Passive decay heat removal from the core region

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Abstract. The decay heat in commercial Light Water Reactors is commonly removed by active and redundant safety systems supported by emergency power. For advanced power plant designs passive safety systems using a natural circulation mode are proposed; several designs are discussed. New experimental data gained with the NOKO and PANDA facilities as well as operational data from the Dodewaard Nuclear Power Plant are presented and compared with new calculations by different codes. In summary, the effectiveness of these passive decay heat removal systems have been demonstrated; original geometries and materials and for the NOKO facility and the Dodewaard Reactor typical thermal-hydraulic inlet and boundary conditions have been used. With several codes a good agreement between calculations and experimental data was achieved.

1. INTRODUCTION

The decay heat in commercial Light Water Power Reactors is commonly removed by active safety systems which require redundant systems as well as emergency power. This is expensive and requires time for maintenance and testing.

Therefore – when studying advanced power plant designs – the decay heat removal by passive safety systems was re-evaluated. In Fig. 1 some passive safety systems under consideration are shown.

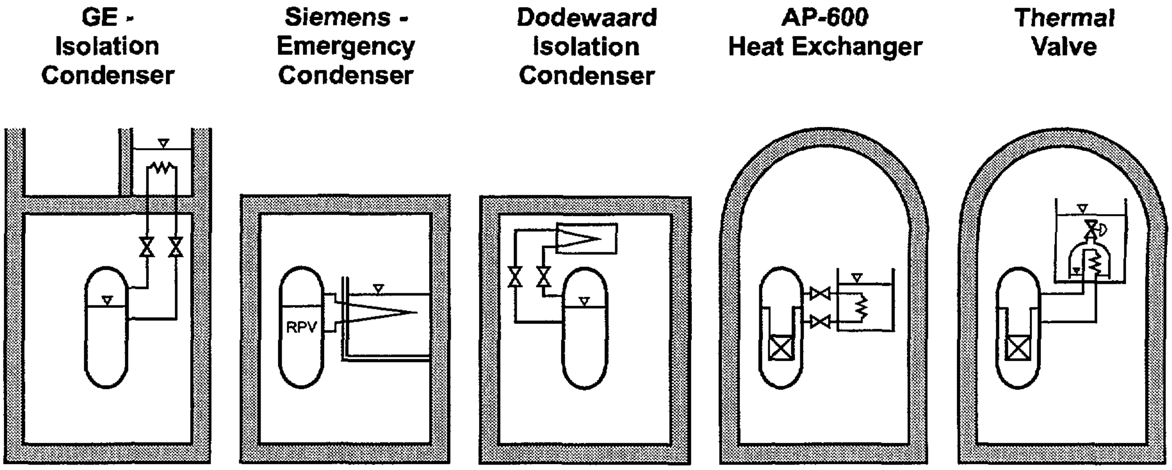

FIG. 1. Design for passive decay heat removal.

For PWR the use of heat exchangers submerged in a large water pool (up to several thousand m^3) is evident. The working principle is well known and can be calculated with well validated codes. However, to avoid heat losses during normal operation in the range of several per cent of the total thermal power valves have to be installed in the pipes to and/or from the heat exchanger. This definitely reduces the reliability of the decay heat removal as well as it results in additional costs. The expensive valves can be avoided if the principle used for the so-called

"Thermal Valve" is applied: the heat exchanger – now without valves in the high-pressure lines – is installed within a bell-shape volume. On signal by the reactor protection system or by manual operation a valve at top of the volume opens allowing heat removal by water circulation. This proposed design, however, has to be validated against experiments and related code calculations.

The principle already used in BWR's and again proposed for advanced BWR designs is the Evaporation – Condensation mode: water in the core region is evaporated by decay heat and condensed within a heat exchanger placed in a water pool, the condensate returns to the core region.

This principle has been used in the Dodewaard Reactor and some other reactors already decommissioned. This principle has been proposed for the advanced BWR, the SBWR and the SWR 1000. Experimental results and comparison with code calculations will be given below.

The two new designs – for the SBWR and the SWR 1000 – show some remarkable differences; some will be discussed below.

1) Both designs need a large water pool. Due to the fact that the heat exchanger for the SWBR can be placed above the Reactor Pressure Vessel (RPV) – thus allowing more flexibility in the design – valves are needed in the lines to and from the heat exchanger. Therefore, the heat exchanger can also be placed outside the containment. The heat exchanger and the water pool of the SWR 1000 have to be placed at the elevation of the core and within the containment.

2) The operation of both designs is quite different. When opening the valves in the connecting lines the full heat exchanger capacity is available from the beginning while the heat exchanger of the SWR 1000 will start slowly from zero to full capacity.

3) These passive heat exchangers are mainly designed to be used for a decay heat removal without a loss-of-coolant sequence; for some time they assist the heat removal in case of small breaks – for large break LOCA they are of no benefit.

4) The modelling of the phenomena and system behaviour with these designs is not always easy as it will be shown below, because the condensation behaviour inside the heat exchanger tubes – including the presence of non-condensables – as well as the heat transfer from these tubes to the water pool has to be considered.

5) Heat exchangers using condensation of steam are always sensitive to the accumulation of non-condensables. If no venting capability is installed the concentration has to be kept below a value, where the non-condensables can be dissolved in the condensate.

6) There exists some operating experience mainly in the Dodewaard Reactor.

2. EXPERIMENTAL AND ANALYTICAL RESULTS REGARDING THE EFFECTIVENESS OF CONDENSERS

The results presented in the following chapters were gained within the project "European BWR-R&D Cluster for Innovative Passive Safety Systems (INNO-IPSS)" supported by the EU within the 4th framework programme.

2.1. The Emergency condenser

The design of the Emergency Condenser, as already used in the Gundremmingen Unit A Power Plant, is shown in Fig. 2. The tubes are about 10 m long. The tube inner diameter is 38.7 mm and the wall thickness 2.9 mm. Because the wall thickness resulted in a thermal conductivity of about two thirds of the total thermal conductivity a second bundle was designed with an inner diameter of 44.3 mm and the minimum acceptable wall thickness of 2 mm. Tests with the second bundle were performed with the bundle oriented in a vertical position, under an angle of 40.9° and in a horizontal position. The orientation under an angel of 40.9° should decrease the height between a flooded bundle (with zero energy transfer) and an empty bundle (with maximum energy transfer to the pool); in addition the mixing within the pool should be enhanced.

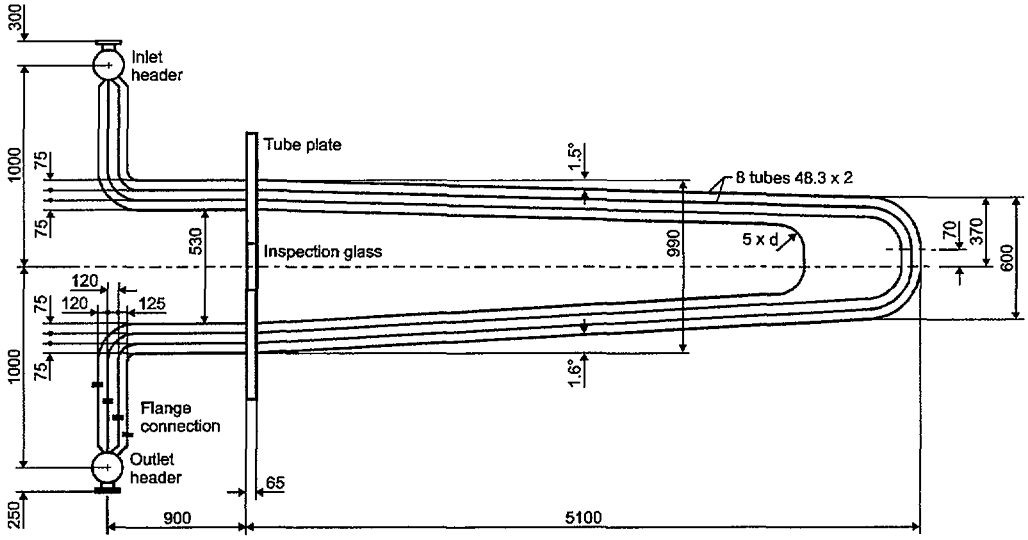

FIG. 2. Bundle of the emergency condenser with dimensions

The tests have been performed under the same thermal conditions as in a real BWR; the pressures chosen were 7, 5, 3 and 1 MPa. The tests were performed in the NOKO facility, see Appendix A. The test procedure started with a flooded bundle, then the water level in the pressure vessel was decreased stepwise until the bundle was empty.

In Fig. 3 and 4 the experimental results are given. It should be added that the accuracy of the results ranged between less than 10 per cent for high powers and several ten per cent for power levels below 1 MW; the conditions for a flooded bundle are - on the other hand – relatively accurate.

In principle, the dependence of the transferred power on the water level in the pressure vessel is similar for both bundles. The influence of the orientation of the bundle is only minor, see Fig. 4.

Post-test calculations with ATHLET are shown in Fig. 3 for the first bundle and in Fig. 5 for the second bundle; the agreement is good. The distortion at about 5 m is due to the vertical part of the bundle.

It was shown that despite the good agreement for the (integral) transferred power the local deviations in the heat transfer during condensation as calculated by the ATHLET and CATHARE, see Fig. 6, are large.

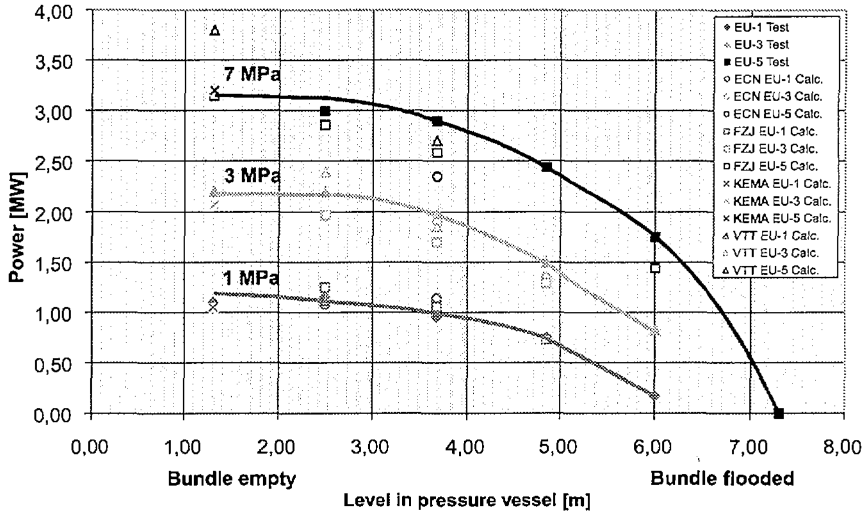

FIG. 3. Results of the first NOKO-EC bundle tests (4 tubes).

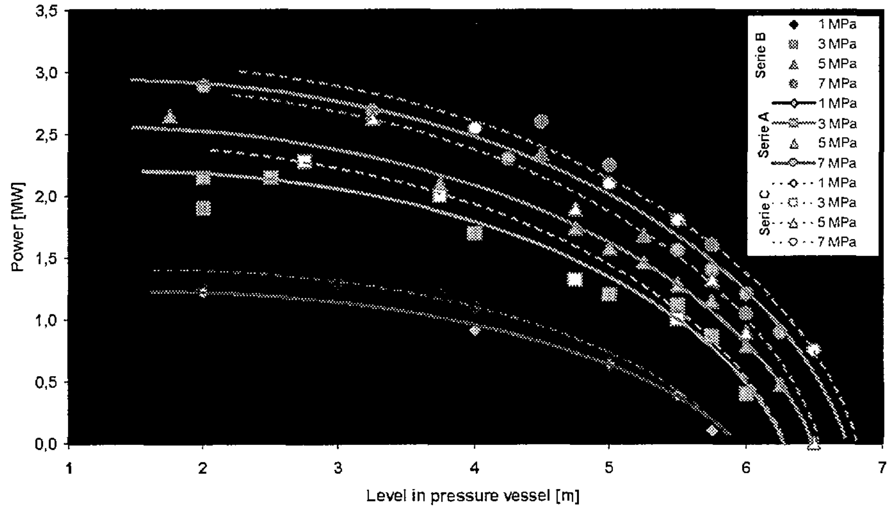

FIG. 4. Results of the second NOKO-EC bundle tests (3 tubes, for horizontal bundle 4 tubes).

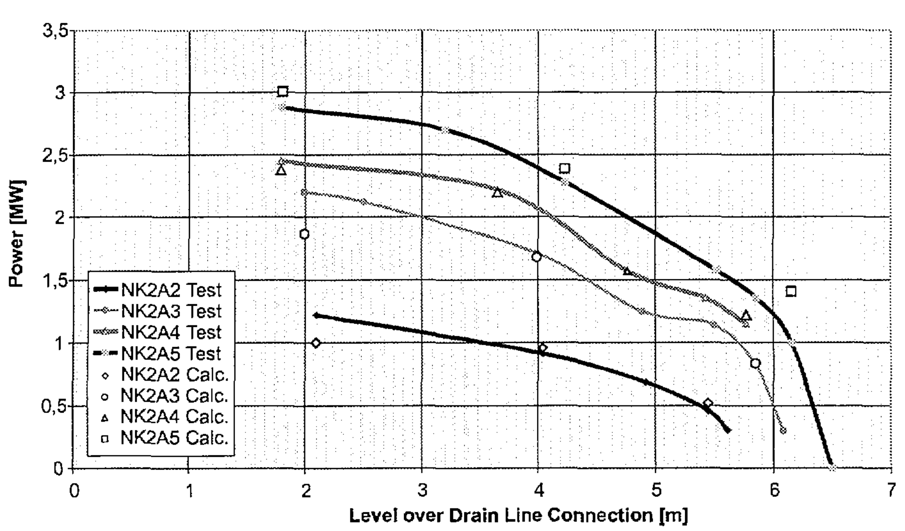

FIG. 5. NOKO-2 power levels from tests and calculations for the bundle in vertical position

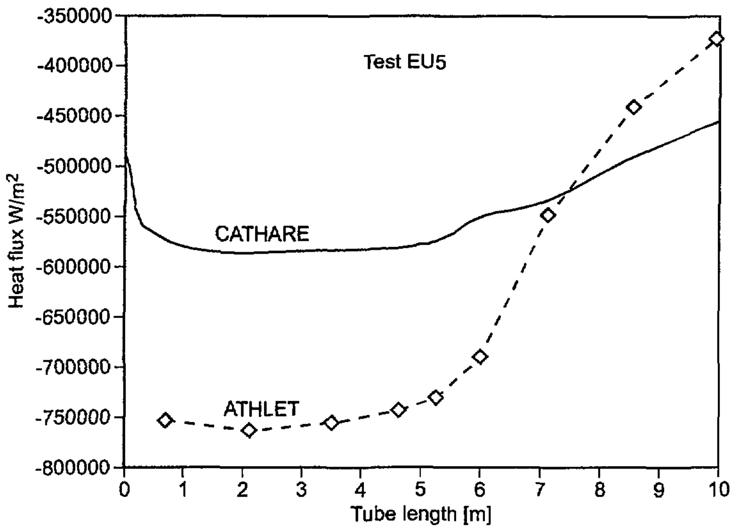

FIG. 6. Comparison between ATHLET and CATHARE calculation results.

Therefore, for orientation tests were performed with a single tube (dimensions of the first bundle) instrumented with needle probes for the identification of the film thickness. To better study the film thickness a test tube with a tube of the second bundle and movable film probes are underway.

It was a result of the single tube tests that non-condensables were accumulated in front of the condensed water rather than been distributed along the tube.

2.2. The isolation condenser

Fullscale tests with an Isolation Condenser (IC) as proposed for the SBWR from GE have been performed in the PANTHERS facility. Because the results are proprietary special tests have been performed in the PANDA facility, see Appendix B.

The design of an IC is schematically shown in Fig. 7; vertical tubes are connected to an upper (inlet-) header and a lower header.

Tests with pure steam as well as tests with a mixture of steam and helium (up to about 14 per cent) were performed.

In Fig. 8 test results with pure steam and calculated results with ATHLET are shown.

2.3. The Isolation Condenser in Dodewaard

The design of the Isolation Condenser in the Dodewaard Reactor is shown in Fig. 9. Some operational tests have been performed as well as some sequences occurred where the isolation condenser was used to cope with transients.

Because the operational instrumentation did not completely cover the phenomena needed for a detailed analysis and because some manual operation (not documented in detail) was used to cope with the transient a detailed evaluation of the operational data is not possible. Therefore, in Fig. 10 calculated values for the Dodewaard Isolation Condenser is given. One power level could be compared with a TRAC calculation; the agreement is good.

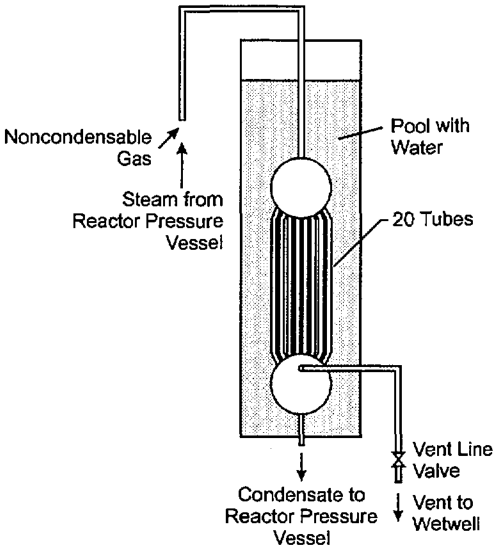

FIG. 7. Arrangement of the PANDA-IC in the pool.

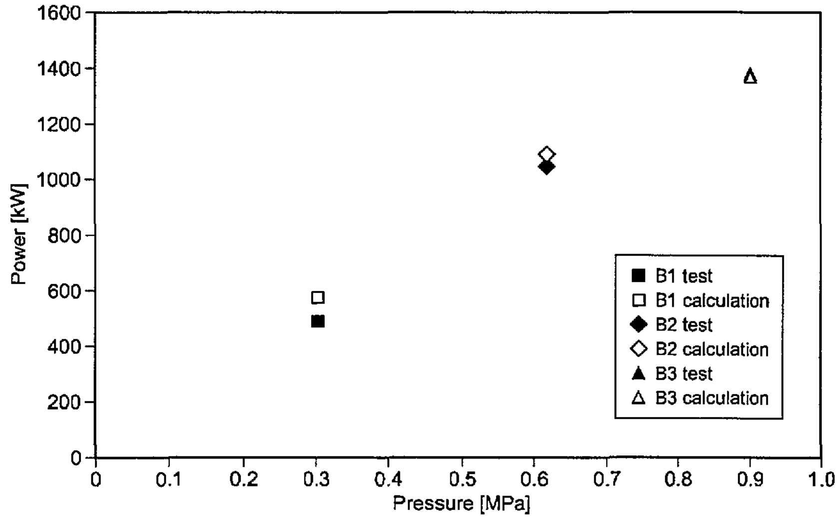

FIG. 8. Power levels of the PANDA-IC calculated with ATHLET as a function of pressure for the pure steam tests.

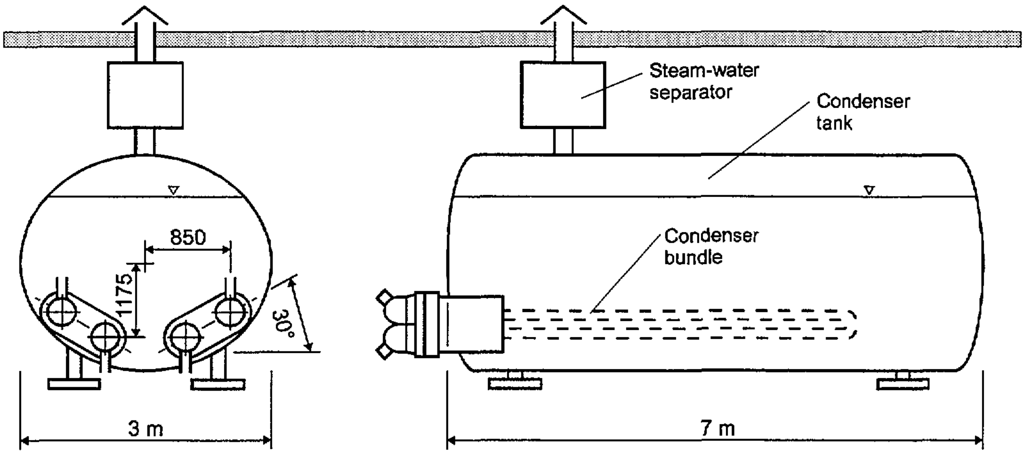

FIG. 9. Arrangement of the isolation condenser in the condenser tank of the Dodewaard nuclear power plant.

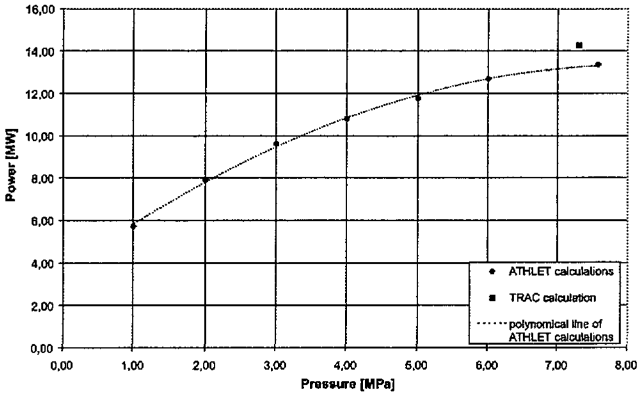

FIG. 10. Power levels of the Dodewaard Isolation Condenser calculated with ATHLET as a function of pressure

3. DISCUSSION AND CONCLUSIONS

The requirements from licensing bodies for the acceptance of experimental and analytical data in a licensing process are quite higher now than 10 or 20 years ago.

To the extend possible original geometries and materials should be used; if this is not possible, reliable scaling rules should exist.

> For the Emergency Condenser (EC) and the Dodewaard Isolation Condenser (IC) original geometries and materials were used. The Isolation Condenser in PANDA is a scaled-down test section. However, the components with original geometries and materials have been tested in the PANTHERS facility; the data are not publicly available except for the licensing bodies.

The equivalent thermal-hydraulic initial and boundary conditions should be used.

> This is the case for the EC and the Dodewaard IC. The PANDA IC was limited to 1 MPa, but the full pressure has been used in PANTHERS.

To the extend possible the components should be tested also with beyond-design thermal-hydraulic conditions and for low-power or shutdown situations.

> The EC and PANDA IC have also been tested with non-condensables in the inlet flow. The EC has been tested with shutdown situations.

The data and procedures should be documented; an uncertainty analysis should be available.

> With the exception of the Dodewaard IC those requirements could be met.

The sequences tested should be simulated with at least one computer code and the results compared with the experimental data.

> This has been extensively done for the EC and PANDA IC test series.

In conclusion, tests as well as related calculations with several computer codes have been performed for passive decay heat removal systems. The spectrum tested and the quality should allow its use in a licensing process.

Appendix A

NOKO Facility

The NOKO test facility located at the Institute for Safety Research and Reactor Technology of the Research Center Jülich is a thermal hydraulic test rig, which was constructed within the framework of a research task in a joint project of the Research Center Jülich (FZJ) and SIEMENS AG, Power Generation Division (KWU), with support from the German Federal Ministry of Education, Science, Research and Technology and German utilities. The facility is suited for a broad spectrum of experiments in the field of thermodynamics and fluid dynamics of water, water vapor and non-condensable gases. Different passive safety systems can be investigated with only minor modifications.

The parameter limits given by the design are:

- maximum primary pressure: 7 MPa;
- maximum secondary pressure: 1 MPa;
- maximum power: 4 MW.

The maximum temperatures are the corresponding saturation temperatures.

The NOKO facility is composed of three sections. The first section is the primary circuit with the pressure vessel, the bundle of the emergency condenser and the associated connecting lines. The second section is the secondary side with condenser tank, relief lines and relief tank. The system of steam generation with electric boiler, separator and the associated lines forms the third section. The arrangement and linkage of the individual sections can be seen from Figure A1.

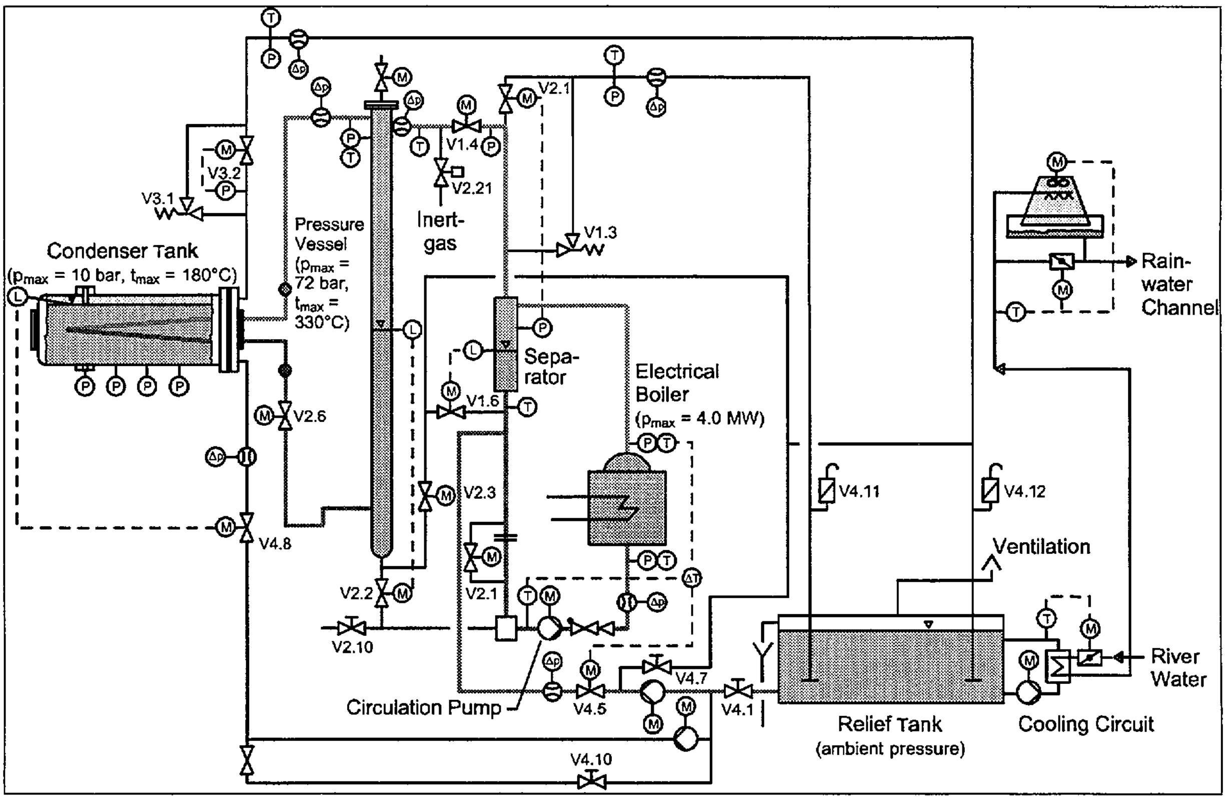

Fig. A1. System diagram of the NOKO facility.

The steam-water mixture produced in the electric boiler is passed into the water - steam separator where the steam is separated from the water. The water is pumped back into the electric boiler. The separated steam is either passed into the pressure vessel or - if more steam was produced than is needed - the excess steam blown off into the relief tank. The steam is condensed in the relief tank which is cooled by an external cooling circuit. The components are made of austenitic steel. An exception is the condenser tank, which consists of ferritic steel and is internally coated with XYVADUR 569 for reasons of corrosion protection. This coating is resistant up to 200°C.

Appendix B

PANDA facility

The PANDA test facility was erected in the early 1990s within the framework of the so-called ALPHA Program (Advanced Light Water Reactor Passive Heat Removal and Aerosol Retention Program) at the Paul Scherrer Institute. The PANDA test facility is a large-scale thermal hydraulic low-pressure test facility for investigating passive decay heat removal systems for the next generation of Light Water Reactors. In the first instance, PANDA is used to examine the integral long-term performance of the Passive Containment Cooling System for the Simplified Boiling Water Reactor (SBWR). The facility is an approximately 1:25 volumetric, full-scale height simulation of the SBWR containment system.

Within the project here, experiments with newly developed components were carried out in the PANDA test facility. This included the PANDA isolation condenser, the SWR-1000 building condenser and a plate condenser. All three components serve for heat removal from the containment after a serious accident.

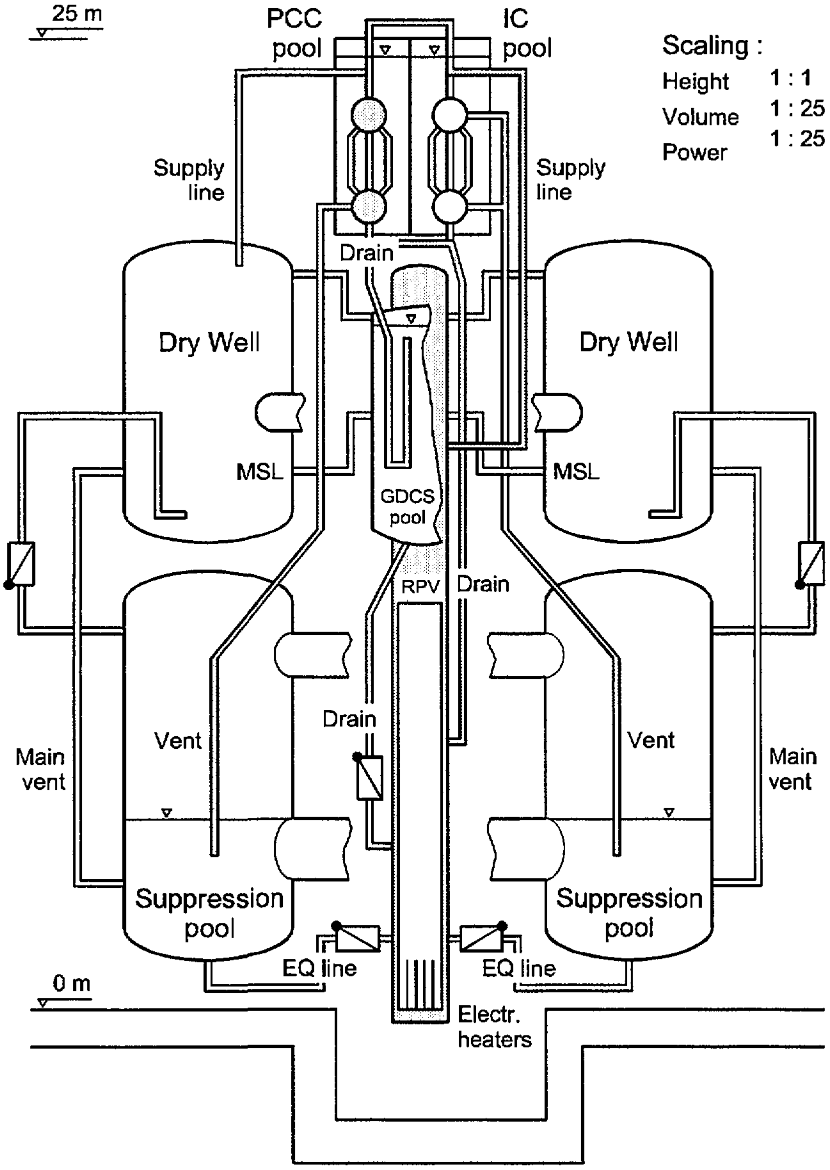

FIG. B1. Schematic setup of the PANDA test facility.

The PANDA test facility is of modular design. It consists of a pressure vessel simulating the reactor pressure vessel, two dry-well and two wet-well containers as well as a Gravity Driven Cooling System (GDCS) pool. The facility has two separated water pools. In a water pool two passive containment coolers (PCC) are installed. In the other pool one PCC which was also used as an isolation condenser (IC) was placed. The condensers are full-scale mock-ups which only differ from those projected for the SBWR by the number of tubes. The setup of the facility is shown in Figure B1 comprising also the connections between the containers, which are not described here in detail.

The PANDA-PCC consists of 20 vertically arranged tubes connected at their ends with drum-type headers. The upper header has a connection for steam supply, the bottom header has a drain for the condensate produced and a drain for non-condensable gases. The tubes of the PCC have an outside diameter of 50.8 mm and a wall thickness of 1.65 mm. They are made of austenitic steel.

The PCC as well as the IC are passively acting components. They are heat exchangers serving to condense steam. The gas flows to the condensers without the use of pumps. It enters into the upper drum and most of the steam is condensed in the vertical tubes. The condenser pool has a ground surface of 1.5 m × 2 m and a height of 5 m. The water level is approx. 4.50 m.