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Long-Term Containment Cooling System using a Water Turbine Driven Pump

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ABSTRACT

Westinghouse has designed and patented a Long-Term Containment Cooling System (LCCS) to support the Severe Accident Management (SAM) at VVER-440/V-213 nuclear power plant reactors with implemented In-Vessel Melt Retention (IVMR) strategy. The LCCS ensures stable heat removal and effective containment depressurization in case of a Severe Accident (SA), without the need of contaminated water leaving the containment and without the need of filtered venting. Crucial component of the system is a Water Turbine Driven Pump (WTDP) able to operate for prolonged periods of time under harsh conditions during SA. The pump has been designed and tested to be qualified for operation under SA conditions together with the pump manufacturer KSB. This paper summarizes the main features of the new LCCS and data from the pump qualification.

INTRODUCTION

In case of a Severe Accident (SA), In-Vessel Melt Retention (IVMR) strategy may successfully preserve the integrity of the Reactor Pressure Vessel (RPV). With IVMR, the primary system is depressurized and the reactor cavity (below and around the RPV) is flooded prior to core relocation. This allows for better decay heat removal via the vessel wall after relocation occurs, thus preventing RPV failure. However, in a long term, the sump water needs to be cooled to allow for pressure suppression inside containment, that is, to avoid a vaporization of the water and a pressure build-up inside containment, which can challenge the containment integrity and result in radioactive releases to the environment.

IVMR strategy has been implemented for the VVER-440 designs at Loviisa (Finland), Bohunice (Slovakia), Mochovce (Slovakia), Dukovany (Czech Republic), and Paks (Hungary) Nuclear Power Plants (NPP). However, this strategy does not consider an autarkic long-term containment cooling system, which shall be available in case of a persisting Station Blackout (SBO) with non-availability of all nominal cooling systems.

Westinghouse has designed an LCCS to support the Severe Accident Management (SAM) at VVER-440 nuclear power plant reactors with IVMR strategy. The Westinghouse LCCS ensures stable heat removal and effective containment depressurization in case of a severe accident. One main component of the system is a novel Water Turbine Driven Pump (WTDP) able to operate for prolonged periods of time (over six months). The WTDP (so-called RTS Pump™ by KSB) has been designed and tested to be qualified for operation under severe accident conditions together with the pump manufacturer KSB.

The main features of the new LCCS and results from the RTS Pump qualification are provided and discussed here.

WESTINGHOUSE LCCS

Requirements

The long-term containment pressurization of VVER-440 during SA is one of the last remaining open items after the Fukushima NPP Accident, recognized during the stress tests in the European Union and neighboring countries. The action plans of the most countries are asking for implementation of an appropriate solution for protection of the containment from overpressure.

By Regulatory Bodies, a dedicated long-term heat removal system [1] can be considered as most preferable technology. In this case, the utility is responsible to propose the specific requirements and mission function to ensure a proper accident management strategy.

The following plant specific requirements were derived based on the outcomes of the Post-Fukushima studies, VVER-440 plant specific requirements, and further analysis:

- The design of the long-term heat removal solution shall follow a good and simple technical approach.
- The LCCS shall be able to remove a decay heat rate of well over 6.1 MW (design capacity) from the containment of a VVER440/V-213 reactor and shall operate independently of the Alternative Spray System ACS, and when the ACS is no more available (at the latest, when the pressure reaches 3.5 bar (abs)).
- The LCCS shall not use electrically driven components inside the containment, and contaminated water shall not leave the containment (cooler to be located inside containment). However, external mobile power supply is available.
- The LCCS shall be able to withstand the harsh environment inside the containment and being operable in case of a severe accident with contaminated atmosphere and water, temperatures up to 140 °C, and gas phase pressures between 0.8 and 3.5 bar (abs).
- In a long term, the LCCS shall maintain approx. atmospheric pressure inside the containment. The system shall be operable up to the point when the decay heat is fully dissipated by the building structures (up to 6 months).

LCCS Concept

The simplified general Westinghouse LCCS concept is illustrated in Figure 1 below.

The aim of the LCCS is to remove the decay heat from the containment. For that purpose, the LCCS has two cooling loops. The prime in-containment loop does not require electrical power supply inside the containment, as it is based on the operation of one or more water turbine driven pumps (WTDPs). The WTDPs draw hot contaminated water from the containment sump and pump that hot water via strainers through the primary side of a first heat exchanger (HX1) placed inside the containment. The cooled sump water is further pumped to a spray ring situated inside the containment. By spraying cooled water into the containment atmosphere, the containment pressure is effectively reduced.

The cooling water of the second cooling loop is also used as the working fluid driving the turbine of the WTDPs. The driving pressure and water flow supply for the turbines is provided by an external cooling water pump powered for example by an external mobile Diesel (generator). The pressure of the turbine loop is chosen to be higher than the pressure of the pump loop, thus avoiding any transfer of contaminated water outside the containment. The removed heat is finally dissipated to an external ultimate heat sink.

In a first concept variant (Layout 1), atmospheric air is used as the ultimate heat sink. In this case, a second heat exchanger HX2 is required, for example, a (hybrid) cooling tower. In a second concept variant (Layout 2), an almost unlimited external water source (for example a river, a pond, or a lake) is used as the ultimate heat sink. In this case, the external water source is directly used as the cooling medium and no second heat exchanger HX2 is required.

The RTS WTDP has been designed as a submersible pump to be possibly located within the containment sump, e.g., in the steam generator boxes. However, the RTS Pump may also be located outside containment sump, well below sump water level in lower containment compartments (connected by inlet and outlet ducts) thus increasing the inlet water pressure and effectively evading any cavitation issue, in particular when the sump water temperature is close to saturation conditions.

A European patent EP 3 451 346 B1 [2] (filed Sept-2017) was granted for this concept and validated in affected countries. A similar general concept for the heat removal system was presented in the United States Patent US 10 032 530 B2 [3] (filed Feb-2016).

Currently, Dukovany NPP is requesting an additional and autarkic long-term containment cooling system, able to reduce the pressure and temperature in the containment by adopting the LCCS concept with a water turbine driven pump. The system shall be available also in case of a persisting Station Blackout (SBO) with non-availability of all nominal cooling systems.

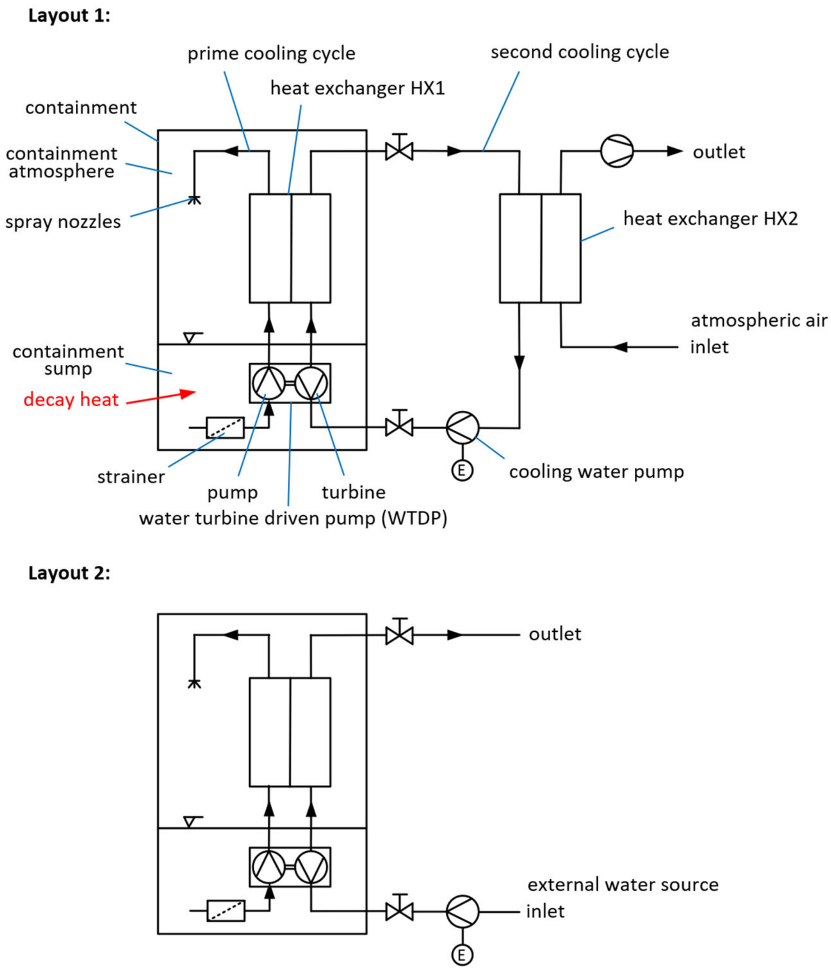

Figure 1: Sketch of the simplified LCCS concept

WATER TURBINE DRIVEN PUMP

Essential component of the system is a Water Turbine Driven Pump (WTDP) able to operate for prolonged periods of time under harsh conditions during Severe Accident (SA).

Westinghouse assigned KSB to design, manufacture, and test an adequate, high-end customized and engineered WTDP prototype based on common KSB pump/turbine hydraulics and well proven components (with lubricated bearings, double mechanical seal, etc.), with materials resistant to temperature, pressure, radiation, and chemical properties of the pumped sump water, with considerable amounts of dispersed solid debris particles.

The KSB Reactor-Turbine-Sump Pump (RTS Pump™) was developed to be used for such emergency cooling of a nuclear reactor containment. Note the RTS Pump can be scaled up/down to adapt its hydraulic parameters (e.g., volume flow and pressure head ranges) to a particular application.

Design Features

The RTS Pump has been designed for dry or wet installation, to be possibly partially or fully submerged in hot contaminated sump water. It withstands a radiation dose of up to 3.65 MGy during an emergency operating time of at least six months. Its design (maximum ambient und pumping fluid) temperature is 150 °C.

The RTS Pump consists of a pump stage featuring a waste-water hydraulic capable of pumping aggressive, abrasive water with large amounts of solid debris particles, sized well more than 10 mm, as caused by the severe accident. The turbine stage consists of a pump hydraulic used as a turbine. A double mechanical seal separates the pump stage from the turbine stage.

The double mechanical seal prevents contaminated pump water to flow into the clean turbine water stage. During standstill, the mechanical seal is leak tight up to a specified pump to turbine stages differential pressure (e.g., 5 bar). During operation, the pressure levels inside the turbine and pump stages are chosen to force any mechanical seal leakage into the pump side.

Turbine and pump impellers are connected to a common shaft which is supported by radial and axial plain bearings. Turbine impeller, bearings, and mechanical seal are located inside the turbine housing, whereas the pump impeller is located inside its own pump casing. Thus, the bearings and the driven end side of the mechanical seal are always in contact with clean turbine water. Only the non-driven end side of the mechanical seal and the pump impeller are in contact with contaminated fluid.

A sketch of the RTS prototype is shown in Figure 2.

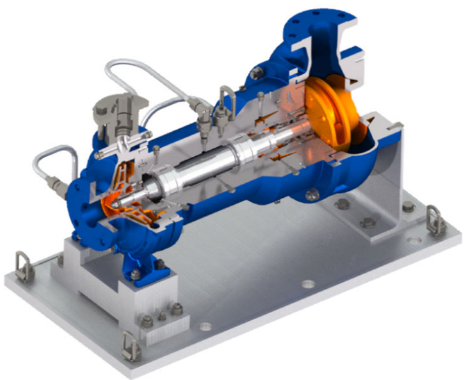

Figure 2: 3D-Sketch of the KSB RTS Pump prototype

Qualification Tests

The implemented test program for qualification of equipment under severe accident conditions was defined and developed based on IAEA recommendations (e.g., TECDOC-1818 [4]), available international standards and guides (e.g., ISO 9906 [5]), and Westinghouse and KSB experience in development of new and innovative equipment.

Besides leak tightness tests of the mechanical seal, hydrostatic pressure tests of the turbine and pump housings, and visual tests, RTS Pump qualification requires:

- **Hydraulic Performance Tests (HPT)**

Westinghouse specified the nominal hydraulic performance of the RTS Pump prototype as fixed values for the volume flow rate and differential pressure head of the pump (Q_P, ΔH_P) at fixed values for the volume flow rate and differential pressure head of the turbine (Q_T, ΔH_T). Prime aim of the HPT was to experimentally verify and validate that nominal hydraulic performance, and to prepare an operational map (see Figure 3) of the RTS Pump prototype in terms of Q_P as a function of ΔH_P within specified ranges of (Q_T, ΔH_T).

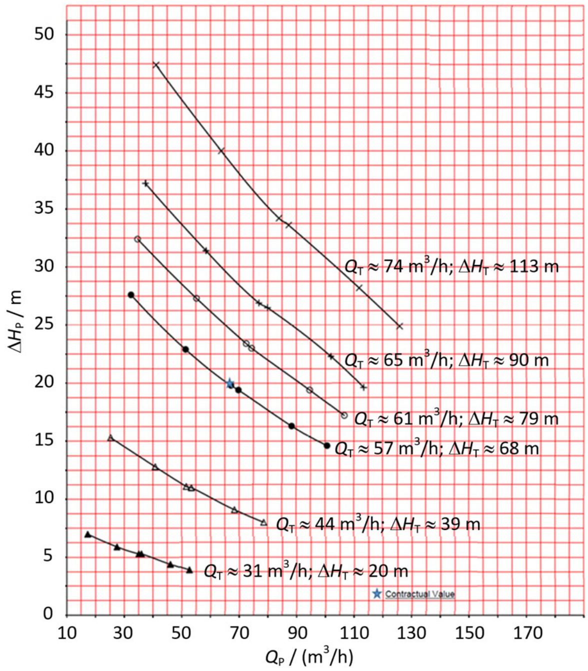

Figure 3: Operational map of the KSB RTS Pump prototype

Note the LCCS allows two options to evade cavitation, particularly when the sump water temperature is close to saturation conditions. Either the water inlet suction pressure is increased by locating the RTS Pump in lower containment compartments (connected by inlet and outlet ducts), or the water inlet suction temperature is reduced by a dedicated injection of some cold water into the pump suction line (e.g., turbine driving water during system startup, and reflux chilled pumped water during system operation).

- **Harsh Environment Tests (HET)**

Scope of the HET was to ensure proper operation of the RTS Pump under severe accident harsh environment conditions, with debris loaded water, high temperature and pressure on the pump side, and operation for a period of 35 days.

The RTS Pump was placed inside a flooded and isolated pressure vessel which recreates the containment sump (see Figure 4). Water temperature inside the vessel was controlled by electrical heating devices and an external recirculation pump plus heat exchanger cooler unit, also avoiding thermal stratification inside the vessel. Pressure inside the vessel was controlled via a pressurizer connected to a compressed air system and solenoid valves.

A booster pump provided the flow and pressure necessary to drive the RTS Pump.

The RTS Pump side was fed by debris loaded water inside the vessel (carbon and stainless steel, basalt fiber, and paint). The water flowed back into the vessel via external piping.

During HET, a particular temperature/pressure-time profile, with temperature and pressure ranging from 40–150 °C and 1–5.3 bar (abs), was applied to the water and the RTS Pump inside the vessel. The profiles were based on results from thermohydraulic analyses performed with MAAP. The bounding scenario was a double-ended Large Break Loss of Coolant Accident (LB LOCA) in combination with a station blackout leading to SA.

The emergency stop/start capability of the RTS Pump was further verified with more than ten stops/ starts of the booster pump during periods of high temperature and pressure in the vessel.

Figure 4: KSB test bed for HET of KSB RTS Pump

CONCLUSIONS

The RTS Pump is not driven by electricity but by a pressurized water flow from a mobile pump station (a booster pump powered by a Diesel motor). It can be used inside containment in case of severe accident with a persisting station blackout with non-availability of all nominal cooling systems.

The RTS Pump can be coupled with an in-containment heat exchanger to remove heat from the containment, and with an in-containment spray system to ensure effective containment depressurization in case of severe accident, without need of filtered venting. Application is particularly important in case of damage of containment hermetic isolation or for containments with relatively large leakage rates, e.g., the VVER-440 containment.

A double mechanical seal prevents contaminated pump water to flow into the clean turbine water stage, thus enhancing the plant safety by impeding any radioactive release from the containment via the RTS Pump.

Due to its turbine water lubricating bearing design, the RTS Pump operation is free of maintenance.

The RTS Pump has been designed and tested to be qualified for operation under VVER-440 severe accident conditions. KSB robust and well proven components' design and materials allow the RTS Pump for normal operation well beyond six months under the expected radiation dose and prevailing sump water harsh conditions (for temperature, pressure, amounts of debris particles, and chemical composition).

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[4] IAEA-TECDOC-1818: Assessment of equipment capability to perform reliably under severe accident conditions
[5] DIN EN ISO 9906: Rotodynamic pumps – Hydraulic performance and acceptance tests