Proceedings of ICAPP '10
San Diego, CA, USA, June 13-17, 2010
Paper 10339

Reactor Coolant Pump Type RUV for Westinghouse Reactor AP1000

Dr. Sven Baumgarten, Bernhard Brecht, Uwe Bruhns
KSB Aktiengesellschaft
Johann-Klein-Str. 9, 67227 Frankenthal (Germany)
Email: bernhard.brecht@ksb.com

Pete Fehring
Westinghouse Electric Company
Email: FehrinPJ@westinghouse.com

Abstract – *The RUV is a reactor coolant pump, specially designed for the Westinghouse AP1000 reactor. It is a hermetically sealed, wet winding motor pump. The RUV is a very compact, vertical pump/motor unit, designed to fit into the compartment next to the reactor pressure vessel. Each of the two steam generators has two pump casings welded to the channelhead by the suction nozzle.*
The pump/motor unit consists of a pump part, where a semi-axial impeller/diffuser combination is mounted in a one-piece pump casing. Computational Fluid Dynamics methods combined with various hydraulic tests in a 1:2 scale hydraulic test assure full compliance with the specific customer requirements.
A short and rigid shaft, supported by a radial bearing, connects the impeller with the high inertia flywheel. This flywheel consists of a one-piece forged stainless steel cylinder, with an option for several smaller heavy metal cylinders inside. The flywheel is located inside the thermal barrier, which forms part of the pressure boundary. A specific arrangement of cooling water circuits guarantees a homogeneous temperature distribution in and around the flywheel, minimizes the friction losses of the flywheel and protects the motor from hot coolant.
The driving torque is transmitted by the motor shaft, which itself is supported by two radial bearings. A three-phase, high-voltage squirrel-cage induction motor generates the driving torque. Due to the wet winding concept it is possible to achieve positive effects regarding motor lifetime. The cooling water is forced through the stator windings and the gap between rotor and stator by an auxiliary impeller. Furthermore, this wet winding motor concept has higher efficiency as compared to a canned motor since there are no eddy current losses.
As part of the design process and in addition to the hydraulic scale model, a complete half scale model pump was built. It was used to verify the calculations performed like coastdown, temperature distribution and cooling flows. During extended episodes of start/stop cycles the bearing material combination and also transient capabilities were proven.

I. INTRODUCTION

The RUV is a reactor coolant pump, specially designed for the Westinghouse AP 1000 reactor. It is a hermetically sealed, wet winding motor pump. The RUV is a very compact, vertical pump/motor unit, designed to fit into the compartment next to the reactor pressure vessel (Fig. 1). Each of the two steam generators has two pump casings welded to the channelhead by the suction nozzle. All major components of the pump itself that are described in the following paragraphs can be found in Fig. 2.

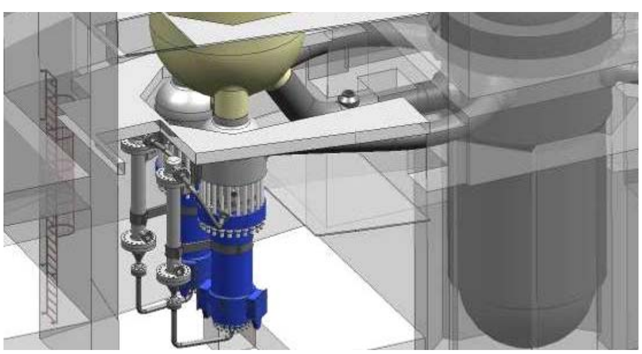

Fig. 1: Mounting position of the AP 1000 RCPs

The pump/motor unit consists of a pump part, where a semi-axial impeller/diffuser combination is mounted in a flow-optimized, one-piece pump casing. The impeller/diffuser combination is of very high efficiency and is based on the well proven RER-hydraulics, an RCP type that has been supplied to WEC for almost 30 years. Modern computational fluid dynamics methods (CFD-methods), combined with various hydraulic tests in a 1:2 scale hydraulic test assure full compliance with the specific customer requirements, best efficiency and lowest $NPSH_{req}$-values.

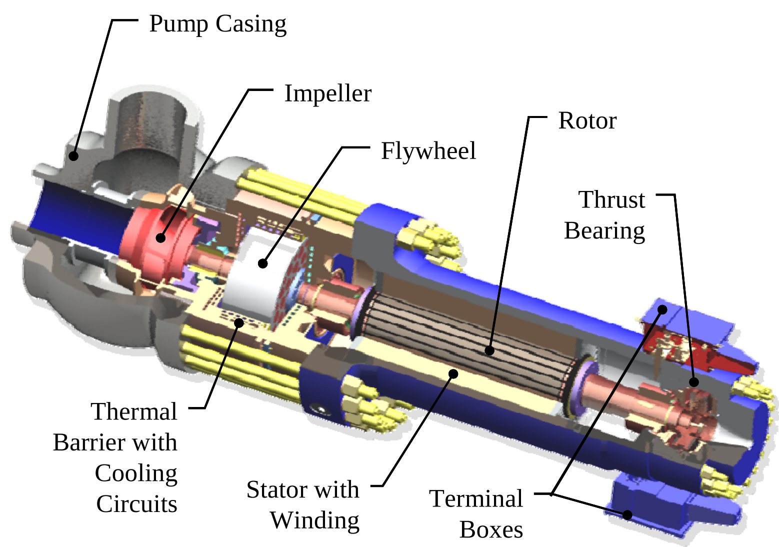

Fig. 2: Main pump components of the RCP type RUV

A short and rigid shaft, supported by a radial bearing, connects the impeller with the high inertia flywheel. This flywheel consists of a one-piece forged stainless steel cylinder, with an option for several smaller heavy metal cylinders inside. In order to avoid circumferential stress in a central bore, the flywheel is connected to both pump shaft and motor shaft via Hirth serration adapters. Therefore, no central bore is necessary and high stress levels can be avoided. In addition, no shrink fit to a shaft is needed to transmit the torque.

The flywheel is located inside the thermal barrier, which forms part of the pressure boundary. A specific, highly sophisticated arrangement of cooling water circuits guarantees a homogeneous temperature distribution in and around the flywheel, minimizes the friction losses of the flywheel and protects the motor from hot coolant.

Number of Pumps/Plant:	4			
System Temperature:	280	°C	(537	°F)
System Pressure:	155	bar	(2250	psig)
Capacity:	17 886	m³/h	(78 750	gpm)
Head:	111	m	(365	ft)
Total Power Input:	6 600	kW		
Motor Voltage:	6 900	V		
Length of Stator Cable:	4 800	m	(15 748	ft)
Overall Pump Length:	6 730	mm	(265	in)
Total Mass:	63 250	kg	(139 442	lb)
Mass of Removable Assembly	45 770	kg	(100 906	lb)

Overview of AP 1000 / RUV Technical Data

The driving torque is transmitted by the motor shaft, which itself is supported by two radial bearings. A three-phase, high-voltage squirrel-cage induction motor generates the driving torque. It is mounted in a one-piece forged motor casing with a bolted cover at the lower end side. Due to the wet winding concept it is possible to achieve an optimal cooling of the stator and avoid internal hotspots with positive effects regarding motor lifetime. The cooling water is forced through the stator windings and the gap between rotor and stator by an auxiliary impeller. Furthermore, this wet winding motor concept is of very high efficiency as compared to a canned motor with its enormous eddy current losses. A specially designed cable penetration forms the interface between internal wiring and the two terminal boxes, which accommodate the customer's electrical connectors.

As part of the design process and in addition to the hydraulic scale model, a complete half scale model pump was built. It was used to verify the calculations performed like coastdown, temperature distribution and cooling flows, showing that all calculation methods were suitable and the measured data agreed very well with the calculated results. During extended episodes of start/stop cycles the bearing material combination and also transient capabilities were proven far beyond the required extent.

II. FLYWHEEL

For reasons of plant safety it is required that the recirculation of primary coolant through the reactor core continues for a certain time after a loss of electrical power. Thus the rotor assembly of the RCP has to provide a large amount of inertia, the majority of which is concentrated in a flywheel. The flywheel is located between the impeller and the motor and is encompassed by two radial bearings.

Flywheels usually rotate in air or even in evacuated chambers in order to reduce frictional losses at the outer shell. In this case the pump is not allowed to have a shaft penetration and therefore the flywheel is located within the pressure boundary. It is surrounded by main coolant, which causes a considerable amount of friction and as a result, heat production. To minimize this effect, flywheel dimensions have to be reduced as far as possible. Usage of very high density materials such as Tungsten Alloy (TA) contributes to the reduction of the flywheel size.

A monolithic high density flywheel has a large mass and therefore high inertia values, but the material may not provide the strength required for safe operation. Moreover, especially when the material is cast or sintered, it cannot be guaranteed that the resulting solid is without any cracks or other flaws. A solid steel flywheel on the other hand may not provide enough inertia within the space envelope. The advanced bi-metallic design of the RUV (Fig. 3) therefore has a forged steel cylinder as flywheel base along with smaller high density cylinders that are fitted into bores within the flywheel base. This design has several advantages:

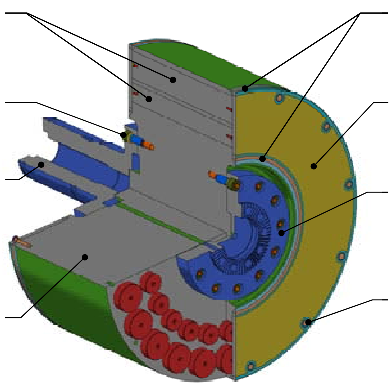

Fig. 3: Flywheel components

- The material for the steel base can be selected from an enormous variety of steels to exactly meet the requirements of the operating conditions (e.g. temperature, corrosive environment, speed, etc).
- Even large size forgings can be produced without flaws that would be relevant for integrity.
- The high density material has to meet only low requirements regarding strength since it is not relied upon structurally.
- The amount of high density material needed in order to provide the same inertia as a monolithic flywheel of that material is considerably lower. With almost the same size but less weight, a bi-metallic flywheel has the same inertia because those cylinders located close to the outer diameter account for the majority of the rotating inertia. In order to achieve highest inertia values and at the same time stress levels as low as possible, the distribution of the high density cylinders within the flywheel is optimized using FEM and an additional optimization module.

The RUV rotating assembly incorporates two shaft sections divided by the flywheel. The connection between shaft ends and the flywheel is achieved by Hirth serrations. Thus the flywheel has no central bore as no shaft penetration is needed. This improves stress distribution and helps to avoid high circumferential stresses at the inner face of the bore. Stresses like these could lead to crack growth starting at this surface. So the absence of such a surface greatly increases the safety margin with respect to loads resulting from flywheel rotation. In addition to that, assembly or disassembly of the rotor assembly is facilitated, since the flywheel is not shrink-fitted to the shaft.

Even though the flywheel design incorporates a high safety margin with regard to maximum stress and crack growth, the case of fragments leaving the flywheel and severing the pressure boundary is also considered. Since the pressure boundary in the flywheel area is also the thermal barrier, it has sufficient wall thickness to withstand the kinetic energy of missiles produced by the flywheel. So it can be ensured that even in the very unlikely case of a flywheel failure, the pressure boundary of the pump remains intact.

Design Features:

- ♦ Bi-metallic design with a high strength steel base and high density cylinders fitted within.
- ♦ Optimized geometry for high inertia values but at the same time lower stress levels, lower total mass and reduced losses.
- ♦ No shaft penetration and therefore no central bore which would cause high circumferential stresses or be a starting surface for cracks.

III. THERMAL BARRIER AND COOLING SYSTEM

Sealless pumps, used as boiler recirculation pumps as well as reactor coolant pumps, have to cope with the problem that one end of the motor is located close to the casing, where high system temperatures occur. In order to keep the motor windings at a reasonable temperature (ensuring a long lifetime), pumps of this kind incorporate a thermal barrier. It is either a passive element with low thermal conductivity or an actively cooled device with flow paths for external cooling water.

In the case of the RUV, the thermal barrier also accommodates the flywheel, which itself produces a considerable amount of heat by dragging the surrounding fluid. This results in a certain temperature distribution around and within the flywheel. The existing homogeneous temperature distribution is ideal in terms of lowering relative deflections and resulting stress levels and losses (Fig. 4). Since the strength of the base material decreases with rising temperatures, the permissible temperature level is limited by the required strength to withstand all cumulative stresses induced in the flywheel by the operating conditions. On the other hand, higher temperatures help to reduce the dragging effects and therefore losses can be reduced. So, as a result, the high ambient temperature in the thermal barrier cavity is essential to keep the required rotating inertia down to a reasonable level. For example, the optimal temperature level identified for the RUV flywheel of about 220°C (428°F) accounts for about 30% lower flywheel losses and about 10% lower required inertia compared to a temperature level of 75°C (167°F).

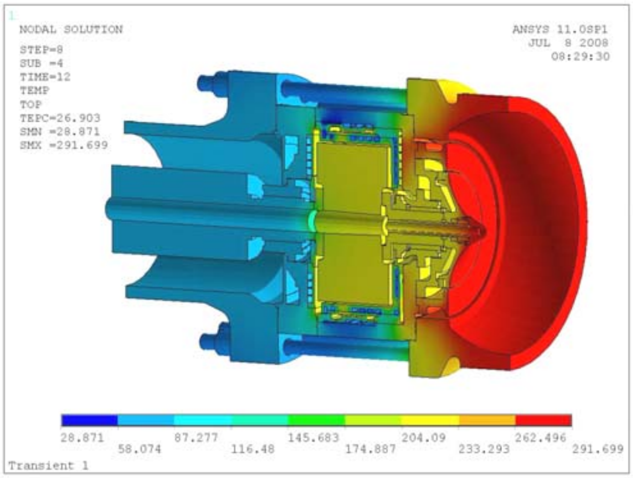

Fig. 4: Plot of the calculated temperature distribution in the heat barrier and surrounding areas (normal operation, steady state). Temperature unit is °C.

Thus, apart from keeping heat away from the motor cavity, the design of the thermal barrier with optimized cooling paths aims at the following:

- Keeping the temperature at a level that reduces losses as far as possible, yet at the same time cooling the flywheel cavity as far as necessary to preserve the required strength values of the base material.
- Keeping the temperature level constant especially within the flywheel.

To meet these requirements, the thermal barrier cooling system of the RUV utilizes a low pressure cooling circuit fed directly by component cooling water as well as an internal high pressure flushing circuit (Fig. 5).

The internal high pressure circuit is essential to the whole system. It is derived from the main pump flow at the end of the diffuser and directed towards the far end of the flywheel cavity through bores in the thermal barrier. In passing the cooling plate of the low pressure cooling circuit this flow is cooled down to a certain extent and finally fed into the flywheel cavity. By flowing around the flywheel and heading back towards the impeller it then picks up heat that is produced by the flywheel. It continues through an auxiliary impeller and is returned to the main impeller suction side through balancing holes. Propulsion for this circuit is provided by the differential head generated the impeller/diffuser combination and the auxiliary impeller located between the flywheel and the main impeller. In addition to the high pressure flushing circuit, direct cooling of the flywheel cavity is provided by the inner cooling plate surface of the low pressure cooling circuit and by the cooling plate which is fed by the high pressure motor cooling circuit.

By adjusting the flows of the aforementioned circuits it can be achieved that the heat produced by the flywheel is dissipated, the temperature distribution within the flywheel is homogeneous and that the temperature level is such that losses are reduced to a possible minimum and the stresses on the flywheel are kept within the allowable limits. Above that, the motor cavity is protected from high temperature exposure. The temperature distribution and the optimization of flows is the result of a highly detailed FEM model with CFD-calculated boundary conditions.

Utilizing the high pressure flushing circuit provides additional safety in the event that the supply of the component cooling water is lost while the pump is still in operation. Although the flywheel cavity temperature will rise during such an incident, the circuit is able to take out a considerable amount of heat, thus limiting the temperature level to a sustainable value, especially with respect to flywheel integrity. This means that flywheel fluid friction will not lead to an overheating of the flywheel which, as a consequence, would have resulted to high stresses and reduced strength values of the flywheel base.

Another important safety design feature of the high pressure flushing circuit is the fact that it is located completely inside the pressure boundary. There is no dependency on auxiliary systems such as connectors, external piping, valves, etc. The design guarantees that whenever the pump is operated the coolant circulation will be provided.

The motor cavity is cooled by another high pressure pumping device which circulates the coolant between the motor and the externally located high pressure heat exchanger. This circuit is also utilized to lubricate the two

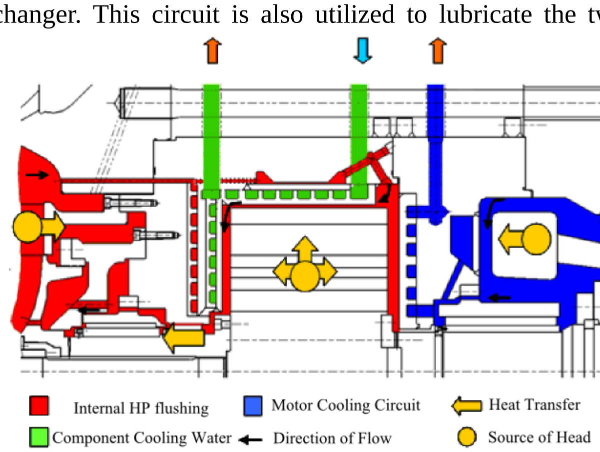

Fig. 5: Cooling circuits and heat transfer around the flywheel and within the heat barrier

lower radial bearings and the thrust bearing. Since cooling of the motor is additional to the thermal barrier cooling system, it can be ensured that temperature within the stator windings is maintained at low levels as there is no influence from the flywheel. Keeping the motor temperature low is vital in enhancing the life expectancy of the windings.

Design Features:

- Unique high pressure flow path for flushing the flywheel cavity. Fluid and heat transport completely within the pressure boundary and independent of component cooling water.
- Additional direct cooling by cooling plates.
- Flow and geometry optimized for homogeneous temperature distribution in the flywheel
- Separate external high pressure cooler and cooling circuit for the motor cavity to keep temperature level as low as possible for increased life expectancy of the windings.

IV. MOTOR AND ELECTRICAL COMPONENTS

The pump is driven by a pressurized sealless three-phase squirrel-cage induction motor with wet rotor and stator of vertical design. A great number of motors of this type have been built for boiler recirculation pumps in conventional power plants as well as in nuclear power plants (Fig. 6).

Fig. 6: View of a wet winding motor

The speed of the motor is variable by the variation of the output frequency of the variable frequency drive.

The rotor consists of magnetic sheet iron with copper bars. The stator is made of magnetic sheet iron and uses specially developed cross-linked polyethylene insulated cables. Because of the wet winding design the water in the motor can circulate between the windings to assist cooling.

The insulation of the motor winding has a high resistance against environmental strain cracking and is extremely stable at elevated temperatures. This property provides a built-in safety factor in case of a temperature fluctuation occurring during failure of the cooling circuit. This gives a safety margin for the stabilization of the system without the need to shut-down.

Compared to the canned type the wet rotor and stator type has a substantially better efficiency due to the absence of eddy current losses and is of simpler design. For pumps of this size the power input with a wet winding design is only about 85% of the power input required for a canned motor. For the RUV this means a reduction in losses of about 900 kW.

The electrical power cables are led through individual pressure-tight, self-sealing passages provided in the motor casing. A specially designed cable penetration acts as an interface between the windings and the two terminal boxes that are attached to the outside of the casing. The terminal boxes are subjected to atmospheric pressure only.

Design Features:

- The wet winding motor is of proven and reliable design. Some thousands of these motors are in operation.
- High efficiency due to sealless wet stator design.
- Simple design and small magnetic gap because of the absence of cans.
- Windings easy to cool with ample margin against overheating.
- Low temperature of the windings increases life expectancy.

V. SHAFT AND BEARINGS

As mentioned above, the RUV utilizes a segmented rotating assembly. It consists of the main parts (from top to bottom): impeller, shaft connection to flywheel, flywheel, shaft with rotor lamination and thrust bearing plate. In three locations, where the available diameter is limited to the shaft diameter, Hirth serrations are used to connect and align the two parts as well as transmit torque (Fig. 7). This type of connection is well known from KSB's RER type RCPs supplied to Westinghouse for about 30 years and it accounts for several advantages:

- Absolutely safe torque transmission without fretting corrosion.
- Easy assembly/disassembly: no (shrink) fits for main parts on the shaft; rotor is assembled/disassembled along with stationary parts, which facilitates handling of components.
- Perfect repeatability of alignment over lifetime.

The rotating assembly of the RUV is guided by three hydrodynamic journal bearings and one double acting thrust bearing (Fig. 8). The bearings are water lubricated and cooled by the closed internal motor cooling circuit.

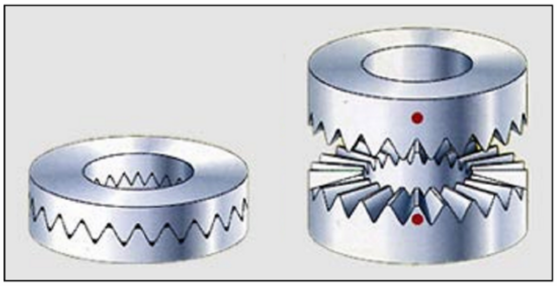

Fig. 7: Hirth serration

Two journal bearings are located close to the rotor laminations, which ensure excellent running conditions. The third one is placed between the impeller and the flywheel. Thus all rotor components with large masses (rotor lamination, flywheel) are guided by two radial bearings at each end.

The material of the stationary bushes of the journal bearings is a carbon fiber reinforced carbon (CFC), which is capable of withstanding very high temperatures (well above 1000°C (1832°F)) and thermal shocks without losing strength since no organic or plastic impregnation is used. The very high temperature resistance capability provides a wide safety margin in case of a reactor trip due to power and cooling water loss, since it assures a safe coastdown of the pump without the risk of overheated bearings. Reinforced carbon possesses also higher ductility in addition to higher tensile strength. The shaft sleeves will be made out of a chromium steel based material. The double acting thrust bearing uses the same materials as the radial bearings. Chromium steel based material is used for the pads. The axial thrust plate has incorporated CFC discs.

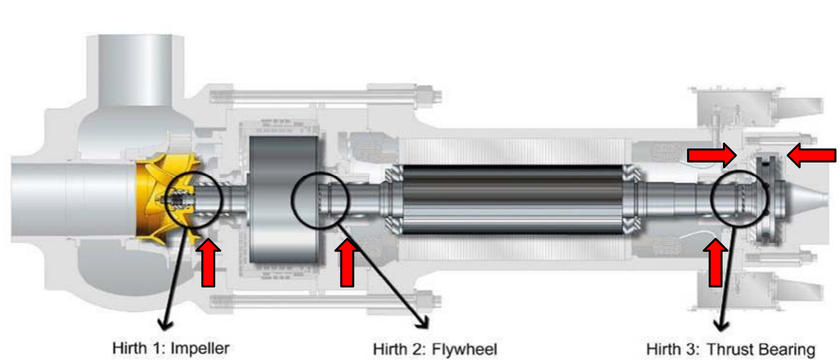

Fig. 8: Principal bearing arrangement – Arrows indicate direction of reaction force

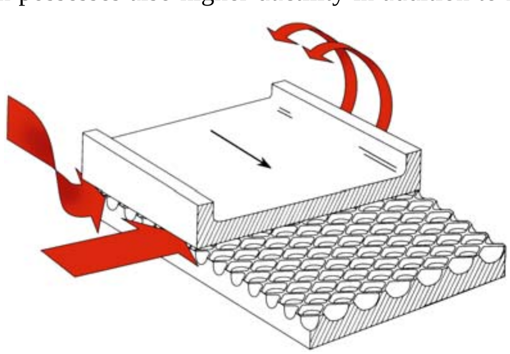

Fig. 9: Image of a cellular wear ring and its mode of action

This material combination is a product of a systematic, long term theoretical and experimental development program for water lubricated bearings setup in 1990 for both horizontal and vertical pump types. This development effort led to numerous bearing solutions for pumps in nuclear and conventional power plants as well as for reverse osmosis applications and deep well applications.

The KSB patented combination of a hard and smooth with a soft and slightly structured material has superior features in terms of friction and thus of wear even under severe conditions. This material combination can withstand high specific loads and has the transition from boundary layer to hydrodynamic lubrication at low speeds.

The load of the radial bearings is reduced to a defined minimum by the vertical design of the pump. Their design allows the flow of water at all times ensuring sufficient lubrication, low friction and increased stiffness. Altogether, stiffness, number and positioning of the radial bearings account for high rotor stability under all conditions. The unbalanced axial thrust resulting from the rotor weight and the hydraulic thrust is absorbed by the thrust bearing. Balancing of the impeller is arranged in a way that a fraction of the upward thrust remains during nominal operation. Again, this guarantees excellent running stability.

Running stability is also increased by KSB's cellular wear rings (Fig. 9), which are located at the front and back shroud of the impeller. This unique pattern is responsible for an increased stiffness and therefore improves rotordynamic stability. It also reduces the internal leakage flow rate which in return increases overall pump efficiency. The pattern also acts as a safety factor as it has very good anti-seizure properties.

<u>Design Features</u>:

- ♦ Wide experience in water lubricated bearings available.
- ♦ Number and arrangement of the radial bearings ensure excellent rotor stability.

- Bearing materials extremely stable even at elevated temperatures.
- Bearing materials provide high resistance against wear.
- Transition to hydrodynamic lubrication already at low speeds.
- Bearings require no external supply of water for lubrication and cooling.
- Double acting thrust bearing with optimized geometry for better stability.
- Cellular wear rings which improve efficiency, running stability as well as availability under emergency conditions.

VI. HYDRAULIC DESIGN

The hydraulic design of the RUV consists of a mixed flow, overhung impeller, a vaned diffuser and a spherical pump casing with one radial discharge nozzle. The impeller with a specific speed of n_s = 116 rpm (in European units, about 6000 rpm in US units) is closed (with front shroud) and has four profiled, 3D-curved vanes. The diffuser is of radial design in order to improve the hydraulic efficiency of the stage and to reduce the radial thrust acting on the rotor.

The impeller / diffuser / casing combination is based on existing hydraulics of the RER-reactor coolant pump and the LUV-boiler circulating pump types with same or similar specific speeds and dimensions. The hydraulic design has been analyzed, modified and optimized with the help of advanced computational fluid dynamic tools (commercial and proprietary CFD codes, Fig. 10). It is designed for best efficiency and lowest $NPSH_{req}$-values over the full relevant flow range and provide a stable performance characteristic.

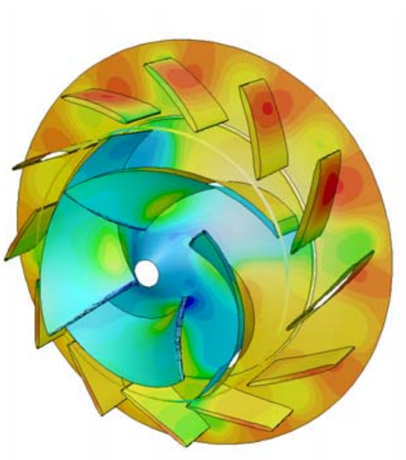

Fig. 11: CFD analysis of impeller/diffuser

The final design was tested in a 1:2 scale hydraulic model pump with both very high manufacturing and measuring accuracy. A detailed test program regarding head curve, efficiency, NPSH-behavior, four quadrant curve, axial / radial forces and pressure pulsation was performed. Full compliance of all hydraulic performance data with the specified requirements was verified.

VII. HALF SCALE MODEL TEST RIG

A new test rig for a half scale RUV model pump was built to perform pump tests under realistic conditions. The test data was used to verify calculations and to calibrate FE models. The validation process was split into two steps. During step one the calculations done for the full size pump were repeated for the scale model pump and validated with the test data. In step two the results were transferred to the models of the full size pump.

The test procedure included the analysis of the main pump components and their influence on the pump performance. Analyses were performed of the rotor coast-down, the functional capability of the thermal barrier, axial thrust, cooling circuits, rotor dynamics, wet winding motor, radial and thrust bearings.

Fig. 10: Scale model pump with test rig

The test rig was designed for operating at high system temperatures. The model pump is installed in the pedestal similar to the situation in the AP1000 where the suction nozzle is welded to the steam generator.

The test rig has an insulated closed piping loop with a high pressure cooler to maintain the system temperature. The piping loop and the pump casing are insulated to reduce heat losses. An external system supplies cooling water to the thermal barrier and the motor cooler. Variable flow rates enable simulating different cooling water conditions or even the loss of cooling water. The cooling water system is connected to a cooling tower for heat dissipation. The static pressure is achieved and maintained by a pressure vessel. Auxiliary systems are installed for chemical dosing and sampling. Around 70 sensors are installed to collect the test data.

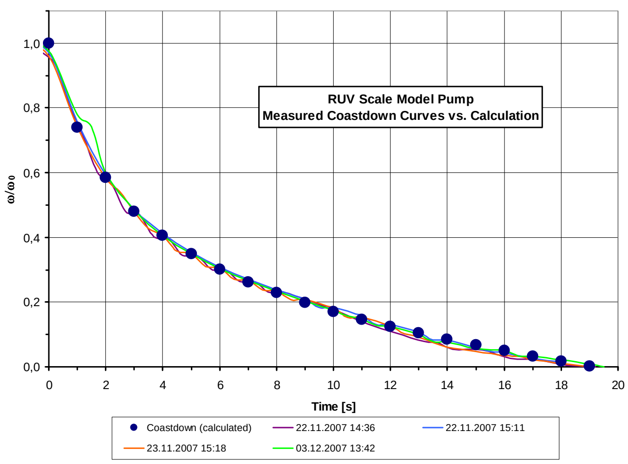

Fig. 12: Measured coastdowns curves vs. calculation

From November 2007 until February 2009 various tests were performed with the scale model pump. The pump ran quietly and showed very low vibration even at the lower end where the maximum deflection can be expected.

The results of all measurements were compared with calculations. An example is shown in where measured coastdown curves from several tests are compared with the calculation (Fig. 12). In this case the prediction matched the measured curves almost perfectly and proves the analytical calculation to be correct.

So far the model pump was operational for about 2500 hours with almost 6500 startups (twice the amount of startups specified for 60 year plant operation). These intensive startup simulations were performed to evaluate the wear behavior of the bearings, showing outstanding results after this large number of cycles. The relevant thrust bearing parts are shown in Fig. 13 and Fig. 14 during the final inspection. The bearing showed no signs of degradation or reduced performance during any of the test procedures. There was only minimal wear, which reflects the running-in process. The bearings have proved to be of superior quality, being fully capable of meeting the operational requirements, i.e. 60 years design lifetime without replacement! The added total wear of both parts was below 10 µm (0.39 mil). Considering measuring accuracy, this can be considered as negligible.

Fig. 14: Thrust bearing pads (stationary) after 6483 startup cycles.

Fig. 13: Thrust bearing plate (rotating) after 6483 startup cycles.

Summary of the Scale Model Pump:

- Before performing the tests, numerous calculations and analyses were completed especially for the scale model pump.
- Various tests were carried out with the scale model pump, including coastdown, thermal and transient behavior and rotordynamic performance.
- The measured values of all relevant parameters were within the expected ranges and proved the calculation methods to be suitable for application in the full scale pump.

- The pump in general and especially the bearings have encountered about 6500 start/stop cycles, which resembles more than twice the required value stipulated in the pump design specification.
- The outstanding performance and the resistance to wear of the bearings show that the material combination is fully suitable for application in an RCP.