured by the RELAP5 model for the entire transient duration, indicating that the code can be used for the investigation of the EC behaviour and the estimation of the EC power.

## 5. Conclusions

With the aim of investigating the behaviour of the KERENA emergency condenser and support the establishment of a test matrix for the INKA experimental facility, a RELAP5 nodalization has been developed at PSI, which includes all necessary components of the INKA facility. The RELAP5/mod3.3 pre-test simulations have shown that in stationary conditions the emergency condenser can reach powers up to about 70 MW at the nominal pressure of 70 bar, when the FPV is kept at atmospheric pressure and filled with water at saturation conditions. The power that can be transferred to the secondary side through the emergency condenser is strongly dependent on the primary pressure and on the water level in the RPV. As expected, the power decreases with increasing secondary pressures.

A transient experimental procedure has been proposed, in order to investigate the performances of the emergency condenser over a wide range of operational conditions. This was necessary because, due to the power limitation of maximum 24 MW of the Benson boiler, which supplies steam to the RPV, only a limited region of the operational range of the emergency condenser can be investigated at the INKA test facility in stationary conditions. The transient experimental procedure designed and tested at PSI with the help of RELAP5 pre-test simulations, was successfully employed by AREVA NP at the INKA facility. The comparison between experimental results and post-test RELAP5 simulations indicate that RELAP5/mod3.3 is able to correctly capture all important phenomena occurring in the EC over a wide range of pressures, and to qualitatively as well as quantitatively reproduce the heat transfer from EC to the containment pool (FPV), and the accompanying depressurization transient of the primary side. Further investigations and validation efforts should be dedicated to the lower pressure ranges.

## 6. Acknowledgements

The authors would like to acknowledge the INKA experimental team for performing the experiments reported in the present work.

## 7. References

[1] IAEA, "Passive Safety Systems and Natural Circulation in Water Cooled Nuclear Power Plants", IAEA-TECDOC-1624, 2009.

[2] J.M. Bermejo, G. Van Goethem, "EC-sponsored research activities on innovative passive safety systems," *Nuclear Engineering and Design*, 201, 2000, pp. 25-40.

[3] P.E. Juhn, J. Kupitz, J. Cleveland, B. Cho, R.B. Lyon, "IAEA activities on passive safety systems and overview of international development," *Nuclear Engineering and Design*, 201, 2000, pp. 41-59.

[4] Z.V. Stosic, W. Brettschuh, U. Stoll, "Boiling water reactor with innovative safety concept: the generation-III+ SWR-1000," *Nuclear Engineering and Design*, 238, 2008, pp. 1863-1901.

[5] S. Leyer, F. Maisberger, B. Schaub, W. Brettschuh, M. Doll, M. Wich, H. Schäfer, "Full scale steady state component tests of the SWR1000 fuel pool cooler at the INKA test facility", Proceedings of the 2009 Int. Conf. on Advances in Nuclear Power Plants (ICAPP'09), Tokyo, Japan, 2009 May 10-14.

[6] S. Leyer, F. Maisberger, B. Schaub, W. Brettschuh, M. Doll, M. Wich, H. Schäfer, "Full scale quasi steady state component tests of the SWR1000 emergency condenser at the INKA test facility", Proceedings of the 2009 Int. Conf. on Advances in Nuclear Power Plants (ICAPP'09), Tokyo, Japan, 2009 May 10-14.

[7] A. Manera, H.-M. Prasser, "Pre-test calculations for the determination of a test matrix at the INKA experimental facility for the emergency condenser of the SWR1000", PSI Technical Report, TM-41-09-23 (SB-XTK-ACT-003-08.001), 2010.

[8] I.E. Idelchik, "Handbook of hydraulic resistance, 3rd edition", Begell House Inc., New York, 1996.

[9] A. Manera, H.-M. Prasser, "Design of a transient experimental procedure for the SWR1000 Emergency Condenser tests at the INKA facility", PSI Technical Report, TM-41-09-26 (SB-XTK-ACT-003-08.002), 2010.