Large Scale BWR Containment LOCA Response Test at the INKA Test Facility

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ABSTRACT

KERENA is an innovative boiling water reactor concept with passive safety systems (Generation III+) of AREVA. The reactor is an evolutionary design of operating BWRs (Generation II). In order to verify the functionality and performance of the KERENA safety concept required for the transient and accident management, the test facility “Integral Teststand Karlstein” (INKA) was built in Karlstein (Germany). It is a mock-up of the KERENA boiling water reactor containment, with integrated pressure suppression system. The complete chain of passive safety components is available.
The passive components and the levels are represented in full scale. Only one of the four passive trains of KERENA is installed in the INKA test facility. The volume scaling of the containment compartments is approximately 1:24. This results in an effective volume scaling related to the passive systems of 1:6. The reactor pressure vessel (RPV) is simulated via the steam accumulator vessel of the Karlstein Large Valve Test Facility. This vessel provides an energy storage capacity of approximately 1/6 of the KERENA RPV and is supplied by a Benson boiler with a thermal power of 22 MW. With respect to the available power supply, the containment- and system-sizing the facility is one of the largest test facilities for passive integral system testing ever operated.
From 2009 to 2012, single component tests of the passive systems Emergency Condenser, Containment Cooling Condenser, Core Flooding System were conducted. On March 21st, 2013, the first large-scale only passively managed integral accident test of a boiling water reactor was simulated at INKA. The integral test measured the combined response of the KERENA passive safety systems to the postulated initiating event: “Main Steam Line Break” (MSLB) inside the Containment with decay heat simulation. The decay heat was simulated by simultaneous steam introduction and liquid water removal from the pressure vessel.
The results of the performed integral test (MSLB) showed that the passive safety systems alone are capable to bring the plant to stable conditions meeting all required safety targets with sufficient margins. Therefore the test verified the function of those components and the interplay between them as response to an anticipated accident scenario.
The test provided evidence that the INKA test facility is capable to perform integral system verification tests of passive safety concepts under plant-relevant scaling and plant-like thermodynamic conditions, including the feedback of the accident to the pressure vessel.
Being equipped with a state of the art pressure suppression containment INKA is capable to perform also containment response tests for Generation II BWRs. Those test results could be used to validate containment response calculation for various LOCA and non- LOCA scenarios. The test could tackle the

heat intake and temperature distribution that establishes in the gas and water volume of multi compartment containment or the re-distribution/relocation of non- condensable gases depending on the momentum of the LOCA coolant jet introduced into the containment.

KEYWORDS
Passive Systems, Experimental Validation, BWR, Accident Simulation

1. INTRODUCTION

KERENA is a medium-capacity boiling water reactor developed by AREVA GmbH in cooperation with E.on Kernkraft GmbH. It combines innovative passive systems with active systems of service-proven design. The passive systems utilize basic physical laws, such as gravity, pressure differences or heat transfer enabling these systems to function without electrical power supply or actuation by powered instruments and control (I&C) systems. They are designed to transfer the plant to a safe and stable state without the help of active systems. Furthermore the passive safety features partially replace the active systems which leads to a significant cost reduction and provides a reliable, safe and economically competitive plant design [1].

The key elements of the KERENA passive safety features are the Emergency Condenser (EC), the Containment Cooling Condenser (CCC) and the passive core flooding system. For the experimental validation of the functionality of these systems AREVA has carried out a test program at the test facility INKA [2] (INKA: Integral Test Facility Karlstein). The test set-up allows testing of the single components individually to determine the performance characteristics of the systems. The tests were carried out in a full scale set-up, in terms of the components size, levels and piping systems - 1 by 1 realization compared to the KERENA design. The results of the tests have been published in several papers.

Furthermore INKA is capable to perform integral system tests simulating accident scenarios under plant like thermodynamic conditions. The pressure vessel of the test facility is represented by the steam accumulator vessel of the Karlstein Large Valve test facility (named GAP). This vessel is designed for operating pressures up to 160 bar and is fed by a Benson boiler with a maximum power output of 22 MW. It has a storage capacity of roughly 1/6 of the KERENA Reactor Pressure Vessel (RPV). Having one out four passive system trains installed in the INKA test facility the effective containment volume scaling related to the components is also 1:6. The INKA test facility consists of three large scaled vessels representing the compartments of the KERENA containment as well as a large water volume representing the SSP (called Shielding Storage Pool), located above the containment. The SSP represent the heat sink for passive accident handling. The volumes are scaled down by a factor of 1/24, while the real plant height level differences are realized.

The energy storage capacity of the pressure vessel as well as the test facility infrastructure in terms of power and water supply allows to perform experimental accident simulation starting from the initial conditions that correspond to BWR plant like conditions (p_{RPV}=75 bar, T_{satt}=292°C). Therefore no pre-conditioning of the test facility is required and the accident scenario can freely develop with time. The time limitation for test execution is determined by the fresh water supply. The available resources allow accidents simulation with a duration up to three days.

The goals of the tests is to determine the interaction of the systems as well as the response of the safety features including the pressure suppression containment to the accident scenario. Thus the ability of the passive safety systems to achieve all safety goals shall be demonstrated. The test data provide a solid basis for the validation of numerical tools used for accident analysis.

The paper is divided into three parts. Section 2 describes the philosophy of the tests. Section 3 gives an overview of the test set-up and the instrumentation concept. Section 4 explains the test performance and shows the test results.

2. Goals of the test program

The philosophy of the INKA test program is a combination of full scale single component and the integral system testing to provide an appropriate data base for the validation of numerical tools used for accident analysis. The designers of passive systems are challenged by the small driving force passive systems rely on and by the strong link between heat transfer and mass flow, as far as heat removal systems are concerned. Furthermore state of the art models (e.g. for heat transfer) are not necessarily applicable to passively driven systems due to low driving forces or the wide thermodynamic operational parameter range. Therefore a full scale component size and 1:1– level- scaling set-up was chosen for the tests. Mismatches between computed and experimental data for passive systems have already been identified in the cause of previous experimental campaigns. An example is the validation performed on the basis of the Emergency Condenser single component tests [3]. The low pressure heat transfer system Containment Cooling Condenser is subject to instabilities depending on the operation parameters. The prediction capabilities of numerical codes in this field is still limited [4]. To improve the simulation capabilities dedicated test programs associated to the INKA program have been performed. An example is the program "Condensation in a Horizontal Heat Exchanger tube" addressing the improvement of heat transfer modelling for passive driven heat transfer systems. The project is carried out in the frame of a consortium between AREVA GmbH, ETH Zürich and the HZDR [5]. Furthermore the GENEVA Project dealt with the stabilization of low pressure 2-phase flow heat transfer systems. This project was executed at the Technische Universität Dresden in Cooperation with E.ON Kernkraft GmbH, HZDR and AREVA GmbH [6].

Passive Systems heavily interact and influence each other during the various anticipated accident scenarios. For example the gravity driven injection is a function of the containment pressure and therefore depends on the performance of the Containment Cooling Condensers. This is only one example that motivates the performance of integral system tests including all relevant passive safety systems – passive residual heat removal and depressurization systems as well as passive RPV replenishing system. INKA is equipped with a complete train of those systems taken from the KERENA design. INKA allows simulating all anticipated design basis accidents – Loss-Of-Coolant-Accidents and non-LOCA – for real plant like thermodynamic conditions.

This paper deals with the first performed accident simulation on the INKA test rig. The chosen scenario was the rupture of a main steam line.

Due to the fact, that only passive systems are involved the only active measures during the test execution were the initiation of the leak mass flow and the simulation of the decay heat in the pressure vessel via steam supply by the Benson boiler system. The accident simulation was started from normal BWR conditions (pressure of 75 bar and temperature of 292°C in the pressure vessel).

3. Test set-up

INKA was erected at Karlstein, Germany, in 2008. Figure 1 shows pictures of the test facility taken from two different views. A detailed description of the test facility is given in [2].

Figure 1: View on INKA from west (left) and east (right).

INKA simulates the KERENA containment in a volume scaling of 1:24. Figure 2 shows a comparison between the KERENA containment and the INKA test facility.

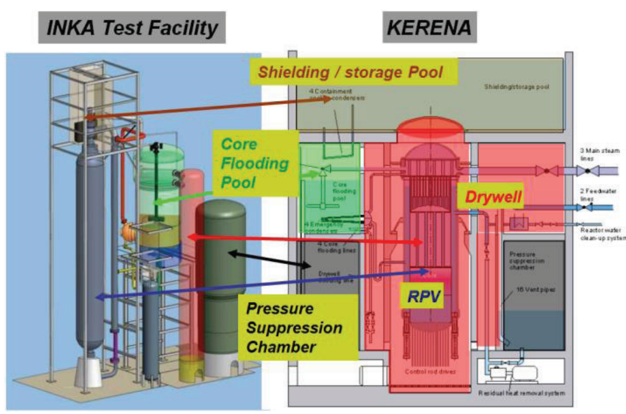

Figure 2: Comparison between the KERENA Containment and the INKA test facility.

The Flooding Pool Vessel (FPV, green) simulates the four KERENA Flooding Pools containing the passive safety systems. The residual gas volume of the drywell is represented by the drywell vessel (DWV, red). Two pipes connect the FPV with the DWV to represent the connections between the gas filled headspaces of these compartments. The wetwell function is provided by the Pressure Suppression Pool Vessel (PSPV, black).
The RPV is simulated by the steam accumulator vessel of the Large Valve Test Facility GAP (GAP: Großarmaturen Prüfstand). It has a storage volume of 125 m^3 and is fed by a Benson boiler with a maximum power supply of 22 MW. All components

- the Emergency Condenser, EC,
- the Containment Cooling Condenser, CCC,
- the Passive Core Flooding System

as well as the level differences that dominate the function of the passive components are realized like in the real plant (1:1). For the integral test all components and vessels are operated.

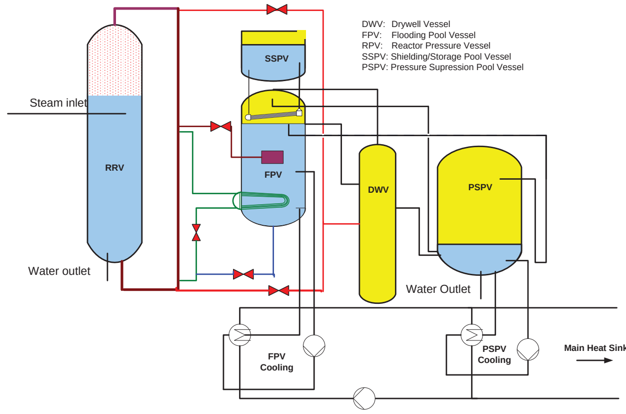

Figure 3: Simplified process diagram.

Figure 3 shows the main piping systems of INKA. The FPV is connected to the PSPV via the overflow pipe limiting the FPV water level. A 10 m deep siphon in the pipe serves as PSPV vacuum breaker, limiting the PSPV overpressure to approximately 1 bar. A second connection is the hydrogen overflow pipe used for pressure limitation necessary for KERNA severe accident mitigation strategy. The third connection is the Passive Core Flooding Line which connects the FPV water inventory with the EC return line. The DWV and the PSPV are connected via a full scale vent pipe providing the containment pressure suppression functionality. Additionally, the function of the Safety and Relief valve is included in the design, discharging steam form the pressure vessel into the water inventory of the FPV. For LOCA test scenarios two different lines connect the RPV with the DWV - one for the simulation of breaks of a water line, the other for breaks of a steam line (red lines). This setup provides a realistic simulation of the jet injection of the coolant into the containment. The break size scaling can be adapted via throttling the leak mass flow.

3.1. Instrumentation

There are more than 300 sensors available at INKA. Most of them are standard instrumentation like temperature, mass flow, pressure and differential pressure sensors.
Additionally, 2-phase flow instrumentation (Thermo Pin Probes and Gamma densitometer) developed in cooperation with Helmholtz Zentrum Dresden-Rossendorf (HZDR) are installed. The Thermo- Pin Probes allow to follow the depletion of the Emergency Condenser heat exchanger tubes. This parameter triggers and determines the performance of the system and depends on the water level in the pressure vessel. The Gamma- Densitometer is an integral void measurement device that allows to determine the void fraction downstream the Emergency Condenser as well as the Containment Colling Condenser.
The gas mixture in the vessels is measured by a mass spectrometer with a probe sampling system (Cooperation with Paul Scherrer Institut in Switzerland).
The system is used to determine the gas composition in the INKA vessels. In the FPV the goal is to determine the buildup and erosion of gas layers and their influence to the performance of the Containment Colling Condenser. In the DWV and the PSPV the gas composition is measured at different levels on the vessel axis.

Figure 4 gives an overview of the sensors installed at the INKA test facility. The FPV has the largest sensor density due to the fact that this vessel contains the passive systems EC and CCC. Basically, in all vessels the water levels, the pressures and the temperatures in the water and gas volumes (spatially resolved) are measured.
In the main pipes the temperature and pressure profiles as well as mass flows are measured (CF).

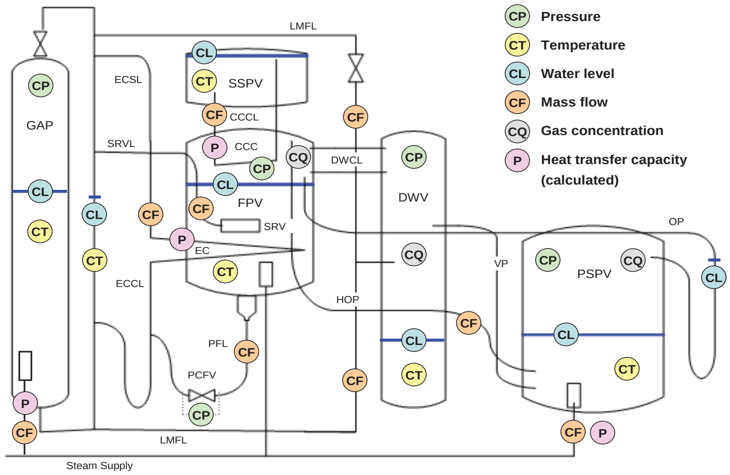

Figure 4: Simplified P&ID of INKA.

During the tests, selected global parameters (like e. g. EC power, mass flow, water level or decay heat simulation) can be observed online (Figure 5).

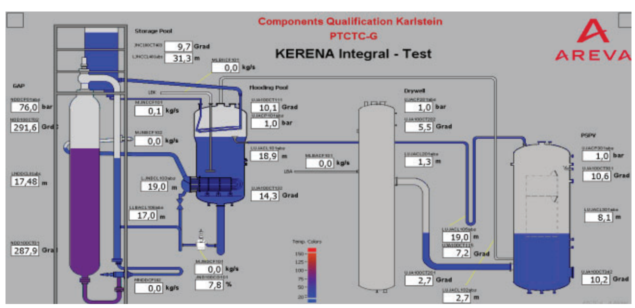

Figure 5: Online P&ID, showing real-time test data (INKA control room view).

4. Test performance and results

4.1. Test performance

Initially the vessels were filled with cold demineralized water produced by the water treatment plant of the Karlstein facility.
The Flooding Pool Vessel (FPV), the Pressure Suppression Pool Vessel (PSPV) and the Shielding/Storage Pool Vessel (SSPV) were filled to the dedicated water levels. The Drywell Vessel is initially only filled with gas (Air instead of N_2). The GAP vessel, simulating the RPV, was filled with water, too, but additionally heated up to the RPV conditions of 76 bar, saturation condition (see also Figure 6). The heat-up was performed by injecting steam from the steam generator into the RPV simulator.
At INKA, downstream of the EC an isolation valve is installed to “deactivate” the EC. This valve is installed in the INKA test facility to run the single component tests. KERNEA is not equipped with such a valve. There the Emergency Condenser is trigger by the RPV water level.

This valve was closed during heat-up of the primary system and opened shortly before the start of the test. When the levels where balanced, the integral test was started by opening the LOCA-simulation line. Then, the test facility was left to its own devices.

Simulation of decay heat:
The injection of steam into the RPV continued in order to simulate decay heat. Since this form of heat intake is linked to a mass injection, the corresponding water inventory was released simultaneously.

4.2. Test results

Figure 6 shows the pressures in the pressure vessel and the compartment of the INKA containment as function of time.

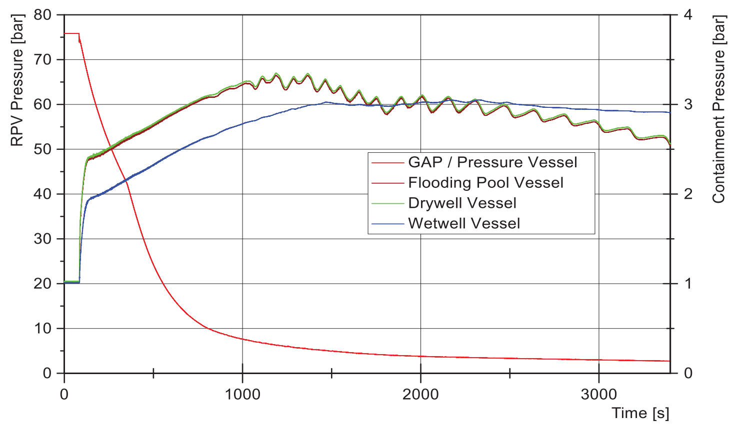

Figure 6: Pressures as function of time.

The test execution is started by opening the valve in the leak mass flow line initiating the coolant discharge from the pressure vessel into the Drywell. This causes a drop of the pressure vessel water level so that the Emergency Condenser heat exchanger tube are depleted starting the system operation with a delay of approximately 300 s (see figure 7). The pressure vessel coolant loss combined with the Emergency Condenser heat transfer results in a decreasing pressure vessel pressure (red line, figure 6). On the other hand the introduced steam causes a pressure increase of the containment pressure (FPV: green and black line; PSPV: blue line). The initial pressure difference between the drywell- and wetwell pressures reflect the vent pipes being submerged approximately 3 meters into the wetwell water inventory. In the course of the accident progression the non-condensable gas inventory initially stored in the drywell is washed over into the drywell. Therefore the wetwell pressure exceeds the drywell pressure in the long term range of the accident (after approximately 2000 s, see figure 6).
At approx. 1250 seconds the containment pressure (green and black line) reached its maximum value of approx. 3.3 bar. Therefore sufficient margin with respect to the design pressure of 4 bar are available.

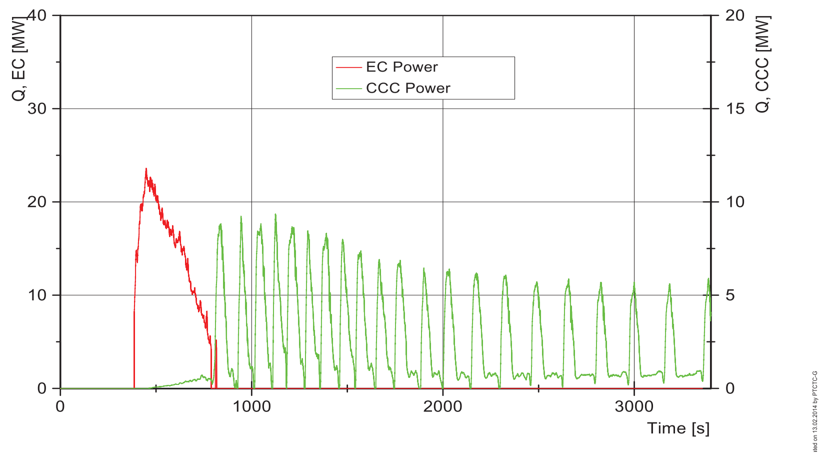

Figure 7: EC and CCC heat transfer capacity as function of time.

Figure 7 show the Containment Cooling Condenser operation as function of time. The start of the system operation is triggered by the temperature in the containment and is the therefore correlated to the containment pressure. The oscillating mass flow is typical for low pressure heat transfer systems using phase transition. The phenomena was already been identified in previous measuring campaigns [4, 7]. The effect of the non-stationary operation is reflected by the oscillation of the containment pressure (see figure 6). Nevertheless the energy storage capacity represented by the containment volume damps the effect. Approximately 800 s after the initiation of the test the major part of the pressure vessel system energy has been transferred to the containment via the leak mass flow and the Emergency Condenser performance. In the subsequent phase of the accident scenario the pressure- and temperature difference between the pressure vessel and the containment are small, so that e.g. the Emergency Condenser heat transfer rate decreases below the measuring tolerance. Heat is essentially transferred via the leak mass flow.

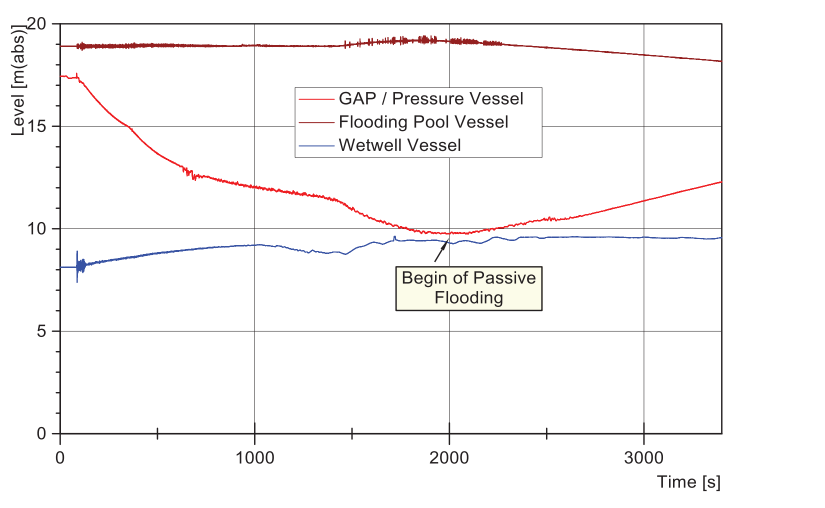

Figure 8: Water levels.

Figure 8 shows the water levels in the RPV, the FPV and the wetwell. Due to the leak flow, and also due to the operation of the EC the water level in the pressure vessel decreased. After approximately 1500 s the

pressure vessel water level drops below the set point “low water level” initiating the opening of the Safety & Relief Valves, so that a further mass- and energy transfer connection between the pressure vessel and the containment is established. Therefore the pressure reduction is accelerated.
The pressure balancing process activates the passive core flooding valve providing a hydraulic connection between the pressure vessel and the water inventory of the core flooding pools. As a result the gravity driven replenishing of the pressure vessel starts roughly after 2000 s, increasing the water level in the pressure vessel and decreasing the water level in the flooding pool. The performance of the Passive Core Flooding System was validated already in previous single component test campaigns [6]. The water level increase in the PSPV (wetwell) was caused by the injection of steam from the drywell via the vent pipe.

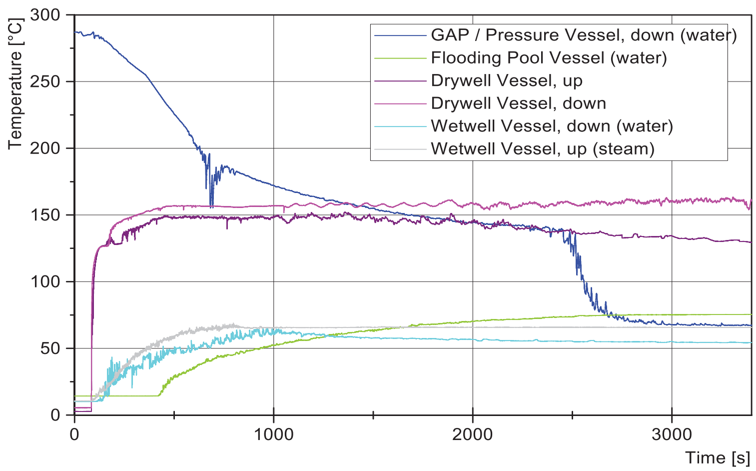

Figure 9: Temperatures in different compartments.

Figure 9 shows the liquid and steam/gas temperatures as function of time in different compartments. Until 2500 s after the initiation of the test the gas temperature in the pressure vessel is correlated to the vessel pressure, so that saturation conditions can be presumed. Driven by the injection of cold water from the flooding pools (passive core flooding) the liquid inventory becomes rapidly subcooled.
At the same time the water temperature inside the FPV rises due to the EC heat transfer.
The pressure increase inside the DWV and in the FPV is caused by the steam discharge form the pressure vessel into the containment via the leak and later during the test also via the Safety and Relief Valve line. The temperature difference between the DWV vessel top and bottom may be driven by differences of the steam Air gas compositions that establishes. After the pressure difference between drywell and wetwell reaches approximately 0.3 bar the vent pipe is activated, so that a steam-gas mixture is discharged into the wetwell. The wetwell gas temperature rises earlier than the temperature of the water inventory, which is heated up by the steam condensation. Considering the gas volumes of the vessel and the wetwell pressure increase it can be estimated that roughly 99 % of the non-condensable gases located initially in the FPV and the DWV are discharged into the wetwell during the blow down.
The pressure oscillations indicated in the pressure curves can also be seen in the temperature curve of the Drywell Vessel.

4.3. Interpretation of the test results

The initiation of the accident simulation by opening the leak mass flow line and the EC caused a response of the passive safety systems. The coolant discharged into the containment activated the containment pressure suppression system so that a steam and air mixture is injected into the wetwell. The forced steam condensation limits the containment pressure to a value sufficiently lower than the containment design pressure. Furthermore the discharged coolant caused a reduction of the pressure vessel water level

activating the EC so that a further energy transfer path between the pressure vessel and the containment is opened transferring heat without additional coolant loss. After reaching a low water level in the RPV the Safety & Relieve Valve is activated, opening a further mass- and energy transfer path, supporting the pressure relief process. As soon as the required pressure difference is reached the valve in the passive core system opens, so that the pressure vessel replenishing process is started. As a consequence the water level is increased so that long-term core cooling is ensured. In the long term phase of the accident the residual heat is transferred to the main heat sink pool outside of the containment via the Containment Colling Condenser.
The experimental results prove the appropriate passive systems response so that all safety design goals are achieved – core cooling, containment pressure suppression and residual heat removal – with sufficient safety margins.
The test results are being used to perform a validation of the numerical code systems used for the KERENA accident simulation. The currently achieved status is summarized in [9]. Nevertheless deviations between experimental and calculation data in terms of the passive system performance have been observed. Further research effort is required to overcome these deviations. In addition to the passive systems issues the complex containment configuration of modern BWRs challenge the predictability of the response of the pressure suppression systems. This issue can partially be resolved by adapting the nodalization. Nevertheless a further assessment of this issue is recommended.

5. Conclusion

The test results showed the response of the KERENA passive safety systems to the experimentally simulated accident scenario "Main Steam Line Break inside the Containment". The results confirmed the functionality of the passive systems experimentally derived from earlier single component testing. Furthermore, the interaction among the systems and the pressure suppression containment as well as feed back to the pressure vessel was demonstrated. During the experimental accident progression the design criteria of the test facility and thus also of KERENA were met, so that all safety goals were achieved with sufficient margins. The test therefore proves the capability of the passive safety concepts for the accident handling of Boiling Water Reactors.
Further experimental activities also on other accident scenarios like

- RPV bottom head leak,
- feed water line break inside the containment or
- station black-out

will be performed including validation of numerical codes. The test and validation results will be used for the qualification of components and for licensing requirements issues for existing (operating) BWRs.

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