

## Research Article

# The Integral Test Facility Karlstein

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The Integral Test Facility Karlstein (INKA) test facility was designed and erected to test the performance of the passive safety systems of KERENA, the new AREVA Boiling Water Reactor design. The experimental program included single component/system tests of the Emergency Condenser, the Containment Cooling Condenser and the Passive Core Flooding System. Integral system tests, including also the Passive Pressure Pulse Transmitter, will be performed to simulate transients and Loss of Coolant Accident scenarios at the test facility. The INKA test facility represents the KERENA Containment with a volume scaling of 1 : 24. Component heights and levels are in full scale. The reactor pressure vessel is simulated by the accumulator vessel of the large valve test facility of Karlstein—a vessel with a design pressure of 11 MPa and a storage capacity of 125 m<sup>3</sup>. The vessel is fed by a Benson boiler with a maximum power supply of 22 MW. The INKA multi compartment pressure suppression Containment meets the requirements of modern and existing BWR designs. As a result of the large power supply at the facility, INKA is capable of simulating various accident scenarios, including a full train of passive systems, starting with the initiating event—for example pipe rupture.

## 1. Introduction

The KERENA is a medium-capacity boiling water reactor (BWR). It combines passive safety systems with active safety equipment of service-proven design. The passive systems utilize basic laws of physics, such as gravity and natural convection, enabling them to function without electric power or actuation by electric instrumentation and control (I&C) equipment. They are designed to bring the plant to a safe and stable condition without the aid of active systems. Furthermore, the passive safety features reduce the number of active systems, significantly reducing costs, while providing a safe, reliable, and economically competitive plant design [1, 2].

The Integral Test Facility Karlstein (INKA) test facility was designed and erected to experimentally analyze the passive safety systems of KERENA. Therefore, all passive safety features necessary to simulated accident scenarios (loss of coolant accident [LOCA] and non-LOCA) are included in the design. The following section gives a brief description of these passive systems. The INKA setup simulates the KERENA Containment in a 1 : 24 scale. Component size and levels are full scale in order to match the driving forces

for natural circulation in systems. The steam accumulator vessel of the large valve test facility in Karlstein represents the reactor pressure vessel.

At INKA, the systems can be tested individually analyzing their performance, and during integral tests analyzing the interaction between the systems and therefore the capability of the KERENA passive systems performing their design function. Even as KERENA is the reference for INKA, other tests dealing with generic tasks for BWR plants or even other Light Water Reactor design could be performed. The detailed instrumentation concept also allows investigation of several single effect problems. Within this paper, the design of the test facility and the potential of the test facility will be shown. The instrumentation concept will also be briefly explained.

For Generation III BWRs, like for example, the ESBWR (formerly SBWR), several test programs at the test facilities PANDA [3, 4], PUMA [5], and Giraffe [6] have been performed to validate the passive safety features. Recently, tests for the passive containment cooling system for the ABWR have been performed at the TIGER test facility [7, 8]. The qualification program for the AP 1000 passive safety system has been done at the APEX and SPES test facilities [9–14].

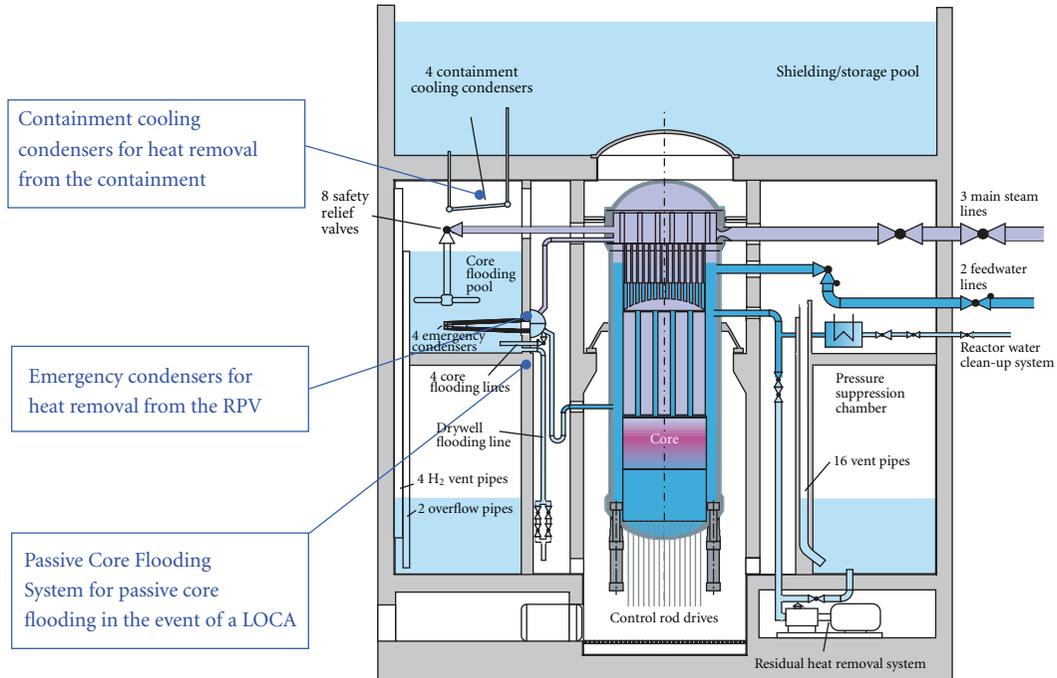


FIGURE 1: Section through KERENA containment with passive safety systems to be tested at INKA. (Passive Pressure Pulse Transmitter is shown in Figure 2.)

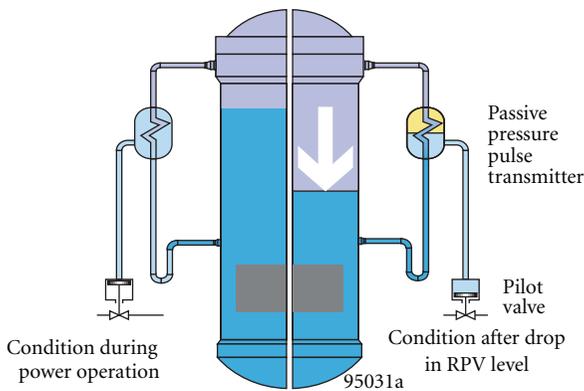


FIGURE 2: Operating Principle of the Passive Pressure Pulse Transmitter.

## 2. Passive Safety Systems at INKA

Figure 1 shows a section through the KERENA containment with the passive safety systems that are included in the INKA design. The Passive Pressure Pulse Transmitter is illustrated in Figure 2. In the event of an accident, the Passive Pressure Pulse Transmitters actuate reactor scram, containment isolation, and an automatic depressurization of the reactor pressure vessel. They operate without any power supply or actuation by electronic I&C signals, activating their designated functions as a result of a drop of the reactor pressure vessel water level.

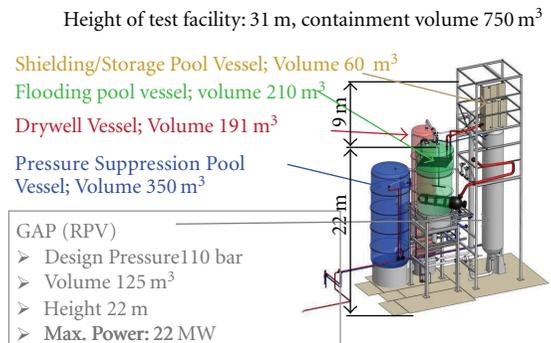


FIGURE 3: 3-D Image of INKA Test Facility at Karlstein.

The Emergency Condenser (see Figure 1) system is provided to remove residual heat from the reactor after shut-down. It consists of four tubular heat exchangers with a nominal heat transfer capacity of about 60 MW each. During normal plant operation, the heat exchanger tubes are full of water and the Emergency Condenser is not in operation. If there is a drop in reactor pressure vessel water level after, for example, a reactor scram caused by an LOCA, steam fills the tubes and the Emergency Condenser operates. The efficiency of the Emergency Condenser increases with increasing reactor pressure and decreasing reactor water level. The temperature of the Core Flooding Pools and the Containment pressure (on the secondary side of the heat exchanger) have only a small effect on Emergency Condenser efficiency. The Containment Cooling Condenser

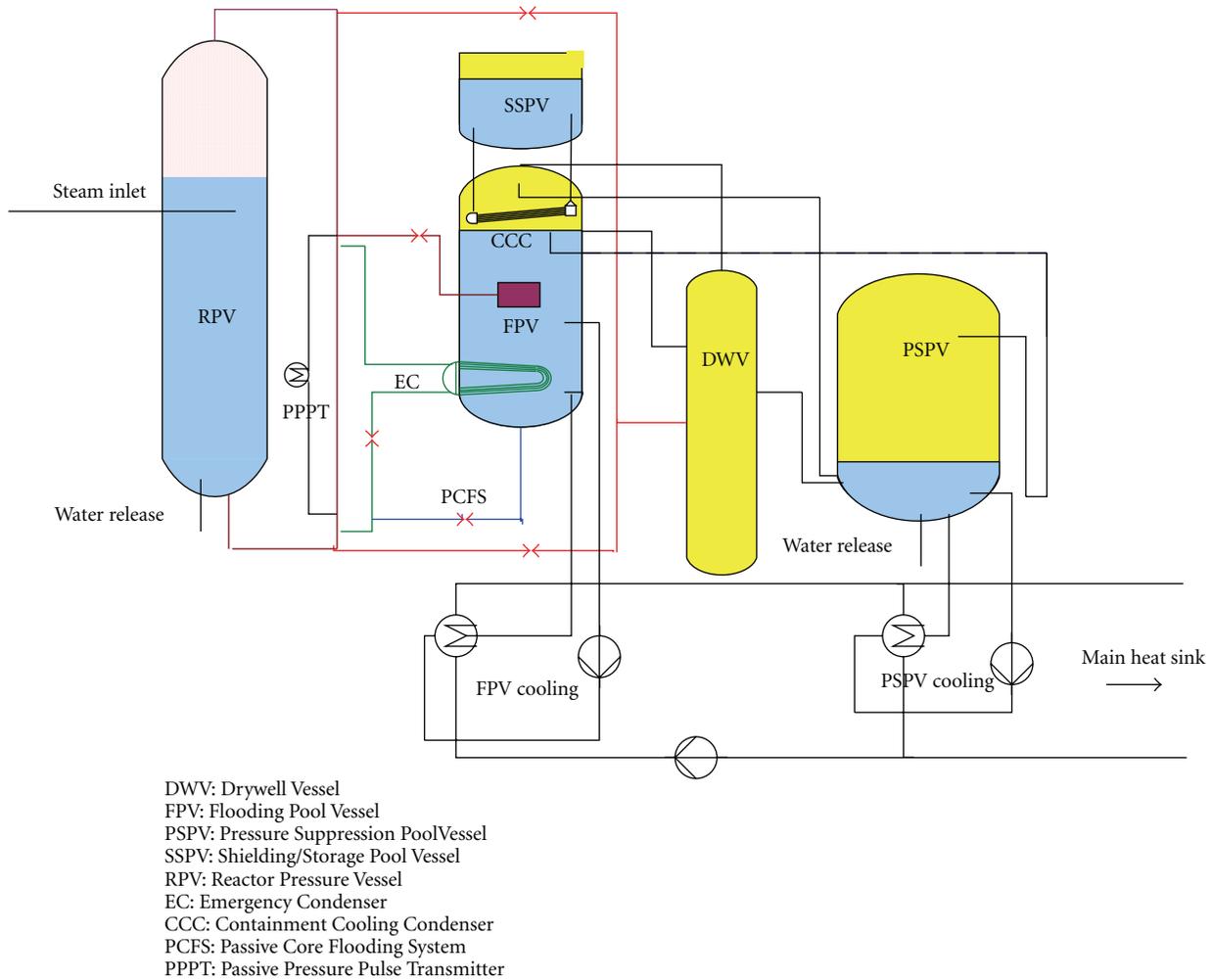


FIGURE 4: Simplified P&ID of the INKA Test Facility.

is designed to ensure long-term containment heat removal (for a grace period of approximately three day). The system also consists of four tubular heat exchangers. The tubes of each Containment Cooling Condensers are filled with water from the shielding/storage pool above the containment. Steam released into the drywell in the event of an accident condenses on the primary side of the Containment Cooling Condenser (inside the containment). The water inside the Containment Cooling Condenser tubes heats up, causing natural circulation to be established. The efficiency of the system increases with increasing containment pressure. The Emergency Condenser and Containment Cooling Condenser together represent the passive cooling chain connecting the heat source (reactor pressure vessel) with the heat sink—the shielding/storage pool located above the containment.

The Passive Core Flooding System is designed to ensure sufficient core cooling in the event of an LOCA. A check valve opens as soon as the pressure difference between the reactor pressure vessel and the Core Flooding Pools reaches a defined value. Water then flows from the pools into the reactor pressure vessel. The components of the passive systems are installed in a full-scale configuration at INKA.

### 3. INKA Test Setup

The INKA test facility has been designed for performing steady-state full-scale Emergency Condenser, Containment Cooling Condenser, Passive Core Flooding System, and Passive Pressure Pulse Transmitter tests and for simulating transients/LOCA conditions in a smaller-scaled configuration [15]. The Passive Pressure Pulse Transmitter is used to actuate the safety-relief valve during the tests. The Containment volumes are modeled to a scale of 1 : 24. The interconnecting piping is designed such that the pressure drops match those of a real KERENA plant. Instrumentation is provided to determine the heat transfer capacity of the components as well as the thermodynamic conditions in the vessels simulating the various KERENA containment compartments.

The vertical distances between components, water levels, floors, and ceiling of the KERENA containment that are important for the performance of the tested components are simulated in full scale at INKA. Figure 3 is a 3D computer image of the test facility. The vessel water and gas volumes result from downscaling of the KERENA volumes by a factor

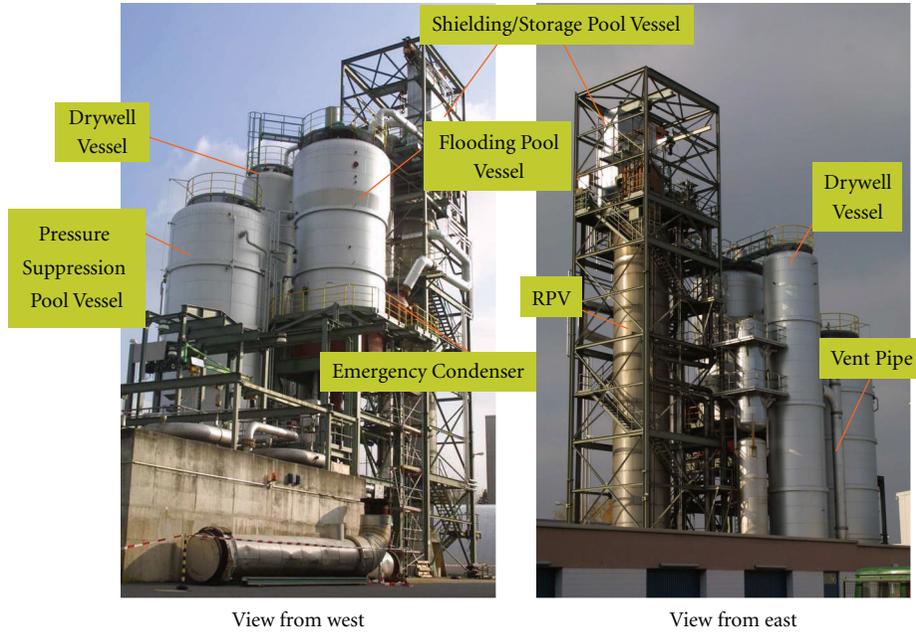


FIGURE 5: Picture of the INKA Test Facility from two different views.

- ◆ Level (20)
- ◆ Mass Flow (9)
- ◆ Pressure, Pressure Drop (16)
- ◆ Temperature (200)
- ◆ Acceleration (4)
- ◆ Water level by Thermo Needle Probes (11)
  - In cooperation with Research Center FZD Rossendorf.
- ◆ VOID measurement with Gamma source
  - In cooperation with Research Center FZD Rossendorf.
- ◆ Gas content with Mass Spectrometer
  - In cooperation with research center PSI, Switzerland.
- ◆ Fatigue Monitoring System FAMOS
  - by AREVA NP GmbH

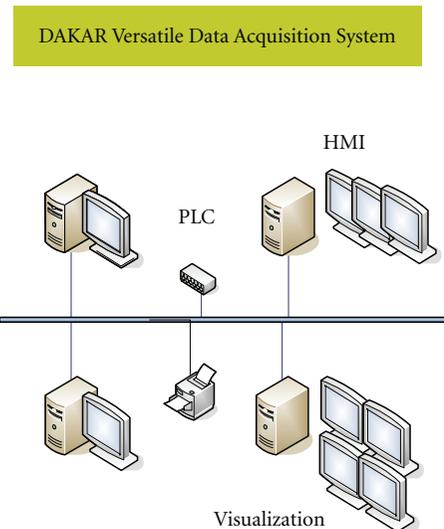


FIGURE 6: Instrumentation and Data Acquisition System.

of 1 : 24. The volume of the vessels and the test facility height are given in Figure 3.

INKA is integrated into the Large-Valve Test Facility Grossarmaturen-Prüfstand (GAP) that has been in operation in Karlstein for many years. The GAP test facility consists of a steam accumulator (height: 21.7 m, volume: 125 m<sup>3</sup>) fed by a 22-MW boiler. This accumulator (GAP Vessel—in the following called pressure vessel) will supply the steam needed for the experiments and will replicate the reactor pressure vessel in the integral tests. An additional vessel with a water volume of about 50 m<sup>3</sup> is placed inside the GAP support frame at the top. This vessel simulates the shielding/storage pool and will therefore supply water for the secondary side of

the Containment Cooling Condenser. The containment will be simulated by three vessels.

The Flooding Pool Vessel represents the core flooding pools that contains the Emergency Condenser and the Containment Cooling Condenser. The Passive Core Flooding System connects the Flooding Pool Vessel with the return line of the Emergency Condenser. The Passive Pressure Pulse Transmitter is connected to the down comer line. The Drywell Vessel simulates the residual gas volume of the drywell. The Pressure Suppression Pool is simulated by a third vessel.

During tests of the individual passive components, only the Flooding Pool Vessel is needed.

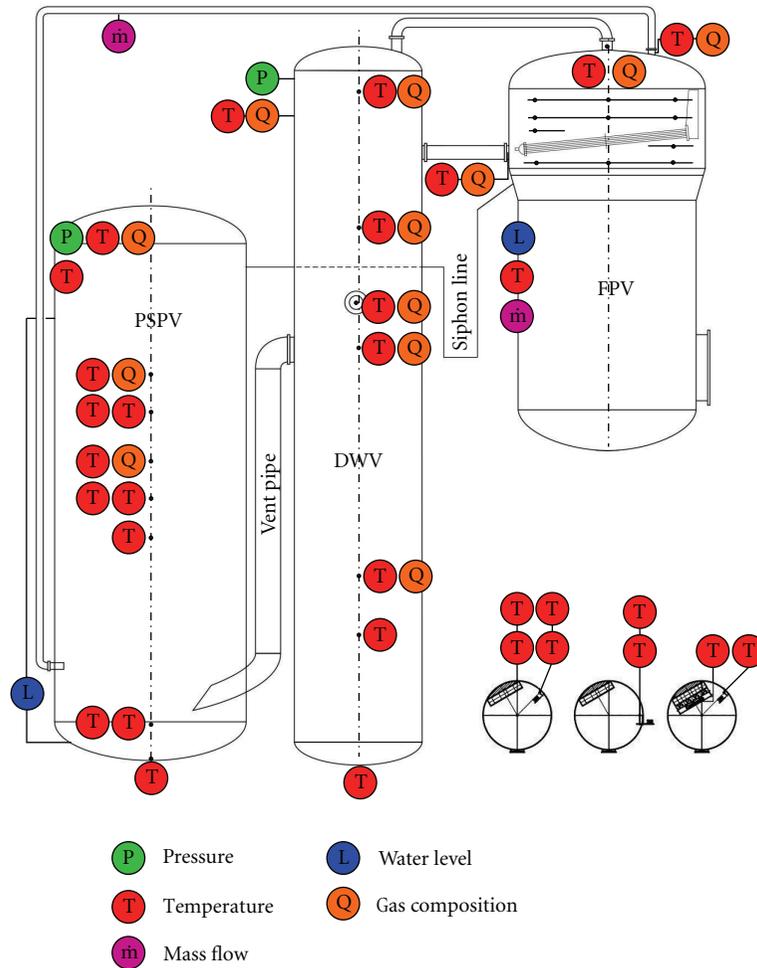


FIGURE 7: Drawing of the INKA vessel instrumentation.

For the integral transient and LOCA experiments, all vessels and components are in use.

Figure 4 shows a simplified P&ID of the INKA test facility with the containment vessels Flooding Pool Vessel, Drywell Vessel, and Pressure Suppression Pool Vessel. Two pipes connect the Flooding Pool Vessel with the Drywell Vessel and represent the connections between the gas spaces of these compartments. The Flooding Pool Vessel is connected to the Pressure Suppression Pool Vessel via the overflow pipe limiting the Flooding Pool Vessel water level. A second connection is the hydrogen overflow pipe used for pressure limitation during severe accident mitigation at KERENA. The Drywell Vessel and the Pressure Suppression Pool Vessel are connected via a full-scale vent pipe. Additionally, the function of the Safety and Relief valve is included in the design. The system is connected to the down comer line and goes into the Flooding Pool Vessel. For LOCA test scenarios, two different lines enter the Drywell Vessel, one for the simulation of breaks of a water line and the other for breaks of a steam line.

The water of the Flooding Pool Vessel and the Pressure Suppression Pool Vessel can be cooled down via two pool

cooling systems. These systems are used for the preconditioning of the test facility and can be used for the experimental simulation of active system accident management. At KERENA, the active heat removal from the containment is done via the cooling of the Core Flooding Pools and the Pressure Suppression Pool. Active core cooling and flooding of the KERENA reactor pressure vessel is done via low pressure injection systems injecting water taken from the wetwell into the reactor pressure vessel. Currently no such active low pressure injection is installed at INKA. The impact of this active system can be simulated by removing water from the Pressure Suppression Pool Vessel and water introduction into the pressure vessel.

Figure 5 shows two pictures of the test facility taken from two different views.

#### 4. Instrumentation Concept

Figure 6 gives an overview of the sensors installed at the INKA test facility. Overall, there are more than 300 sensors available at INKA. Most of them are conventional instrumentation like temperatures, mass flow measurements, pressures,

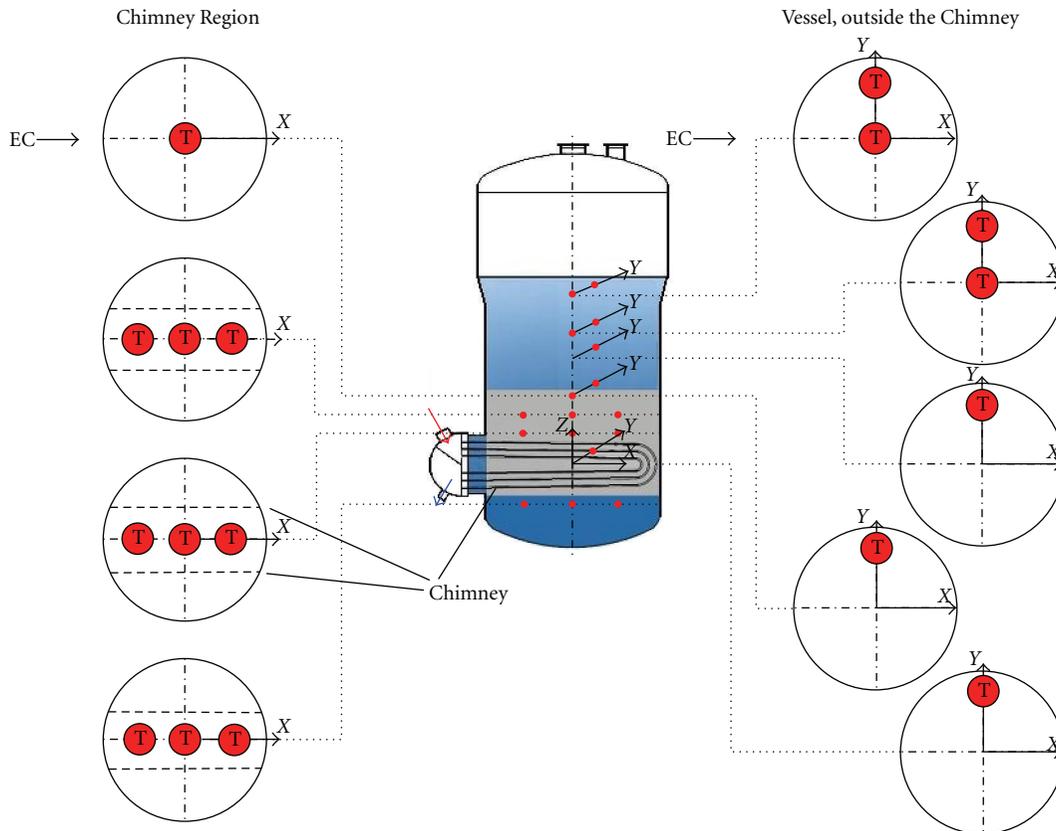


FIGURE 8: Instrumentation of the water volume of the Flooding Pool Vessel.

and differential pressure sensors. Additionally, two-phase flow instrumentation (Thermo Needle Probes and Gammadensitometer) in cooperation with Forschungszentrum Dresden/Rossendorf (FZD) is installed. The gas mixture in the vessels is measured via a probe sampling system analyzed by a mass spectrometer (cooperation with Paul Scherrer Institut in Switzerland). In the Emergency Condenser condensate line, the AREVA Fatigue Monitoring System (FAMOS) is tested under plant relevant conditions.

The data acquisition system Data Acquisition System Karlstein (DAKAR), which was developed by AREVA in Karlstein, is used. The system allows the time synchronized combination of fast and slow data recording.

**4.1. Instrumentation of the Test Vessels.** Figure 7 gives an overview of the instrumentation of the INKA vessels. The Flooding Pool Vessel has the highest sensor density due to the fact that this vessel contains the passive systems Emergency Condenser and Containment Cooling Condenser. The Pressure Suppression Pool Vessel has thermocouples in the water volume at four different levels, located in three different chains (parallel to the vessel axis). In the gas space of the vessel, the temperature field is measured at five levels in the same three chains. At all levels in the gas space, the thermocouples at the chain in the center line of the vessel are connected to a gas probe sampling sensor. Like in all other vessels, the pressure and the water level is measured.

In the Drywell Vessel, the gas temperature is measured at six levels. The upper five levels are equipped with a probe sampling sensor.

The instrumentation of the water space in the Flooding Pool Vessel is shown in Figure 8. The temperature of the water space is measured at nine levels along the vessel axis and on a parallel chain outside the chimney of the Emergency Condenser bundle. Like in the other two vessels, the pressure and the water level is measured. In the Flooding Pool Vessel, the water level cannot exceed the level of the inflow of the overflow pipe connecting the Flooding Pool Vessel with the Pressure Suppression Pool Vessel. The gas space of the Flooding Pool Vessel is extensively instrumented with thermocouples and probe sampling sensors in order to determine the impact on gas compositions to the heat transfer capacity of the Containment Cooling Condenser and the influence of the Containment Cooling Condenser operation to gas and temperature stratification (see Figure 9).

The Emergency Condenser system instrumentation is shown in Figures 10 and 11. The system is connected to the stand pipe of the large valve test facility which represents the down comer of the KERENA reactor pressure vessel. In the test facility, pressure vessel itself and the water and steam temperature, pressure, and water level are measured. In the down comer, the differential pressure and the temperature are measured at different elevations to be able to determine the water level with sufficient accuracy. Above the water

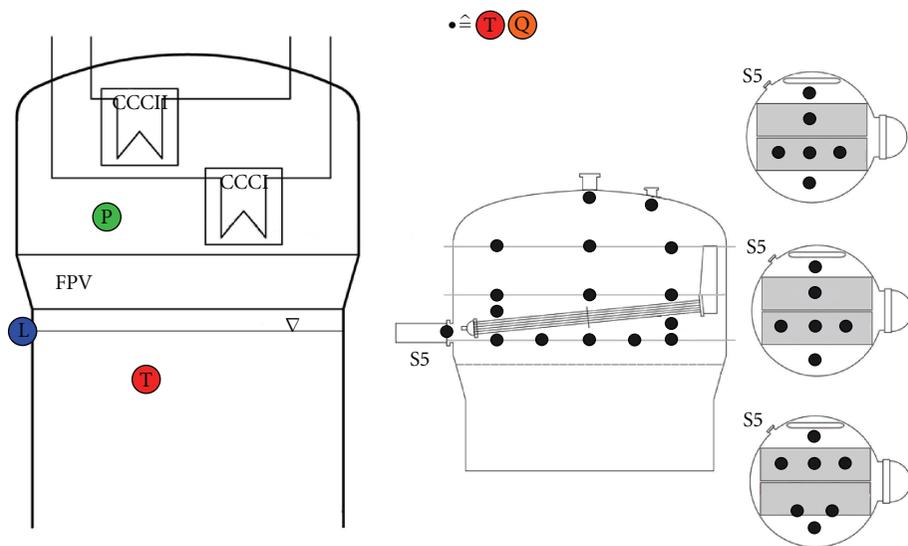


FIGURE 9: Instrumentation of the water space of the Flooding Pool Vessel.

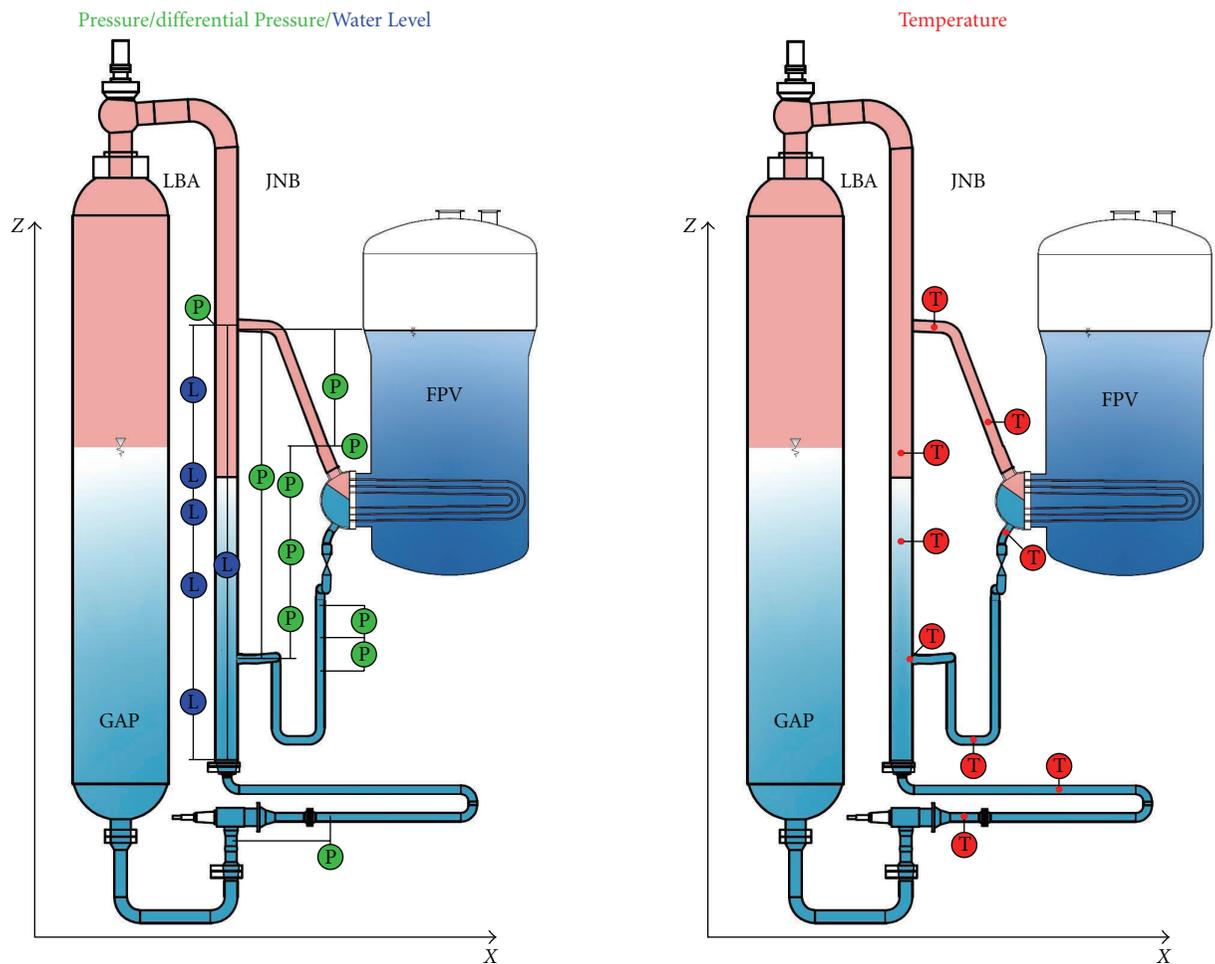


FIGURE 10: Instrumentation of the Emergency Condenser System (I).

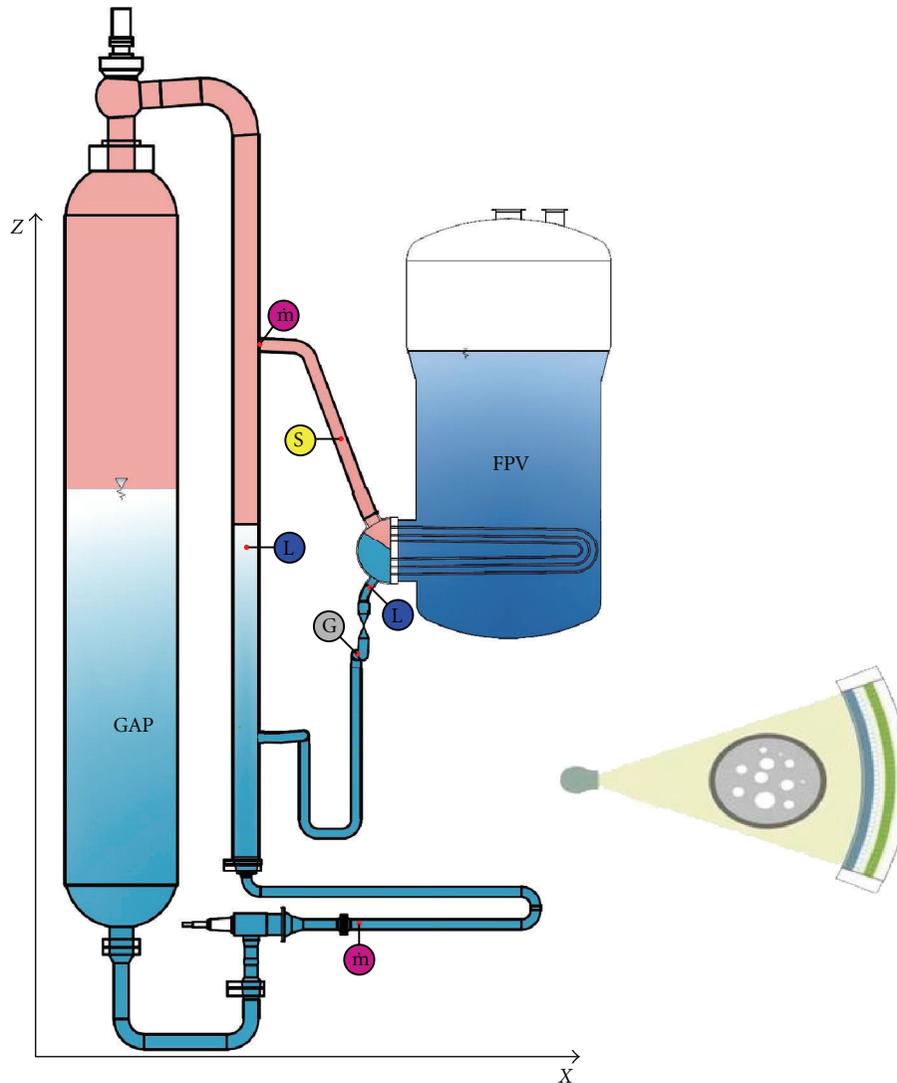


FIGURE 11: Instrumentation of the Emergency Condenser System (II).

level, the absolute pressure is measured. The inlet line, return line, and the Emergency Condenser component itself are equipped with several differential pressure measurements. In the piping system the temperature is determined at different positions. Figure 12 highlights the mass flow measurements, the local void fraction measurement outside the Emergency Condenser component (Thermo Needle Probes in the Emergency Condenser outlet line and the down comer line), the acceleration measurements for the determination of vibrations in the system during operation, and the integral void measurement in the outlet line. The operation principle of the latter measurement is described in Figure 11. It consists of a radiation source and a detector array. The pipe in which the void fraction should be determined is located in between. Based on the attenuation of the emitted radiation, the void fraction in the pipe can be determined.

**4.2. Instrumentation of the Systems.** Two of the outer heat exchanger tubes in the Emergency Condenser heat exchanger

bundle are equipped with instrumentation. One with thermocouples and the other with nine thermo needle probes. At most of the locations indicated in Figure 12, the thermocouples are located in the tube axis. At three different positions, there are four additional thermocouples at the inner side and the outer side of the heat exchanger tube wall. With the combination of the local void fraction measurements, and the five thermocouples per location, the heat transfer and the type of two-phase flow in the tube can be determined.

Figure 13 shows the instrumentation of the Containment Cooling Condenser system and component. The differential pressure of the inlet line, return line, and the component itself is measured. In the return line also the absolute pressure is measured. Thermocouples are installed at different locations in the piping system. In the return line, several thermocouples are located at different position over the pipe cross-section to identify stratification of the flow. In the case of two-phase flow operation, the integral void fraction can be determined via a gammadensitometer located

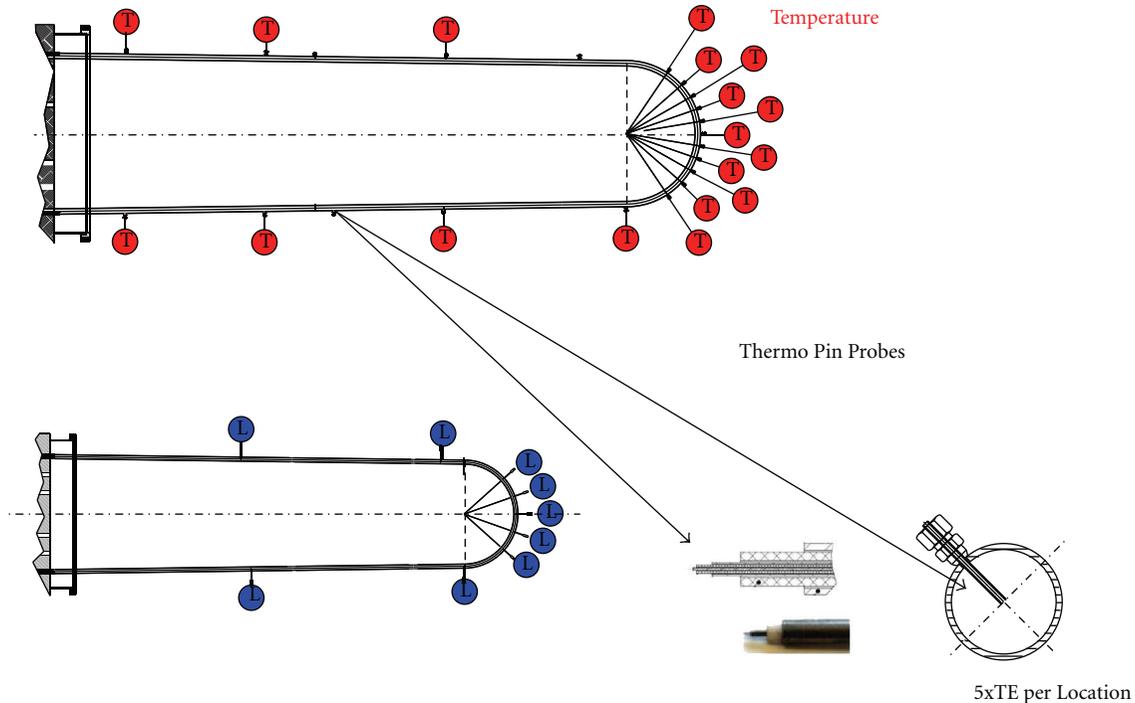


FIGURE 12: Instrumentation of the Emergency Condenser component.

on the return line. The heat exchanger tubes are equipped with thermocouples along the tube axis to determine the heatup of the coolant.

Figure 14 shows the instrumentation of the Passive Core Flooding System. The differential pressure over the valve and the line connecting the valve to the Flooding Pool Vessel is measured. At the lowest location of the system also the absolute pressure is measured. At different locations in the system, thermocouples are installed. The mass flow measurement can determine flow in both directions.

## 5. Preconditioning of the Test Facility

All vessels and systems of INKA can be operated individually. The connections between the vessels are realized by pipes that can be opened and closed as needed. Each of the vessels can be heated independently via direct steam injection. The water volume of the Flooding Pool Vessel and the Pressure Suppression Pool Vessel can be cooled via the two pool cooling systems. The containment vessels of INKA (Flooding Pool Vessel, Drywell Vessel, Pressure Suppression Pool Vessel) are designed for pressures between 0.5 and 4 bar. The water level of these vessels can be set individually (the water level of the Flooding Pool Vessel is limited via the overflow pipe). The test facility pressure vessel is designed for a maximum pressure of 110 bar. The water level can be set and controlled during test execution with the help of water release. Energy can be introduced via steam introduction with a maximum power of 22 MW.

## 6. Test Programs Performed at the INKA Test Facility

Several test programs have already been performed at the INKA test facility. All of them were done in the cause of the KERENA development program. The first test program in 2009 dealt with the KERENA Fuel Pool Cooler. The goal was to qualify the component and to validate the CFD model [16].

Since 2009, the key features of the KERENA passive safety concept are tested in full-scale single component tests at INKA. The goal of the tests was again to qualify the components/systems and validate the numerical tools used for the KERENA accident analysis. Among these features are the Emergency Condenser (2009-2010, [17, 18]) and the Containment Cooling Condenser (2009, [17]). In 2010 the passive core flooding system has been tested as single component and together with the Emergency Condenser in order to determine the interaction between the passive residual heat removal and the passive replenishing of the reactor pressure vessel [19]. The passive pressure pulse transmitter has already been tested in 2003 at Karlstein in a single component qualification program. All four systems will be used in the integral test, experimentally simulating accident scenarios and demonstrating the interaction between the systems.

## 7. Test to Be Run at INKA

INKA is a test facility that simulates a multicompartiment containment of a BWR. The reference plant is KERENA.

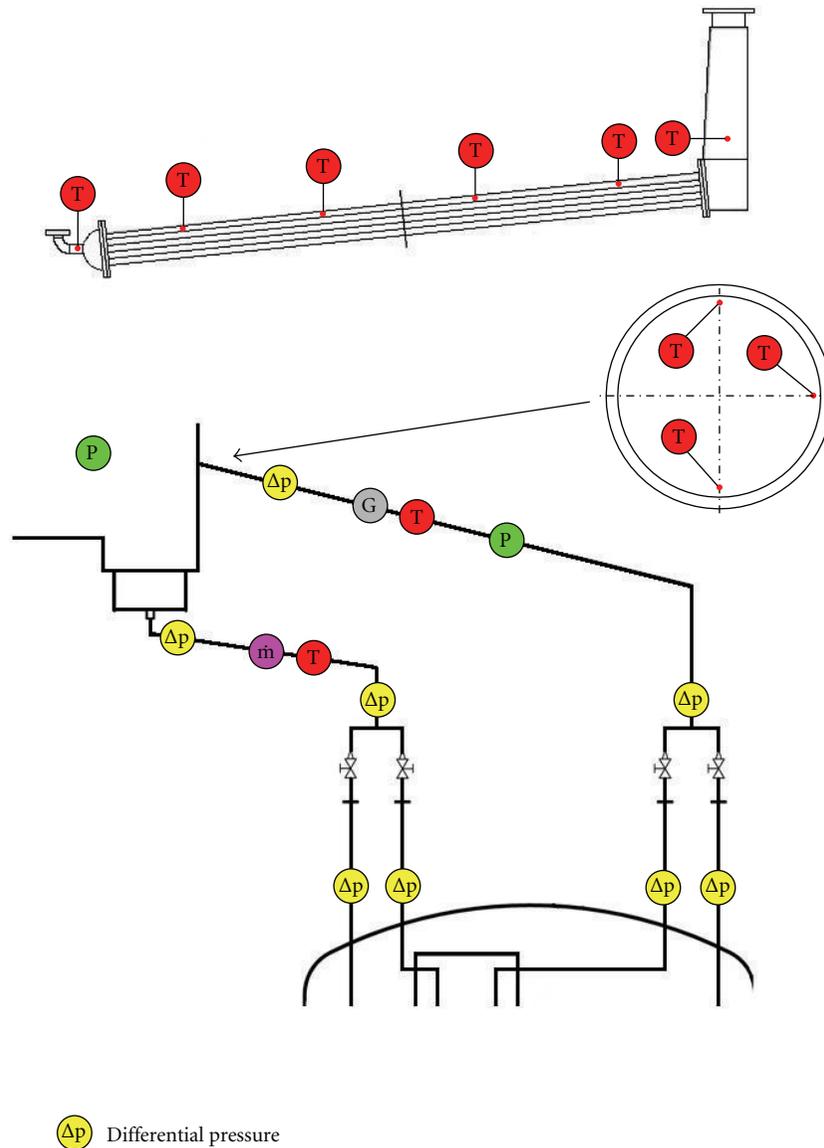


FIGURE 13: Instrumentation of the Containment Cooling Condenser System and Component.

The test facility containment is divided in drywell and wetwell and has therefore a pressure suppression function. The primary system is simulated by the GAP vessel and the down comer line, which simulates a simplified model of a BWR reactor pressure vessel. The primary system is coupled to the containment via the Emergency Condenser the Safety and Relief Valve system and the two lines simulating leak mass flows. A complete set of passive safety features for the performance of passively controlled accident scenarios is available. The function actively controlled safety systems can at least qualitatively be simulated. Therefore, integral tests especially the simulation of accident scenarios for BWRs with passive and active accident management can be performed. These tests can be started with the initiating event, for example, the rupture of a pipe, and can be executed until very late phase of the accident. The required decay heat can be realized via

steam introduction into the GAP vessel. The participating safety features can be chosen individually and even the scaling of the systems can be adjusted if necessary.

Because of the preconditioning capability of INKA and the option to operate all vessels and systems individually, many single-effect phenomena can be addressed.

The following list gives an overview about effects to be analyzed:

- (i) heat transfer on surfaces—water surface containment walls, for example, in the Pressure Suppression Pool Vessel of INKA;
- (ii) heat transfer on the inside and outside of heat exchanger tubes and the impact on natural circulation systems—for example, impact of subcooling to the Emergency Condenser system;

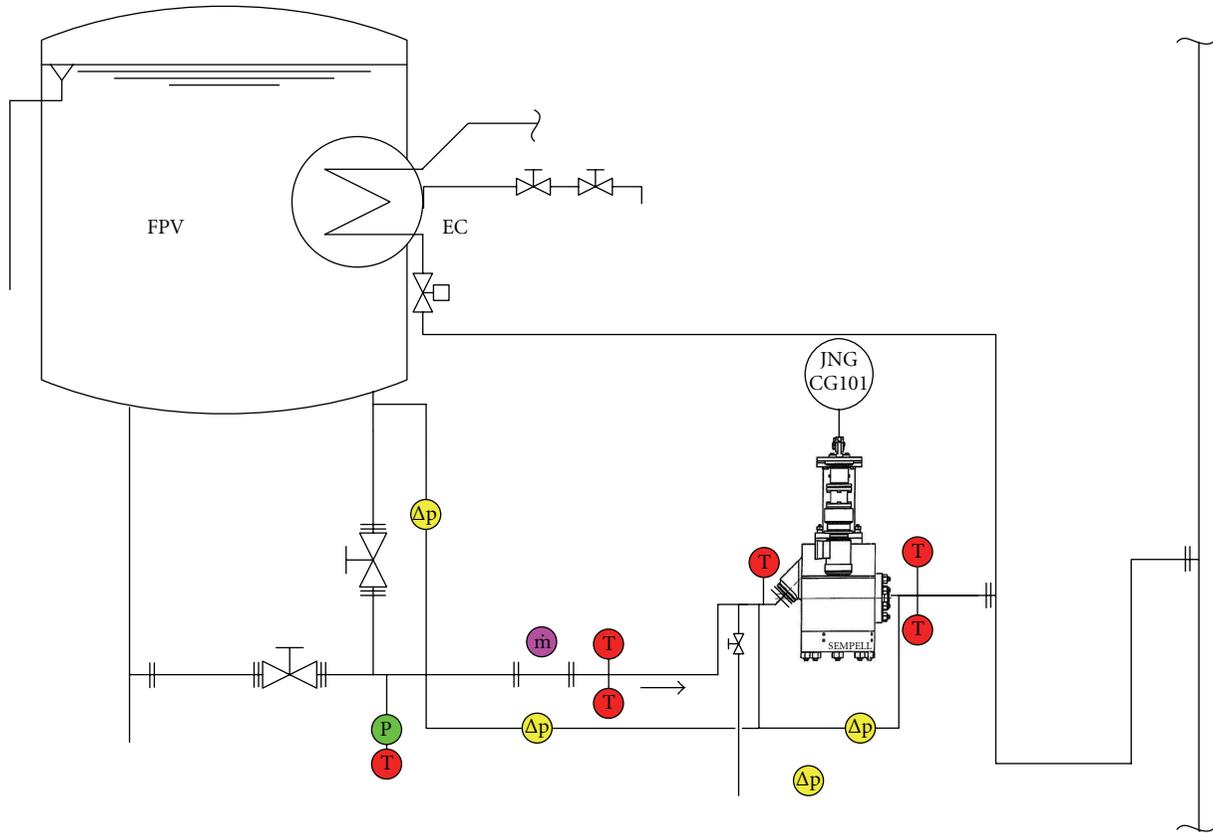


FIGURE 14: Instrumentation of the Passive Core Flooding System.

- (iii) influence of noncondensable gases to the heat transfer—for example, for the Emergency Condenser and Containment Cooling Condenser;
- (iv) temperature stratification in the water and gas space of compartments/vessels—for example, INKA, Flooding Pool Vessel, and Pressure Suppression Pool Vessel;
- (v) gas compositions in the gas space of compartments/vessels—for example, INKA, Flooding Pool Vessel, and Pressure Suppression Pool Vessel;
- (vi) impact of natural convection on temperature stratifications and gas compositions in compartments or vessels—for example, the influence of Containment Cooling Condenser operation on the FPV;
- (vii) gas concentrations in drywell and wet well after blow-down depending on the leak size;
- (viii) temperature stratification in the wet well after blow-down depending on the leak size.

The integral test as well as the single effect tests can be simulated in a scaling close to real plant conditions. The instrumentation concept and the sensor density are sufficient for the validation of thermohydraulic codes like RELAP or TRACE, for example, or containment codes like COCOSYS or GOthic. Nevertheless, for special tasks, the instrumentation concept can be easily upgraded. Also, the installation of

additional systems matching tasks of other reference plants can be realized.

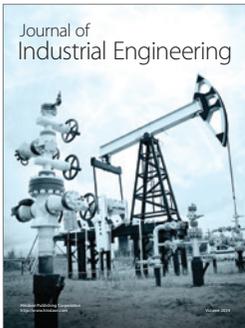
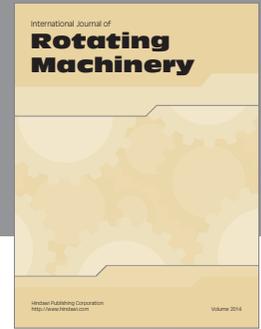
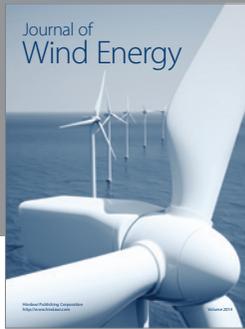
### 8. Summary

The INKA test facility was built to test the passive safety systems of KERENA. INKA simulates the KERENA containment in scaling of 1 : 24. The primary system is represented by the GAP vessel and the GAP main steam line representing the reactor pressure vessel down comer. The systems to be tested at INKA are constructed in full scale. Because of the possibility of INKA to precondition and operate all vessels and systems individually, integral testing such as the experimental simulation of BWR accident scenarios, as well as the analysis of single effects, can be performed. The large energy storage capacity and power supply of INKA allow the performance of tests in a scaling that is relevant for full-scale commercial nuclear power plants.

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