ADVANCED PASSIVE COOLING SOLUTIONS FOR ENHANCEMENT OF SAFETY IN NUCLEAR POWER PLANTS

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Abstract

After the Fukushima accident the development and implementation of additional safety features in nuclear power plants has become even more important. To offer customers the best solutions possible, AREVA is developing, in cooperation with the Technische Universität Dresden, Germany, **new advanced cooling solutions to increase the safety of nuclear power plants.**

By using an inherent safe passive cooling system for wet spent fuel pools, an adequate cooling of all fuel assemblies can be guaranteed, even in case of a station blackout. In Dresden, two large-scale test facilities investigate the thermal hydraulic behavior of single-phase and two-phase passive cooling systems driven by natural circulation. The test results are used for designing cooling systems for the nuclear and the industrial field.

If there is no space on the pool walls for heat exchangers, mobile heat exchangers can be placed into a free position of the fuel storage racks. Those mobile heat exchanger modules are designed in a similar geometry of a fuel assembly called **Advanced Cooling Tube**.

Keywords: passive, safety, advanced cooling, inherently safe, natural convection, autarkic, heat exchanger (HX), fuel assembly (FA), spent fuel pool (SFP)

1. Introduction

Reliable heat removal in nuclear power plants is necessary to ensure safe operation. For operating a nuclear power plant various components and systems are necessary which continuously produce thermal energy that cannot be used for generating electrical energy. Cooling of these components and of spent fuel assemblies is realized mainly by using active cooling systems, which need continuous power supply during operation. In case this power supply can no longer be ensured, these non-cooled components and systems could be overheated. Electronic components can be shut down to avoid overheating but, e.g., fuel assemblies are constantly producing decay heat which has to be removed continuously. The consequences of loss of cooling of fuel assemblies can be disastrous, as the Fukushima accident has shown.

In nuclear but also in non-nuclear power plants there are many different components and systems installed that could be passively cooled. Passive means cooling without any mechanical or human intervention and without external electrical power supply. The IAEA[1] defines four different

[1] IAEA: International Atomic Energy Agency, headquarters in Vienna, Austria, Europe

categories of passive systems. Details about these four categories are shown in Table 1. The developed passive cooling systems are classified as category B. That means there is no I&C necessary, there are no external power forces or sources needed and no moving mechanical parts allowed. The only thing moving is the working fluid that could be, e.g., water, water mixed with antifreeze fluid or for two-phase flow a special fluid with a low boiling temperature less than 35 °C allowing even low freezing temperatures. By using these kinds of passive cooling systems a reliable and autarkic cooling could be ensured. The goal is to provide an inherent safe passive cooling system to not only increase the grace period of cooling systems but rather guarantee a continuous cooling at normal operation conditions.

Table 1 Categories of passive safety systems defined by IAEA [1]

Category A
- no signal inputs of 'intelligence' - no external power sources or forces - no moving mechanical parts, and - no moving working fluid
Category B
- no signal inputs of 'intelligence' - no external power sources or forces - no moving mechanical parts; but - moving working fluids
Category C
- no signal inputs of 'intelligence' - no external power sources or forces; but - moving mechanical parts, whether or not moving working fluids are also present
Category D
- signal inputs of 'intelligence' to initiate the passive process - energy to initiate the process must be from stored sources such as batteries or elevated fluids - active components are limited to controls, instrumentation and valves to initiate the passive system - manual initiation is excluded

A worldwide unique large-scale reference system, which is operating as a single-phase passive cooling system, is installed in a wet spent fuel storage facility in Switzerland since 2008. Today this installation is able to passively cool about 500 fuel assemblies. Until end of 2016 the existing cooling system will be extended to cool more than 1000 fuel assemblies with over 1.2 MW decay heat with this passive cooling technique.

The development focuses on increasing the cooling efficiency without any support of active components. To reach this goal two-phase passive cooling systems are intensively tested. By using the evaporation enthalpy of two-phase systems more heat can be removed compared to single-phase cooling systems at the same size of the heat exchangers.

Until now, passive vaporization systems are not sufficiently investigated in detail yet. The main challenges of the investigations about multi-phase heat removal systems are the occurring instabilities in the intermediate circuit which have to be monitored to find out the reasons and possible improvement options and variants. The principle function is already well proven at a small-scale test facility. For testing the two-phase passive cooling system in large-scale a test facility is built at a scale of 1:1. The results of the first version of the test facility provide important information about possible optimization of the configuration and give suggestions for the dependence of different parameters to each other. Based on this learning it becomes possible to design optimized components for such systems and to further investigate the performance of improved configurations.

The goal of the tests is to design a validated prototype which serves as basis for scaling multi-phase flow heat removal systems and to develop numerical tools for designing such systems which can be further validated with the measurement data.

2. Principle of passive cooling

Passive cooling is based on the principle of free convection which means natural circulation between heat source and heat sink driven by a temperature difference between. There are many different kinds of passive cooling systems. Examples are heat pipes which are most of the time used for passive heat removal in small applications. A heatpipe is a hermetically sealed pipe with a capillary structure on the inside filled with a special coolant in which vaporization and condensation takes place for continuous heat removal. Heatpipes are mainly used in small systems with short distances between heat source and heat sink. Using heatpipes for longer distances and for bigger heat removal systems would cause shear flows which lead to high pressure drops. Due to the limited capillary forces the mass flow in the heatpipe is decreasing the longer the distance, which means a decreasing heat dissipation capacity.

To reach high heat removal capacities for bigger applications like spent fuel pools it is necessary to use large scale solutions with heat exchangers providing large surfaces with a high heat transfer rate. The developed systems using larger heat exchangers implemented into an intermediate cooling circuit. Thereby the coolant is absorbing the thermal energy from the heat source and is emitting it to the surrounding area. Figure 1 shows the principle of a passive cooling system as an example for inherent safe passive cooling of a wet spent fuel storage pool.

The system consists out of three thermally-linked cooling circuits. The first one is the pool cooling circuit (1). Due to the decay heat of the stored fuel assemblies (6) the water around in the pool is heated up. The heated water rises up because of density reduction. On the water-coolant HX (4) at the pool walls the heated water cools down by releasing thermal energy to the coolant in the intermediate circuit (2). By cooling the pool water it falls through the HX and flows to the button of the fuel assemblies, where it can be heated up again. The same effects occur in the intermediate circuit. The heated coolant flows to the coolant-air HX (3) caused by density changes due to temperature changes. The coolant cools down in the HX and flows back to the water-coolant HX in the pool. The heated coolant which is flowing through the coolant-air HX causes heating up of the ambient air above the HX which leads to an upflow of the air. Due to this effect cold ambient air is sucked from the outside into the cooling tower and causes a continuous cold air flow through the HX which cools down the HX and so the coolant inside.

In case of a two-phase flow passive cooling system the coolant in the intermediate circuit evaporates in the water-coolant HX (evaporator) by removing the heat from the warm pool water. The steam flows up to the coolant-air HX (condenser) and will be condensed down by heat dissipation to the surrounding. The condensate flows back to the evaporator and can be vaporized again.

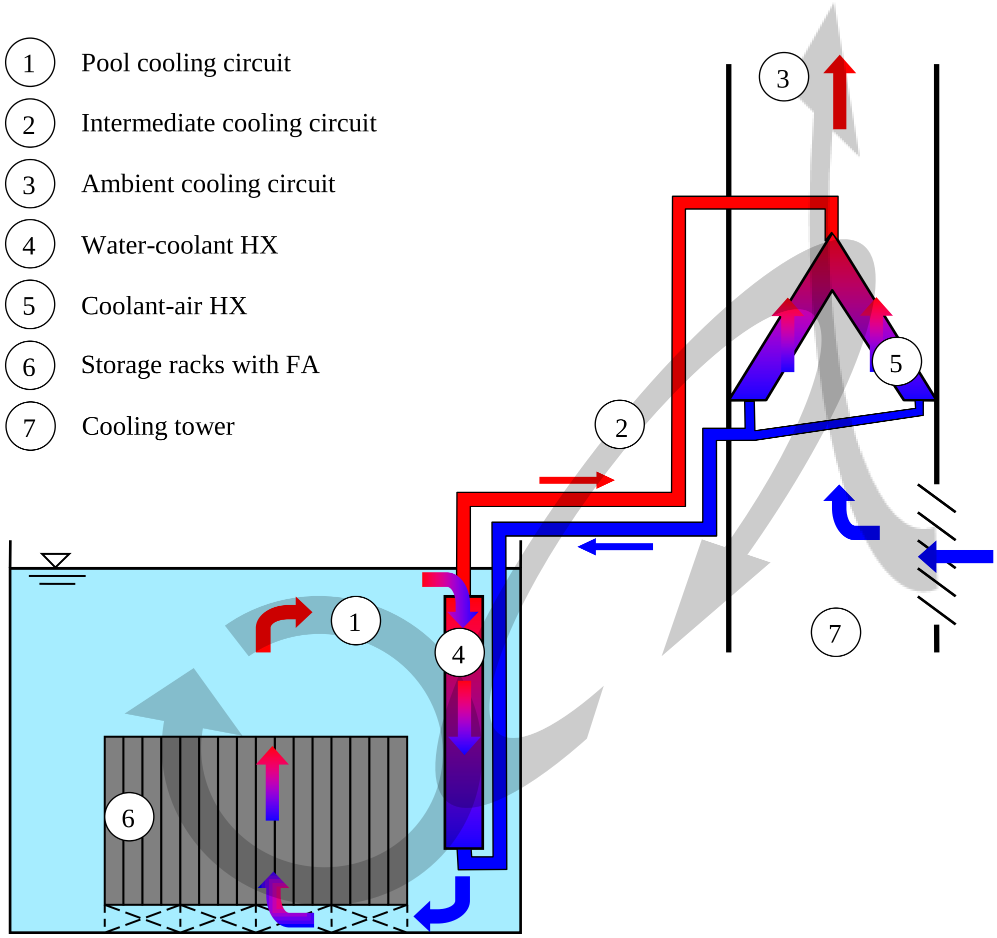

Figure 1 Principle of a passive cooling system

The intermediate cooling circuit of such systems is hermetically sealed to the surrounding. Significant features of these single-phase and two-phase passive cooling are furthermore the low pressure and temperature conditions during operation. Both kinds of systems are operating at an absolute pressure up to maximum 3 bars and up to 45 °C during normal operation. For abnormal conditions the absolute pressure can go up to maximum 5 bars at allowed temperatures up to 60 °C in the pool.

3. Single-phase passive cooling

3.1 Test facility for single phase passive heat removal

At the Technische Universität Dresden a test facility investigates the performance of a single-phase passive cooling system. These tests are directly related to the design of passive systems for wet spent fuel pools. At the test facility many different parameters can be changed and their influence of the performance and thermal hydraulic behavior can be measured. Since 2010 several coolant-air HX variants have been investigated and optimized for improving the amount of heat removal capacity.

In Figure 2 the design of the single-phase test facility with an exemplary configuration is shown. This test facility simulates a single-phase passive cooling system at a scale of 1:5, but with the same phenomena and characteristics compared to a large-scale facility. The fuel assemblies are simulated by electrical heaters with maximum 30 kW electrical power input. The tank contains two different plate heat exchangers with various plate configurations. The system is divided in two cooling lines. Thereby one plate HX in each case is connected to one side of the tube HX inside the cooling tower. Therefore it is possible to carry out tests with either one or two cooling lines to compare the performance and scalability of the components. The coolant-air HX is made out of four modules with two tube rows. Each of these modules can be separately connected to the cooling lines in the system, so the influence of each tube row can be investigated.

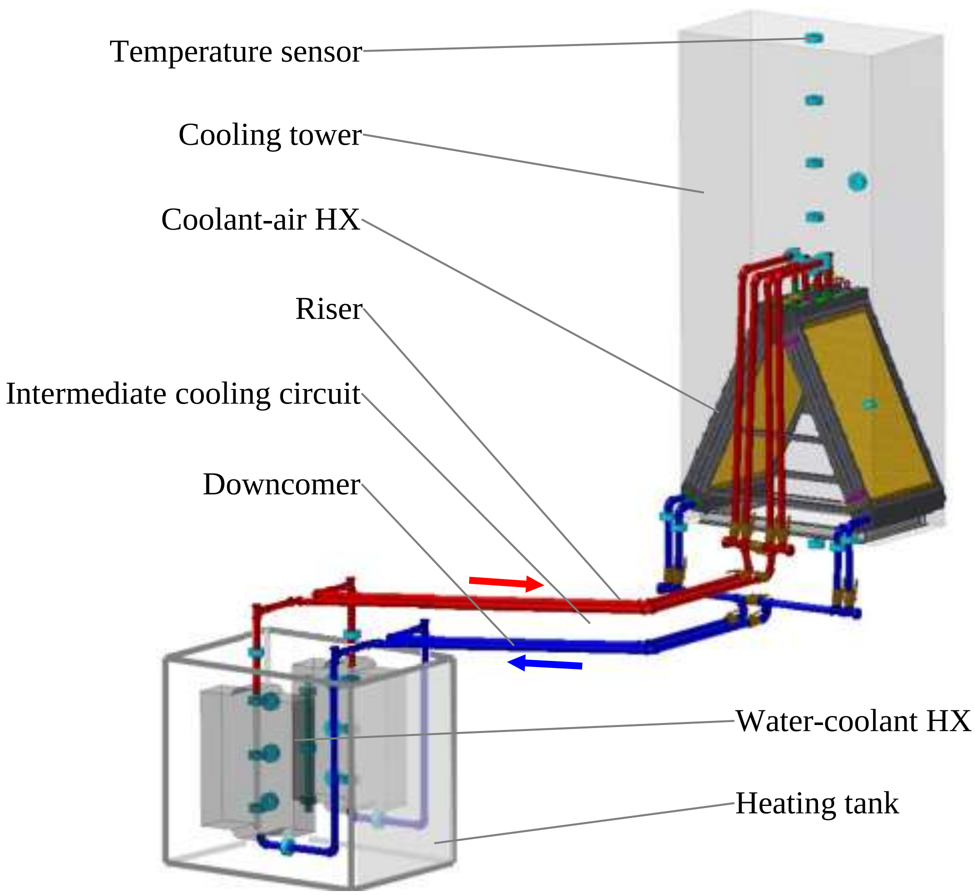

Figure 2 Design of single-phase test facility for passive cooling

To measure the temperatures in the system more than 30 Pt100 resistance thermometers are installed. Especially the inlet and outlet temperatures of the HX or rather the arising temperature differences are important for evaluation. The higher this temperature difference between heating tank and ambient air the better the heat removal capacity of the cooling system, because the mass flow in the intermediate circuit is driven by these temperature differences. Furthermore in the latest configuration of the test facility pressure difference measurement equipment is installed to measure the coolant side pressure drop across the plate HX, the tube HX and the pipes between. To measure the airside pressure drop across the coolant-air HX in the cooling tower inclined-tube anemometers are additionally installed.

3.2 Extract from the results of single-phase tests

Figure 3 shows a diagram with a comparison of results measured at the single-phase test facility in passive mode as well as for active mode with support of ventilation in the cooling tower. The heat dissipation capacity depends on the main driving forces of this heat removal system, which are density changes and pressure differences caused by the driving temperature difference between heat source (heating tank) and heat sink (ambient air).

Because of the huge amount of water in a fuel pool the system responds very slowly to changing ambient air temperatures. That's why for the design of such systems the maximum average ambient day temperature is the reference for defining the boundary conditions for active and passive mode. In the following diagram the defined temperature differences regard to a maximum average day temperature during the last five years of about 25 °C. Considering the maximum permitted pool temperatures of 45 °C for normal operation and 60 °C for abnormal operation temperature difference of 20 K (active mode) and 35 K (passive mode) are available [2]. The results are used for designing the expansion of the cooling system in a wet spent fuel storage facility in Switzerland.

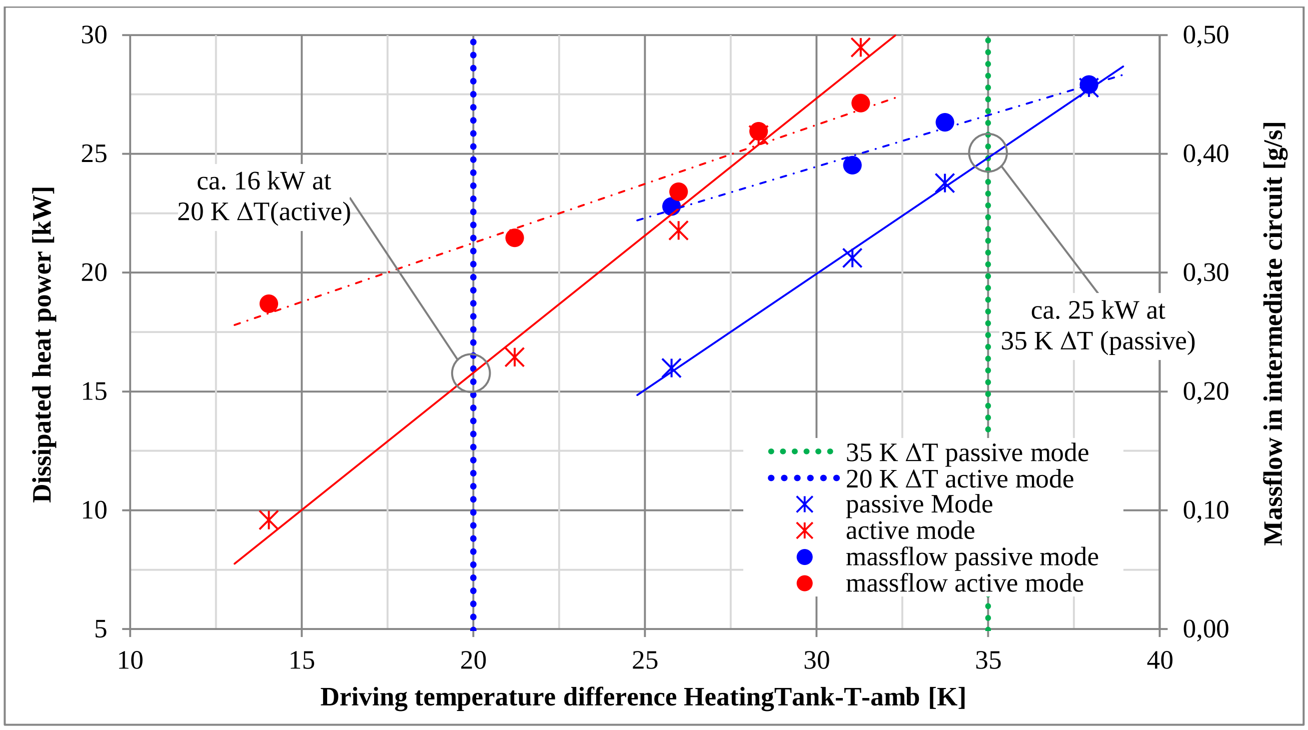

Figure 3 Comparison of the results at the single-phase test facility for passive and active mode

4. Two-phase test facility for passive cooling

4.1 Test facility for two-phase passive heat removal

To reach a higher heat removal capacity with the same size of cooling system and its components two-phase heat removal systems can be used. By vaporization of the coolant in the intermediate circuit a higher rate of heat transfer can be reached due to the evaporation enthalpy. Based on results and experiences of the small-scale test facility the large-scale test facility for two-phase passive heat removal was planned and built in 2015. In Figure 4 a schematic sketch of the two-phase test facility at the Technische Universität Dresden is shown.

The large-scale test facility in its latest configuration consists of one evaporator in the heating tank and one condenser in the cooling tank. The tank can be heated up with electrical heaters with maximum 72 kW. For the first tests the condenser is water-cooled to measure the removed heat capacity without having an additional resistance of a measuring device in the intermediate circuit. It is planned to change the condenser into an air-cooled component to get real boundary conditions. Between evaporator and condenser in the intermediate circuit there is a separator tank to separate gaseous and liquid phase. For sight control of the appearing phenomena there are several viewing windows installed.

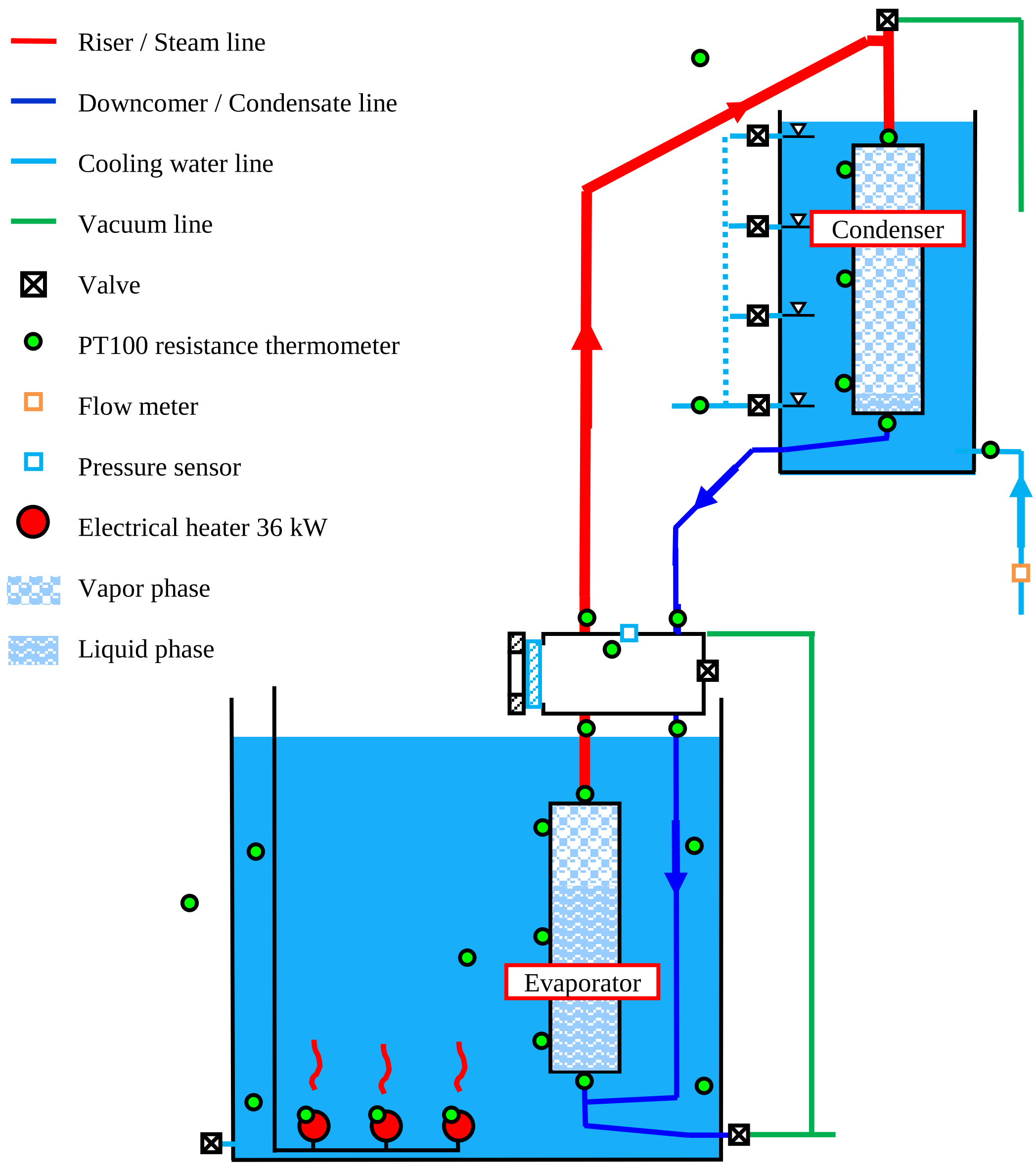

Figure 4 Design of two-phase test facility for passive cooling

One of the main influence parameters for the systems thermal hydraulic behaviour is the filling level of the evaporator. A completely filled evaporator causes instabilities and fluctuations in the intermediate cooling circuit, because of the increasing filling level due to nucleation during evaporation process. A low filled evaporator causes a low performance as well due to the reduced actively used inner heat removal surface of the heat exchanger. Furthermore, the optimal filling level depends on the systems configuration, e. g., with or without using a separator tank and also on the finish roughness of the inner evaporator surface. Moreover, the cooling temperatures in the cooling tank and the mass flow of cooling water around the condenser can be adjusted to measure influences of the systems performance. Another parameter which can be changed is the filling level of the cooling tank which allows adjusting the actively used heat transfer surface of the condenser. By modifying the thermal input power a wide range on different driving temperature differences between heat source and heat sink can be investigated. The different tested evaporation mediums, the flow velocity in the pipes and the heat exchangers, the roughness of the inner evaporator surface and the thermal power input rate can have a huge influence of the systems behaviour and performance.

4.2 Preliminary results of two-phase tests

The measurement data and experimental experiences from the tests carried out at the two-phase test facility of AREVA in the Technische Universität in Dresden are used for finding out improvement possibilities and a basis for further optimization actions of large scale two-phase passive heat removal systems. In Figure 5 an extract from the results of the two-phase tests is shown.

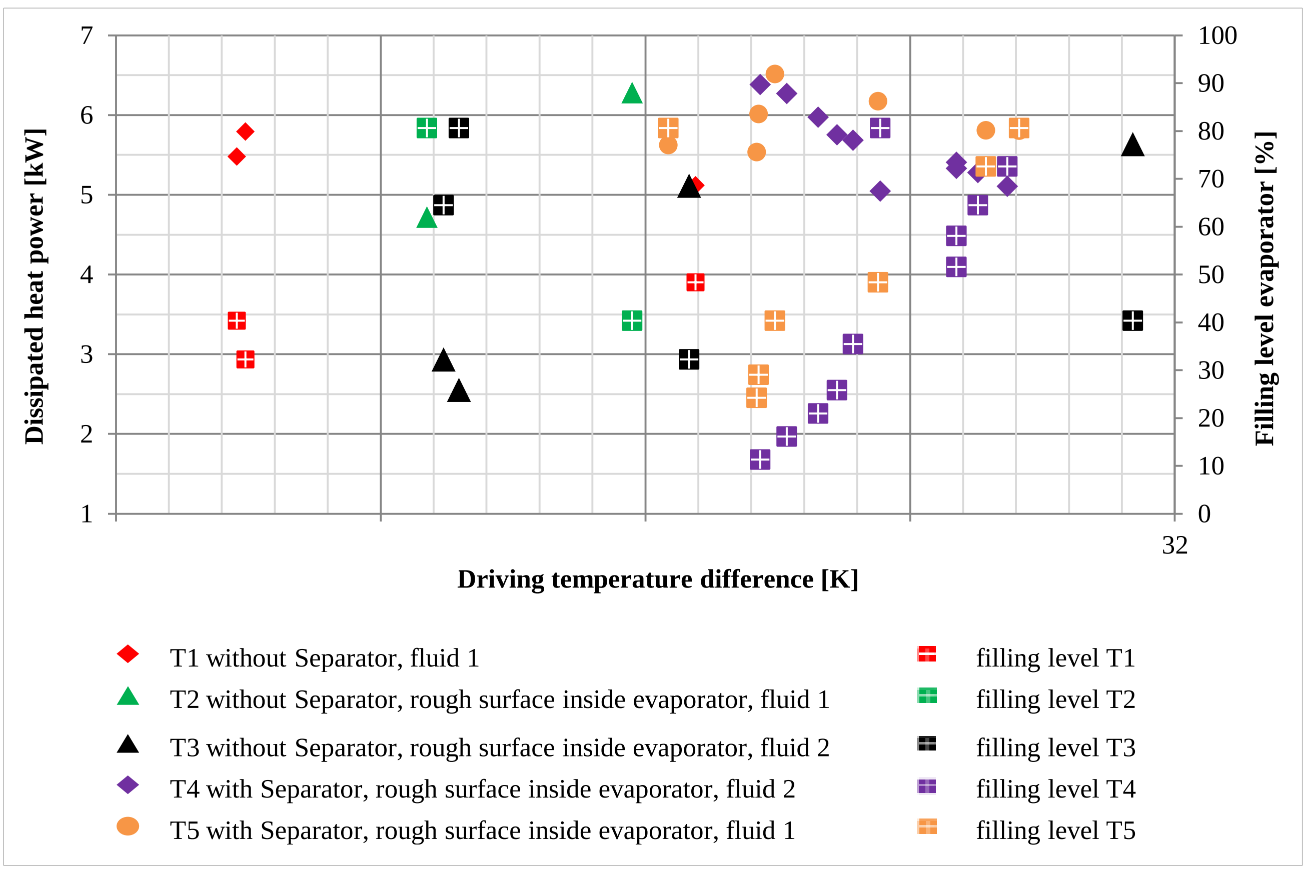

Figure 5 Results at two-phase test facility for different configurations and filling levels of evaporator

This diagram shows the influence of different filling levels in the evaporator on the heat removal capacity of the system. At the diagram the heat dissipation capacity at evaluated stationary points for different configurations over the driving temperature difference between heat source (heating tank) and heat sink (cooling tank) are shown. Furthermore, the diagram shows the corresponding filling level at the secondary axis for each configuration at a certain heat removal capacity. For the test T2 the optimal filling level is e. g. 40 % for a dissipated power of 6.3 kW. For the tests T4 and T5 the optimal filling level is for example approx. 15 to 40 % for a dissipated power of ca. 6.5 kW.

The fundamental information in the diagram should be the fact, that the optimal filling level for the maximum heat removal capacity of each different configuration is not comparable, because apart from the use of a separator tank also the used evaporation medium has got a huge influence of the system's behaviour and performance. Further tests with different evaporator and condenser geometries will increase the range of influence parameters. With the following experimental investigations an optimized configuration, an optimized filling level, an optimized heat exchanger and an optimized evaporation fluid will be found to develop a prototype for such kinds of large scale two-phase passive heat removal systems.

4.3 Further activities at the two-phase test facility

The next step at the two-phase test facility is the optimization of the components based on the present experiences and results. The evaporator will be changed by an optimized plate evaporator with an improved flow pattern for the multiphase flow. Furthermore the structure of this HX will be optimized for evaporation at low pressure and low boiling temperatures. Another possible geometry of the evaporator is a tube bundle, which will also be investigated at the test facility within the next few months. By this procedure an improved geometry for the evaporator will be found.

Then the water-cooled condenser will be changed into an air-cooled condenser which will be closer to real application fields. The new condenser will be a modular construction made out of several tube bundle modules to investigate the optimized transfer surface for a certain heat dissipation power rate. In the intermediate cooling circuit different evaporation mediums will be tested to investigate the behavior of the flow depending on the coolant characteristics. The expected evaporation medium which is currently under investigation has got a low boiling temperature below 30 °C at ambient pressure conditions.

With the optimized two-phase passive heat removal system it will be possible to investigate a large scale prototype for further implement this system into spent fuel pools for inherent safe cooling over long time periods. Furthermore, a numerical tool for calculating the systems performance in advance will be developed and validated based on the measurement data and experiences of the tests.

By help of this tool it will be possible to design single-phase as well as two-phase passive heat removal systems. The most important input data for the tool will be the required heat removal capacity, the available space and footprint for the components in the pool and outside the building, the required temperature in the pool and the available driving temperature differences. Based on that information the output data of the tool will be the required heat transfer surface for the water-coolant HX / evaporator and the coolant-air HX / condenser and the dimensions of the piping between the components.

Table **2** shows heat removal capacities for different flow types and operation modes. With the single-phase system it is already possible to achieve a cooling capacity for long-term storage in a wet spent fuel pool of more than 1 MW. With the two-phase system it is estimated to achieve over 2 MW with the same system size. Both applications will be cooled completely passive without having any active components installed. In the near future it will be possible to install a passive system for the operational spent fuel pool with a heat removal capacity of 9 MW or rather up to 26 MW depending on the allowed pool temperature.

Table 2 Heat removal capacity for different applications

Application	Nature	Function	Temperature	Cooling Capacity
Long-Term SFP for wet FA storage	Single-phase	Operational passive cooling	T < 45 °C	1.25 MW
Long-Term SFP for wet FA storage	Two-phase	Operational passive cooling	T < 45 °C	2 – 2.5 MW*
Operational Spent Fuel Pool	Two-phase	Passive Safety System	T < 45 °C 46 < T < 80 °C	2 to 9 MW* 9 to 26 MW*

* Estimated heat removal capacity, to be proven at test facility

5. Further application for advanced cooling systems

To upgrade, e. g., a wet spent fuel pool with an additional redundant cooling system it is possible to hang water-coolant HX on the pool walls. But one can also install mobile heat exchanger modules in the outer shape similar to a fuel assembly called Advanced Cooling Tube (ACT) [3].

The idea behind this concept is to implement several ACT-modules into free positions of fuel storage racks. The dimensions and geometry of ACT-modules can be adapted to any fuel assembly and storage rack design for different reactor types. At the poolside of the ACT-module natural convection is caused by a permanent generation of decay heat by the fuel assemblies and by cooling of water flowing along the poolside of the ACT-module. The flow inside the ACT-module can be either actively forced by a pump or passively without any active components. The passive mode the performance regarding the heat removal capacity will be investigated until the end of 2016.

The active operation of the ACT-modules is already investigated on a large-scale test facility for mobile heat exchanger modules. There, an ACT-module is installed in a simulated fuel pool with natural convection. In Figure 7 some possible geometry examples of ACT-modules for different reactor types and different overhead cranes are shown. Figure 6 shows a 3D-model of a possible positioning of several ACT-modules in an exemplary storage rack. With this placement all fuel assemblies around the mobile heat exchanger will stay easily accessible in case they need to be moved to other positions.

The ACT can be integrated in existing cooling circuits. But for reasons of redundancy it is recommended to operate the mobile cooling system as a separate system. The heat sink can be a standardized coolant-air-heat exchanger installed on the outer walls of the buildings.

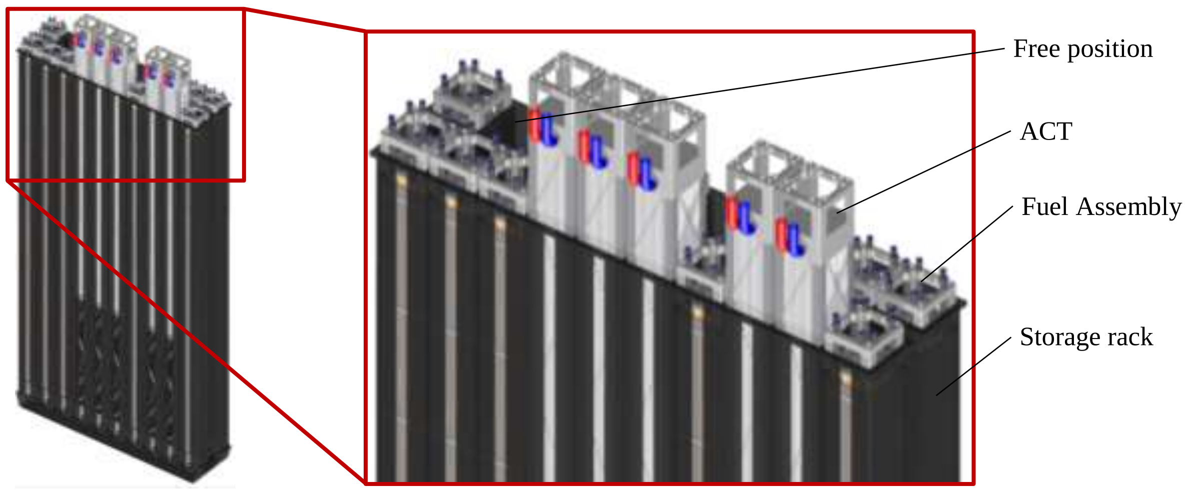

Figure 6 Possible positioning of fuel assemblies and ACT-modules in an exemplary storage rack

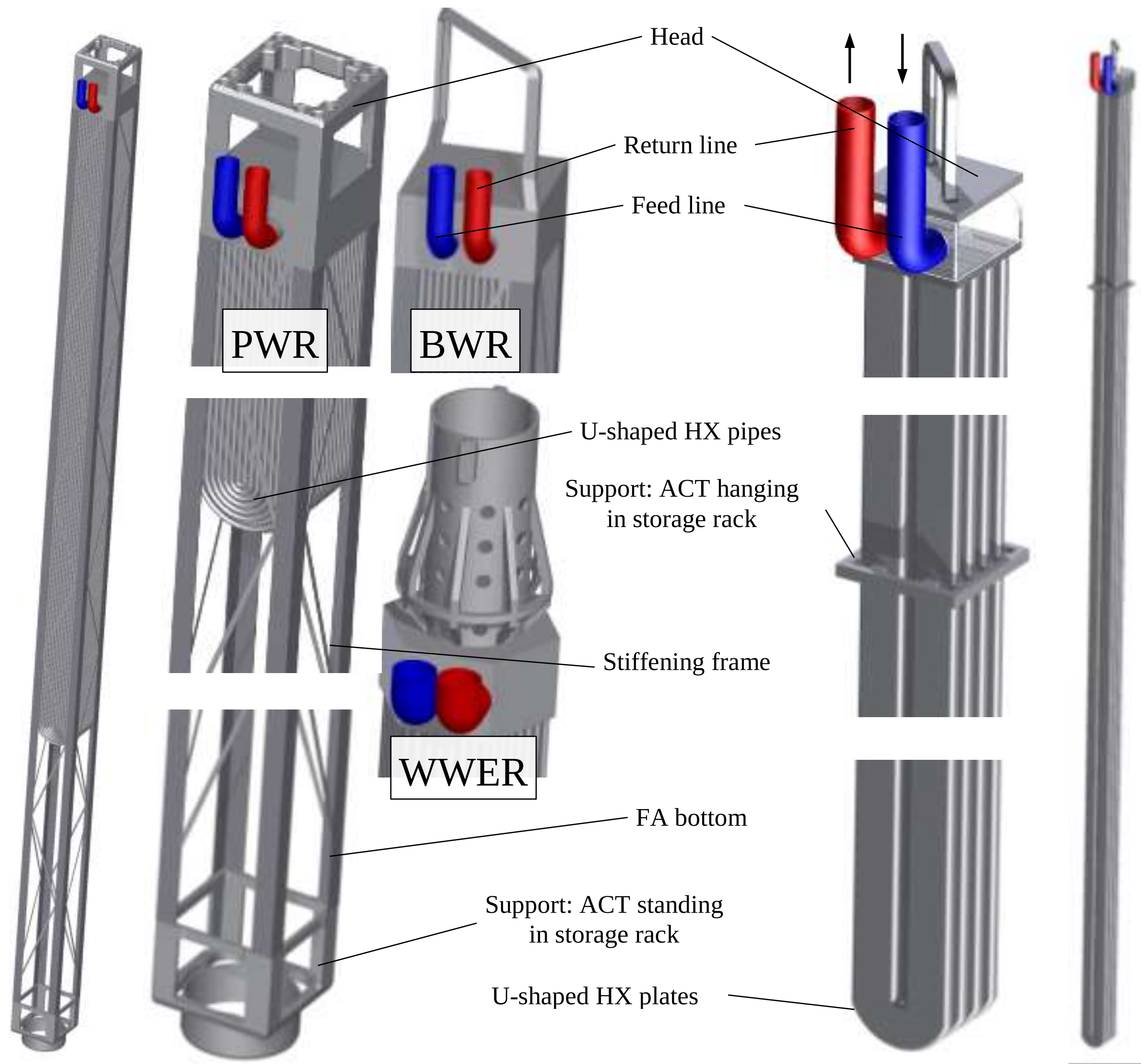

Figure 7 Examples for possible shapes of ACT-modules

6. Conclusion

Passive safety systems can increase safety in nuclear but also non-nuclear power plants. By using passive cooling systems, reliable heat removal and inherent safe operation will be possible without being dependent on any kind of external electrical or mechanical forces or sources. The wet spent fuel storage in Switzerland serves as a reference plant with an installed passive heat removal system.

To optimize these single-phase passive cooling systems a test facility investigates the performance and gives important results and experiences to improve these systems regarding an increasing heat removal capacity at low driving temperature differences for normal operation. The single-phase tests at the test facility at the Technische Universität in Dresden provide important measurement data for further development steps and to improve the design of water-coolant and coolant-air HXs. Furthermore the measurement data is used to validate the existing numerical tools of such systems.

By using phase change and the appropriate evaporation enthalpy in multiphase flow cooling systems even more heat capacity can be removed with the same size of components. This will open new opportunities for different kinds of applications for two-phase passive heat removal. The first version of the large-scale test facility in Dresden provides important measurement data for a better understanding of the occurring phenomena and different effects by two-phase passive cooling systems. Based on these results and the experiences with the test facility an improvement of the components can be made to further optimize the amount of heat removal capacity.

The goal of the investigations about single-phase and two-phase passive heat removal systems is to develop an inherent safe and reliable system to remove heat capacity from a heat source to a heat sink by using an intermediate cooling circuit. The systems are developed to enhance the safety in nuclear as well as in non-nuclear power plants and also for other non-nuclear applications. Using a passive cooling system to be independent from any external electrical or mechanical sources and forces can increase safety and reliability.

7. References

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