Cooling Elements for Passive Heat Removal

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ABSTRACT

To control design basis and to mitigate severe accidents in future nuclear power plants with light water reactors it is necessary to remove the heat from the containment by means of passive heat exchangers. Particularly for the severe accident application a new type of heat exchanging element was designed combining several functions.

The side facing the atmosphere contain cooling fins, combining the effect of enlarging the heat exchanging surface with the advantage that the ribs can absorb energy from impact loads. The cooling water circulates in press-fitted tubes inside the elements.

To determine the thermal properties tests were performed in four test facilities.

INTRODUCTION

For future use of nuclear power and in order to increase public acceptance of nuclear power plants, modern designs of light water reactors must meet new safety standards that incorporate passive systems. Several institutions and companies deal with the aspects of the new safety standard, aiming a safe nuclear technology.

In cooperation with the following institutions the test series were performed in the last four years to get data under different atmospheric conditions:

- Battelle Ingenieurtechnik GmbH	- Siempelkamp
- Siemens AG-KWU	- Forschungszentrum Jülich
- RWTH Aachen	- Paul Scherrer Institut
- Forschungszentrum Karlsruhe	- UNI Karlsruhe

Any safety technology has to aim at mitigating the consequences of accidents, which may lead to massive damage of the core or the containment, and also aim at safely preventing even long-term release of radioactive material.

This deterministic approach allows in future applications the possibility of a core-melt accident, as the containment is pressure-resistant, a core catcher system is provided and the heat being generated over a long time is removed by a passive system. This passive heat removal system consists of a large number of cooling elements which are integrated in the containment wall and, in addition, act as protection against fragment impact.

To examine the heat transfer behaviour under different loading conditions, 4 test series were performed:

a Battelle Containment Tests (Convection)	c NOKO (Condensation, single effect)
b CARLA Induction Furnace (Radiation)	d PANDA (Condensation, integral effect)

In all test series the original shape of the cooling elements remained unchanged.

DESIGN OF THE ELEMENTS

The cooling elements will have to meet the following requirements at the primary side (containment):

- optimum heat transfer at the surface, due to steam condensation or radiation absorption
- passive heat transfer due to natural circulation
- special design of the surface structure
- material: ductile cast iron

Fig. 1: Cooling element

MATERIAL

For production of the cooling elements, ductile cast iron GJS-400 is used. In Europe, this material is included in the DIN EN 1563 standard, in the US correspondingly in ASTM A874M-89 (reapproved 1993).

Material characteristics at room temperature are

tensile strength	R_m	$\geq 360 \text{ N/mm}^2$
offset point	$R_{p0.2}$	$\geq 240 \text{ N/mm}^2$
elongation at fracture	A	$\geq 12\%$
fracture toughness	K_{IC}	$\geq 3,000 \text{ N/mm}^{3/2}$

At the secondary side the requirements are:

- cooling water circulation in press-fitted tubes
- redundant cooling water circuits to natural draught cooling tower.

The rib-structure design of the surface, where the actual heat transfer takes place, creates a large thermodynamic surface.

In addition, these ribs of the cooling elements protect the system against fragments in the case of an accident, as they can absorb impact loads via plastic deformation, without any effects on the cooling system. Fig. 1 shows such a cooling element. The individual vertical tubes are connected by headers.

GGG-40 material has been developed over the past 20 years to a point where reproducible properties can be guaranteed. Fig. 2 shows the σ - ϵ -curve. Ductile behavior is obvious.

Fig. 2: σ - ϵ -curve of GGG-40

This material is used for the production of press components, large engine blocks and castings for tile presses, plastic injection molding machines, and, beyond that, for transport and storage containers for radioactive waste and spent fuel elements.

This type of container, the CASTOR, was subjected to extensive tests, such as fire test and high speed impact.

FABRICATION

Cooling elements are designed as modules which can be produced in any number required. Using a wooden form, the elements are sand-cast. Machining is not required for its as-cast surfaces, only the through holes have to be bored which later take up the cooling water tubes.

As-cast surfaces are sand blasted and coated with a temperature-resistant paint system. Weight of one finished element is about 500 kg.

Cooling water circulates in redundantly installed systems through the cooling elements. As Fig. 3 shows, each element contains seven tubes. These tubes are inserted into the holes and fitted to the walls by means of high pressure from a hydraulic unit (1). This ensures optimum contact between tube and cooling element. It also ensures optimum heat transfer from the cooling element via the tube wall to the circulating cooling water. This type of „pressure-fitting“ has proven very successful in the past; material of the cooling tubes is stainless steel CrNiTi 1810.

Fig. 3: Element with tubes

After installation of the tubes, which are shortened by lateral contraction, headers are welded to their top and bottom ends. Connection to the cooling system via the headers provides for equal flow resistance in all tubes, thus ensuring a uniform heat transfer.

Two elements were used for the experiments described below. For installation in a containment, these elements can be produced in series at low cost.

TESTS

Battelle Model-Containment

In order to effectively demonstrate how the cooling elements work, realistic conditions had to be created, which was possible within the framework of an extensive test series at the Battelle Model Containment. Fig. 4 shows a longitudinal section, indicating the main dimensions and the volume distributions of the model.

The two cooling elements were installed in the top area of the annulus.

Thermohydraulic processes of this type of cooling are well known as state of the art from many tests and calculations. Therefore, reliable results on the heat transfer can be obtained from these experiments (2).

A large number of temperature, pressure and velocity measuring devices were distributed within the model containment. All data were recorded during the tests (3).

Fig. 4: Battelle Model-Containment

Two tests were chosen for calculation of the heat transfer rate and the mean heat transfer coefficient:

Test 1	homogeneous steam/air atmosphere	1.5 bar	86°C
Test 2	stratified steam/air atmosphere	1.5 bar	45 - 90°C

For test 1, steady state operation, an effective heat transfer coefficient of
 $\alpha_1 = 217 \text{ W/m}^2\text{K}$
 was determined.

The effective heat transfer coefficient for test 2, stratified atmosphere, was determined to be

$$\alpha_{20} = 194 \text{ W/m}^2\text{K}$$

at the upper end and

$$\alpha_{2u} = 158 \text{ W/m}^2\text{K}$$

at the lower end.

This means that - depending on the atmospheric conditions - a cooling element is a heat sink that can remove approx. 10 to 13 kW per unit at a cooling water intake temperature of approx. 25°C (4).

To remove in a PWR-containment the decay heat with an initial power of about 20 MW decreasing to about 10 MW after 10 hours, a roughly estimated number of 800 elements is needed. 10 MW can be constantly removed by the cooling water in the first 5 hours and more than 10 MW can be removed by heating up the containment walls including the cooling elements.

The area of about 1800 m² with cooling elements should be placed at the upper side of the containment. A passive draught cooling tower should be placed 15 m above the cooling elements. These are connected to the cooling tower by redundant systems.

CARLA Induction Furnace

The design of the cooling elements provides an application in a core catcher to remove heat from a liquid melt surface with temperatures of more than 2000°C. The heat transfer is done by radiation. To measure the thermal properties a cooling element was installed on the top of the CARLA induction furnace. In Fig. 5 the test setup is shown.

Fig. 5: Test setup

The conditions were: temperature of the melt 1600°C, distance to the cooling element 0.8 m. The test duration was 1.5 h. The rate of heat removed by the element was 24 kW, the rate of water flow was 4.1 m³/h.

Investigations in the NOKO Test Facility

Following the tests at Battelle and Siempelkamp the cooling elements were integrated into the test series of the project „European BWR-R&D-Cluster for Innovative Passive Safety Systems“ (5).

In the large scale test facility NOKO the cooling elements worked as a plate condenser under different atmospheric conditions. These were: saturated steam, steam and oxygen and steam and helium under different pressure conditions varying from 2 bar to 15 bar. In Fig. 6 the condenser vessel with the main dimensions is shown.

Fig. 6: Condenser vessel

During the 17 experiments the effectiveness of the plate condenser was tested. The energy performance depends on the overall pressure and on the partial pressure of the non-condensable gases oxygen and helium. In Fig. 7 the energy performance is shown. The maximum value amounts to about 100 kW. The flow rate of the cooling water was adjusted to the condition that the outlet-temperature was under 100°C.

Fig. 7: Specific energy performance of the plate condenser

Investigations in the PANDA Test Facility

PANDA is a large-scale thermal-hydraulic test facility and well suited for the investigation of containment multi-compartment and 3D effects. Due to the modular construction and a broad variety of vessel interconnections, the effort for modification and adaptation to specific uses can be minimized. In essence, the PANDA facility consists of six cylindrical vessels (with a total volume of 460 m³) and four pools above the vessels (with a total volume of 60 m³) and the height of the facility amounts to 25 m. In one vessel, usually simulating the RPV, heaters with a maximum power of 1.5 MW are installed. The facility is designed for 10 bar over-pressure and 180°C maximum operating conditions.

Since 1995, various investigations related to passive heat removal from the core region and from the containment were performed in the PANDA facility. During the last few months, some integral system tests, using two plate condensers for the passive containment cooling, were carried out. For these tests, the PANDA facility configuration as well as the accidental transient scenarios were based on the advanced BWR design from Siemens (SWR 1000 (6), PANDA Tests (7)). The corresponding facility configuration is shown in Fig. 8. Two plate condensers, back to back in order to expose only the ribbed surface to the containment atmosphere, were mounted in one of the two PANDA drywells. The plate condenser secondary side was connected to a cooling pool, thus forming a natural circulation water loop. The PANDA reactor pressure vessel was used as steam source and one of the two wetwells was connected to the corresponding, drywell through the SWR 1000-specific hydrogen overflow pipe (venting of non-condensable gases and excess steam from drywell to wetwell).

Fig. 8: PANDA facility configurations for plate condenser transient system tests

Fig. 9: System response for simulated transient without loss of coolant

In Fig. 9 the transient system response in terms of pressure and air partial pressures is presented for the simulation of an accidental transient without loss of coolant. Starting at normal operation conditions (i.e. almost 1 bar air pressure in the drywells), Fig. 9 shows both, the pressurization of the containment due to the heat removal from the RPV as well as the removal of the air from the core flooding pool compartment to the wetwell.

Accordingly the plate condenser primary sides consists of almost pure air at the beginning of the test and of almost pure steam towards the end of the test, resulting in heat removal capacities of about 20 and 75 kW for the two plate condensers together, respectively.

The PANDA system tests successfully demonstrated the operation of the plate condenser as a passive containment cooling system for design basis accidents as well as for accidents with assumed core overhear (i.e. simulation of zirconium oxidation by injecting large amounts of helium).

CONCLUSIONS

During the last 3 years experimental data was gathered from experiments in different facilities concerning the heat removal behaviour of innovative cooling elements.

The results show that under different containment atmosphere conditions the cooling elements work very reliable on the secondary side of the heat removal system and they fulfil the expected requirement.

With these results a data base is available to validate system codes, containment codes as well as CFD-codes.

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