Passive BWR Integral LOCA Testing at the Karlstein Test Facility INKA

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I. 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 [Ref. 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 [Ref. 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, meaning that all components, levels and piping systems are available at the test facility in a 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 conditions. The pressure vessel of the test facility is represented by the steam accumulator of the Karlstein Large Valve test facility 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). The INKA test facility consists of 3 large scaled vessels representing the compartments of the KERENA containment as well as a large water volume representing the SSP (called Shielding Storage Pool). The volumes are scaled down by a factor of 1/24, while the real plant height level differences are realized. The test facility infrastructure allows running accident scenarios. Starting from initial conditions derived from Boiling Water Reactor (BWR) operation conditions (e.g. RPV pressures of 70 bar and saturation conditions) therefore no further test preconditioning based on numerical calculation results is necessary.

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

II. Goals of the test program

The philosophy of the INKA test program is a combination of full scale component testing and 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 fast 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. Therefore a full scale system set-up was chosen for the tests. Consequently mismatches between the experimentally determined data and the numerical calculation results have been identified [Ref. 3]. Especially for the low pressure heat transfer system CCC, unstable operation conditions have been observed that are predictable by numerical code systems only to a limited extents [Ref. 4]. Therefore test programs were launched to overcome the modelling deficits. The R&D program “Condensation in a Horizontal Heat Exchanger tube addresses the heat transfer modelling of passively driven heat transfer system. The project is carried out in the frame of a consortium between Areva GmbH, ETH Zürich and the HZDR (Helmholtz Zentrum Dresden-Rossendorf). Furthermore the GENEVA Project deals with the stabilization of low pressure 2-phase flow systems. This project is executed at the Technische Universität Dresden in Cooperation with E.ON Kernkraft GmbH, HZDR and Areva GmbH.

Passive systems interact and influence each other in their performance. E.g. the gravity driven injection is a function of the containment pressure and therefore depends on the performance of the Containment Cooling Condensers. This example demonstrates the necessity to perform integral system tests including all relevant passive safety systems – passive residual heat removal and depressurization systems as well as passive core flooding. 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 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).

III. Test set-up

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

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.

The Flooding Pool Vessel (FPV, green) simulates the 4 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 m³ 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 Valve • as well as the level differences that are important for the function of the passive components are realized like in the real plant.

For the integral test all components and vessels are operated.

Figure 3 shows the piping between the vessels. The FPV is connected to the PSPV via the overflow pipe limiting the FPV water level. A second connection is the hydrogen overflow pipe used for pressure limitation during severe accident mitigation at KERENA. The third connection is the Passive Core Flooding Line with the Passive Core Flooding Valve which connects the FPV with the EC return line. The DWV and the PSPV are connected via a full scale vent pipe. Additionally, the function of the Safety and Relief valve is included in the design, discharging steam from the pressure vessel into the water inventory of the FPV. For LOCA test scenarios 2 different lines enter the DWV – one for the simulation of breaks of a water line, the other for breaks of a steam line (red lines).

III.A. 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 HZDR are installed.

The gas mixture in the vessels is measured by a mass spectrometer with a probe sampling system (Cooperation with Paul Scherrer Institut in Switzerland).

Figure 4 gives an overview of the sensors installed at the INKA test facility. The FPV has the highest sensor density due to the fact that this vessel contains the passive systems EC and CCC.

Basically, in all vessels the pressures, the temperatures in the water and gas volumes and the water levels are measured. In the main pipings (break line, EC inlet line, S+R line etc.) the mass flows are measured (CF).

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

IV. Test performance and results

IV.A. Test performance

Initially the vessels were filled with cold demineralized water produced by the
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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 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 heating-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 only present at INKA due to the fact that the EC was designed for 66 MW and the Karlstein infrastructure “only” provides 22 MW. This valve was closed during the heating-up of the primary system and opened shortly before the start of the test.

When the levels were 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 not only heat was injected, but also mass, this mass had to be released. In the bottom of the RPV-simulator a valve was controlled in order to release the mass which was added by the steam injection.

IV.B. Test results
Figure 6 shows the pressures in the pressure vessel and the compartment of the INKA containment as function of time. The RPV pressure (red line) decreased due to the opening of the LOCA-simulation line. At the same time the Drywell (green line) and Flooding Pool (black line) pressures increased rapidly. The wetwell pressure followed simultaneously, but lower due to the water level covering the outlet of the vent pipe in the PSPV.

At approx. 1,250 seconds the containment pressure (green and black line) reached its maximum value of approx. 3.3 bar, which is significantly lower than the design pressure of 4 bar. Shortly before, the CCC started its operation.

The CCC is operating with an oscillating mass flow which is typical for low pressure systems (see Figure 7), that was already determined within the CCC single component test campaign [Ref. 4 and 5]. The oscillations in the heat transfer are also recognized in minor containment pressure oscillations. The EC starts triggered by the decreasing water level. Its heat transfer supports the depressurization of the pressure vessel. After approximately 800 seconds...
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the major part of the residual heat removal is done via the leak mass flow and the mass flow through the Safety and Relief valve line. Therefore the EC heat transfer capacity is below the measuring tolerance.

Figure 8 shows the water levels in the RPV, the FPV and the wetwell. Due to the break flow, the mass flow through the Safety and Relief Valve and also due to the operation of the EC the water level in the Pressure Vessel decreased. This level increased again when the passive flooding started (at approx. 2,000 seconds). Until the beginning of the passive core flooding, the water level in the Flooding Pool Vessel is kept constant by the overflow pipe. After 2,000 seconds the water level decreases caused by the gravity driven replenishing of the pressure vessel [Ref. 6]. The water level in the PSPV (wetwell) increased by the injection of steam from the drywell via the vent pipe.

Figure 9 shows the gas temperatures as function of time in different compartments. The gas temperature in the pressure vessel follows the pressure in the vessel until 2,500 s after the initiation of the test, so that permanently saturation conditions are given. As mentioned above, the flooding started at around 2,000 seconds, thus the temperature curve of the water inventory of the RPV recognized a rapidly decreasing temperature at around 2,500 seconds.

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 gas volume of the FPV is caused by the steam from the leak injection and later on also from the Safety and Relief Valve. 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 readings of the Drywell Vessel.

IV.C. Interpretation of the test results

The initiation of the accident simulation by opening the break mass flow line and the EC closure valve caused a response of the passive safety systems. The coolant discharged into the containment activated
the containment pressure suppression system so that steam and air is injected into the wetwell. The forced steam condensation limits the containment pressure to a value sufficiently lower than the design value. 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 and Relief Valve is opened, this 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 increasing the water level again and ensuring long-term core cooling. In the long term phase of the accident the residual heat is transferred to the main heat sink pool outside of the containment.

The experimental results prove that the passive systems perform well in their interaction and achieve all design goals – core cooling, containment pressure suppression and residual heat removal – with sufficient safety margins.

The test results were used to perform a validation of the numerical code systems used for the KERENA accident simulation. The currently achieved status is summarized in [Ref. 7]. Nevertheless deviations between experimental and calculation results have been observed, especially concerning the performance of the passive systems. Further outcomes of the calculations are that the predictability of the containment pressure suppression system strongly depends on the nodalization of the containment compartments.

V. CONCLUSIONS

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 as well as the interaction with the pressure vessel and the pressure suppression containment was proven. 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 that passive safety concepts are applicable for large Boiling Water Reactors.

Further experimental activities on other accident scenarios like bottom head or feed water line leak should be performed including validation of numerical codes and used for the qualification of components and for licensing requirements issues.

References


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