Implementation of Multiple Measures to Improve Reactor Recirculation Pump Sealing Performance in Nuclear Boiling Water Reactor Service

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Introduction A modern reactor recirculation pump operating in a boiling water reactor (BWR) circulates a large volume of high-temperature, pure water from the reactor pressure vessel back to the nuclear core by feeding directly into multiple stationary jet pumps, which are located on the outer pe-riphery inside in the downcomer region of the reactor vessel. Using variable speed regulation enables operators to vary coolant flow in a direct way and provides the most stable reactor power output feasible. A technical abnormality with a reactor recirculation pump, such as increased leakage from the mechanical seal, can result in a power station unexpectedly having to be shut down for repair.

This paper describes the sudden increase in stray current activity leading to rapid deterioration of the mechanical end face shaft seal in a reactor recirculation pump. The problem accelerated after the installation of new variable frequency drives replacing the original motor-generator sets. As a result of the seal face damages incurred, two short unscheduled outages were required to refurbish the mechanical seal and continue power station operation.

To facilitate the change out of the old sealing technology using tungsten carbide rotating seal faces with seal faces made from direct sintered silicon carbide, a +2,500 hour laboratory test was conducted under actual reactor recirculation pump sealing conditions. The test results are discussed further on in this document as well as the station's operational experience from September 2013 onwards. Furthermore, this article describes the elaborate shaft grounding and measurement arrangement which has been installed on both reactor recirculation pumps as well as the initial results gathered. The objective of this system is to monitor and minimise potentially damaging stray currents flowing into both the pump- and mechanical seal parts.

The reactor recirculation pump mechanical seal

Sealing a reactor recirculation pump (RRP) using a mechanical end face shaft seal is considered one of the most challenging applications found in the industry. Reactor recirculation pump seals limit the leakage of the reactor coolant fluid along the pump shaft. Therefore, these seals are an integral part of the reactor coolant system (RCS) pressure boundary. Maintaining the pressure boundary integrity under all operating conditions has been demonstrated in the past by the Flowserve type N mechanical seal. The N-Seal cartridge has redundant staging capabilities, whereby each of the two seal stages is capable of handling full RCS operating conditions, while splitting the system pressure in half during normal operation.

Hydrodynamic sealing technology used in the N-Seal revolves around the capability of reliably operating a mechanical seal using a thin fluid film inside the seal gap and avoiding high face wear at the same time. Operating seals with a thin fluid film strongly reduces seal leakage, as leakage is roughly proportional to the cube of film thickness. On average, this film thickness is in the range of 0.5 to 2 µm. The film thickness is achieved by careful control of the seal's design to match the operating conditions of the specific application.

The leakage rates used in RRP seals are typically higher than other mechanical seal applications due to the specific transient conditions this type of mechanical seal needs to withstand during normal BWR plant operation. Having "stability of seal leakage" is considered more critical than having mere low leakage rates by itself, in order to provide extremely reliable service to these unspared pumps. Therefore, the film thickness for such mechanical seals will tend to be more towards the high value side of the indicated film width range. When facing a stationary pump shaft condition, hydrodynamic designed mechanical seal faces are closed and effectively make contact. The seal faces separate immediately once the pump shaft begins to rotate. This seal face separation is the result of strong lifting forces, which are generated as a result of rigid body axial displacement of the flexibly mounted seal face. The stiffness of the fluid film provides the majority of the load support needed to physically separate the seal faces.

A mechanical face seal must have an adequate state of lubrication relative to its materials and environment to operate successfully *[1]*. An adequate state does not necessarily mean using full hydrodynamic lubrication. Mixed lubrication with only a small fraction of the load supported by physical contact is usually acceptable. Since seal face contact needs to be anticipated when going through start/stop and transient conditions, having the option of using dissimilar (e.g. hard vs. soft) seal face materials greatly enhance the capabilities for this type of seal design.

To help achieve an adequate state of seal face lubrication, seal designers may apply features in a sealing surface that promote fluid penetration into the sealing gap. The original N-Seals were equipped with so-called thermo-hydrodynamic circulation slots which were equally divided around the circumference of the tungsten carbide rotating seal face. The principle of these thermo-hydrodynamic circulation slots is based on intense local cooling of the seal face through the strong "out scoop" characteristics of the individual slots. This type of feature also has the favourable characteristics of working equally well under either direction of shaft rotation and the capability of rejecting particulates in the sealed fluid. As the outer ring periphery is cooled more than areas further remote from the sealing interface, the flat seal face surface develops radial wedges in the same quantity as the number of slots made into the seal face. These thermal induced

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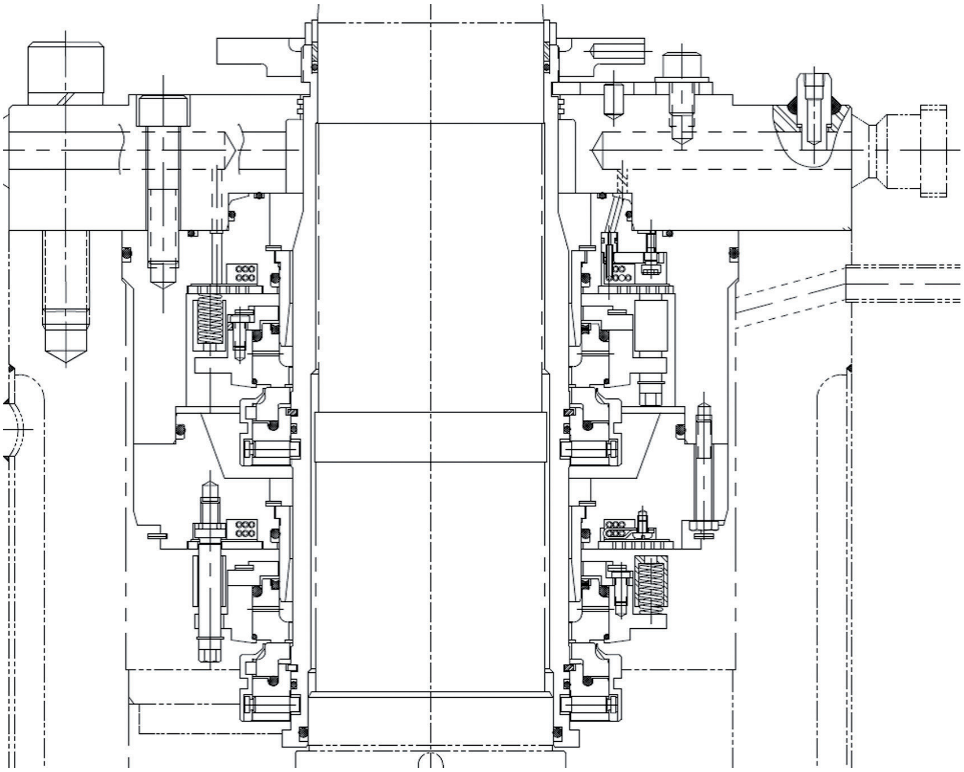

Fig. 1.
The two stage N-Seal cartridge for BWR operation.

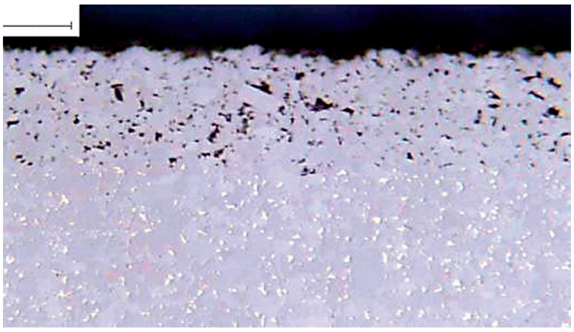

Fig. 2.
Dealloying of nickel binder in tungsten carbide.

lubricating wedges will build high pressure peaks, which are influenced by the pressure differential across the seal gap and the drag flow *[2]*.

Seal designers have a strong pref-erence using rotating seal faces made from hard and stiff materials, such as tungsten- or silicon carbide. Be-sides good tribological properties, these materials also possess superior heat transfer characteristics. Combined with turbulent flow of the water, both frictional heat as well as viscous heat is transferred efficiently into the cold seal water flowing along the seal. The softer carbon graphite stationary seal face on the other hand adds dry running capabilities and adapts to the hard face, thereby limiting the leakage of the seal water.

For a mechanical seal facing a wide range of operating regimes or operating with thin fluid film widths, inevitably one will be exposed to some form of asperity contact between the two seal faces. Therefore, using a "hard-soft seal face material selection" provides the ideal combination for poor lubricating liquids, such as lukewarm, deionised water. **Figure 1** shows the N-Seal design as used in RRP service.

Sealing ultra-pure water

All BWR power stations around the world apply strict primary water chemistry control based on stringent directives provided by their nuclear steam side supplier (NSSS) and industry support organisations such as VGB PowerTech. The guidelines dealing with water qualities for primary reactor water indicate the highest achievable purity levels, which is ex-pressed in electrical conductivity. For BWRs, reactor water conductivity is targeted < 0.1 µS/cm with a neutral pH. The consequence of this chemistry is that this water has become electrically non-conductive or dielec-tric. When a mechanical seal is continuously purged with ultra-pure make-up water it will seal this dielectric water. This fact introduces additional challenges for the mechanical seal face materials, on top of this lukewarm water being a poor lubricator by itself.

Dealloying of nickel binder tungsten carbide seal faces

Nuclear mechanical seals designed in the seventies and eighties, often used seal faces made from nickel binder tungsten carbide. The quantity of nickel binder is in the order of 6 %. Nickel tungsten carbide has good heat conductivity properties, good wear properties and has a good resistance to mechanical shock compared to non-metallic seal face materials. Furthermore, it is very strong, hard and mechanically ductile. When combined with carbon graphite its tribological properties for sealing water are satisfactorily as long as the seal water chemistry is com-patible.

Drawbacks of this material are that it is very dense, which can add gyroscopic characteristics for high speed applications. It heat checks (for-mation of radial cracks caused by thermal expansion) when subjected to high contact loads and it has limited chemical resistance in oxidising environments. In nuclear applications involving ultra-pure water this last characteristic can be observed by dealloying of the nickel binder by the ultra-pure water flowing across which continuously tries to restore its natural ionic balance *[3]*.

The purpose of the binder is to provide toughness and tensile strength by holding the hard particles together. In the case of nickel, it is less electrochemically noble than the tungsten carbide and therefore also dictates the chemical resistance of the material. Lack of binder means lower strength and toughness. What is left behind is a matrix of hard and sharp-edged tungsten carbide crystals, which will easily be released to abrade the surface of its counter face. **Figure 2** shows a picture of a nickel binder impregnated tungsten carbide seal face where the binder has been leached away to some depth leaving this fragile, chalky layer of abrasive particles.

Sealing performance between 2000 to 2010

To comply with regulations and industry guidelines, utilities are required to keep their nuclear installations in the best possible condition con-cerning nuclear safety. To meet this requirement, one nuclear power station had decided to upgrade both its RRPs with new N-6000 mechanical seals.

From 2000 to 2010, performance on the A-pump was good and the new seal cartridge achieved an average mean time between repair (MTBR) of 4 to 6 years with only 1 repair in 2006. In contrast to similar service in pressurised water reactor (PWR) systems, which can show up to 18 years of N-seal MTBR, a reduced seal

MTBR in BWR operation is normal. While the seal faces would show classic wear and tear, they never showed any abnormal damages.

However, in the period from 2001 to 2010 sealing performance on the B-pump was less reliable. In fact, this seal cartridge was refurbished 4 times, with repairs in 2002, 2003, 2005 and 2009. Besides classic seal wear and tear, the tungsten carbide rotating seal faces showed narrow radial canals from the apex of the thermo-hydrodynamic circulation slots to the inner diameter of the rotating seal face. The canals looked somewhat erratic and resembled lightning lines. **Figure 3** shows a picture from 2003 of the tungsten carbide rotating seal face with this abnormal damage. A damage observed in all the eight thermo-hydrodynamic circulating slots.

While seal MTBR on the B-pump was shorter than on the A-pump nuclear safety or power generation was never jeopardised due to a prematurely failing mechanical seal. All B-pump mechanical seals in this period were refurbished during scheduled refuelling outages.

In 2005 and 2006, the station decided to install a set of carbon graphite shaft grounding blocks on the electric motor shafts of both pumps. The motor vendor also made preparations for the 3 existing electric drivers to be connected to a variable frequency drive in the future, by insulating the motor bearings. These modifications initially seemed to have a positive effect as mechanical seal MTBR increased to 4 years for both pumps.

Sealing performance 2010 to 2013

In 2010, another upgrade was conducted involving the RRPs. This time, the original motor-generator sets used to vary electrical output to the pump's electric motors in order to control the pump speed, were replaced by new variable frequency drive systems. While the implementation was a success for operations, the mechanical seals on the B-pump started trending towards instability much faster than before with a first repair needed on both pumps during the August 2012 refuelling outage. This was despite the fact that the new variable frequency drive was of a type specifically designed to produce less damaging harmonic output than early models.

Then after restart the B-pump seal started to degrade by showing decaying sealing pressures, merely two months after start-up. An unscheduled outage was required in January 2013 to repair the mechanical seal. In May 2013, a second unscheduled outage was needed to repair the same B-pump mechanical seal and finally a third seal repair had to be conducted during the August 2013 refuelling outage.

Differing from the damages observed in the period 2001 to 2010, this time the radial erosion canals of the tungsten carbide rotating seal faces had become wide and one could visually detect severe erosion damage due to high speed water flowing across these damaged sections. In addition, one could observe damages between the B-pump shaft and the shaft sleeve of the mechanical seal indicating that arcing had taken place at this specific location. **Figure 4** shows the clear erosion damage of a thermo-hydrodynamic circulation slot in a tungsten carbide rotating seal face of the B-pump mechanical seal.

Besides costs associated with repairing the mechanical seal, such as labour, dose, parts and procurement, lost revenue cost is another significant contributor to the total cost. Most importantly however, is the fact that an increased reliability of the mechanical seals and RRPs reduces the number of transients, such as thermal and mechanical loads for the nuclear installation. All factors combined made the reactor system engineering decide to start a detailed investigation into this problem with the support of external specialist companies.

The outcome of this investigation was diverse and entailed a seal face material and technology upgrade modification for the B-pump mechanical seal as well as the installation of an elaborate pump shaft grounding system, which allows measurement and registration of actual shaft voltages and shaft currents during operation.

Unlike a classic test laboratory setting where one has the luxury of having ample time to test each individual partial solution separately, the utility was forced to implement different partial solutions simultaneously to avoid future unscheduled outages. The following describe the individual solutions which have been implemented since January 2013, as well as station operating experience since.

Applied solution #1

The first solution introduced was to replace the tungsten carbide rotating seal faces and substitute these with rotating seal faces made from direct sintered silicon carbide (SiC). Many years of operating experience using SiC material in nuclear and other challenging sealing applications demonstrated that it is a superior seal face material compared to tungsten carbide. Direct sintered silicon carbide is virtually chemically inert and does not suffer from dealloying of a binder material in ultra-pure water. It also has increased heat conductivity properties and hardness. Furthermore it has a low density. Combined with a carbon graphite counter face, the tribological properties outperform most other seal face material combinations.

Sealing ultra-pure water brings additional challenges, which have been explained in different technical publications and papers *[4]*. To avoid the risk of electro static charges through the flow of electrons accumulating on sharp, machined edges of the thermo-hydrodynamic circulation slots (i.e. spark plug principle), a precision face topography pattern (PFT) was applied on the silicon carbide rotating seal face. The application of PFT technology using micro laser machining capabilities make it possible to machine precise and well controlled hydrodynamic features, which have shown to create very strong hydrodynamic lift. In contradiction to the thermo-hydrodynamic circulation slots, such a profile is just a few microns deep and does not possess sharp edges or material transitions.

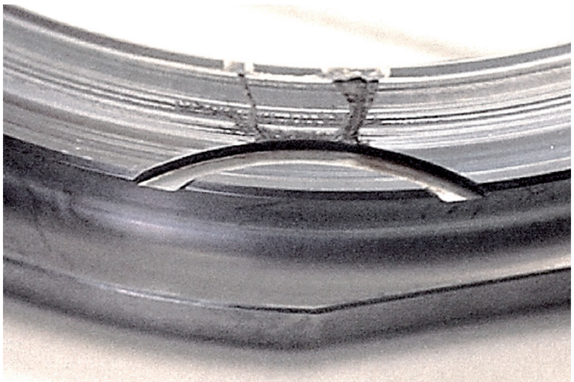

Fig. 3.
Radial canals in the thermo-hydrodynamic circulation slots, August 2003.

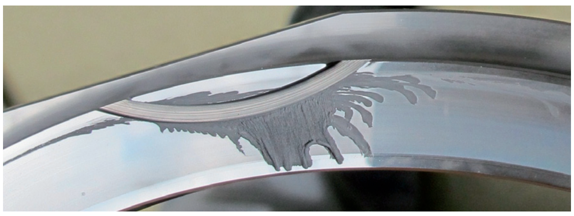

Fig. 4.
Wide erosion radial canals formed in the tungsten carbide rotating seal face, May 2013.

PFT was developed by Flowserve using micro laser machining technology back in the early 1990s. A laser is used to ablate material using a photo-chemical process to selectively remove SiC layers (about 0.4 microns per layer) so as to form micro/macro features that produce dual functions; hydrostatic and hydrodynamic fluid pressure load support between the seal faces. The hydrodynamic part is created using a circumferentially varying sinusoidal shape that results in converging and diverging regions around the seal face that under relative rotation generate high-pressure zones and significant load support and face separation. These same features vary linearly in the radial direction where the maxi-mum depth is at the outside diameter of the face and the zero depth is at a specified seal dam. The hydrostatic capability provides fluid pressure load support during static (non-rotation) conditions providing reduced breakout forces at start-up. The combination of these two char-acteristics provides the seal with significant film stability and non-contact operation in a wide range of (upset) operating conditions. The micro-scopic depth of the features also makes them inherently resistant to particulates in the sealed fluid.

In addition to the PFT technology adding the hydrodynamic lift off pattern, the silicon carbide seal faces receive a second laser treatment, which is referred to as preferential surface treatment (PZ). The purpose of this secondary laser treatment is to ensure that the electrical conductivity of the silicon carbide material is raised to a level where it matches the electrical conductivity of the counter seal face made from carbon graphite material. The theory behind this technology is that if there is no difference in electrical conductivity between the rotating and stationary seal face materials, there is no drive for the redundant electrons to cross the seal gap between the two seal faces.

Researchers discovered that by using a laser and applying a specific energy density beam to the surface of the SiC, they could turn a non-conductive surface into a highly conductive one. This is accomplished by a thermochemical reaction were the peritectic reaction tempera-ture is exceeded resulting in some peritectic phase separation and the formation of carbon. It is the formation of carbon that provides the useful function in the PZ treatment to resist the effects of electro corrosion. The laser process involves overlapping passes of the laser beam on the SiC face in the presence of an inert gas, which amplifies the conversion. This process does not remove any material, as would be the case during ablation at energy levels that would cause a photochemical reaction, but only a slight SiC melting and carbon formation as previously described. Additionally, the melting process leaves behind an ultra-smooth material surface, which is smoother than achieved by traditional lapping. This is considered a major advantage when dealing with debris laden fluids.

Direct comparison of the old and new sealing technology

To provide the utility with more assurance that such a seal face material and technology upgrade would provide improved field service, a 2,500 hour laboratory test was conducted under actual operation conditions. To have a direct comparison, both the existing seal face material and technology was installed in one set up together with the newly proposed seal face material and sealing technology. In contradiction to the station's N-6000 mechanical seals (seal balance diameter of 6.0"), the seal size used for this test was a N-7500 (seal balance diameter of 7.5"), since this is the most commonly installed seal size for RRP mechanical seals used in the US, Europe and Asia. The objective of the test was to see what sealing technology would be superior without potential exposure to external source influences, such as stray currents initiated by the variable frequency drive or other external components.

The test conditions applied were:

- Seal type and size: N-7500,
- Lower seal: tungsten carbide rotating seal face with thermo-hydrodynamic circulation slots against a flat carbon graphite stationary seal face,
- Upper seal: Direct sintered SiC rotating seal face with PFT + PZ against a flat carbon graphite stationary seal face,
- Fluid: Ultra-pure water, electrical conductivity < 0.2 µS/cm,
- Speed: 1800 revolutions per minute,
- Water temperature: 49 °C and
- Sealing pressure: 34.5 barG.

The most critical test parameters were logged by an automated data acquisition system, while other parameters were logged manually during testing.

As expected, even after only 2,500 hours of operation in ultra-pure water, clear differences could be observed in the condition of the seal faces between the old and new sealing solution. Damages found on the edges of features such as in pin slots, grooves and other turbulent areas were consistent with electro corrosion damages seen in other "seal face generated electro corrosion" testing, such as the rotational grooving found on the lower tungsten carbide seal face.

The profilometry made from the thermo-hydrodynamic circulation slots in the tungsten carbide rotating seal face depicted significant changes in surface geometry. Changes of this magnitude, coupled with erosion, negatively affected the seal leakage rates. The trend in leakage suggested that the tungsten carbide rotating seal face was continuing to deteriorate. Continued degradation and a resultant increase in seal leakage would push the seal outside of recommended operating parameters. **Figure 5** shows the erosion established at the edges of the ther-mo-hydrodynamic circulation slots of the lower tungsten carbide seal face after the test.

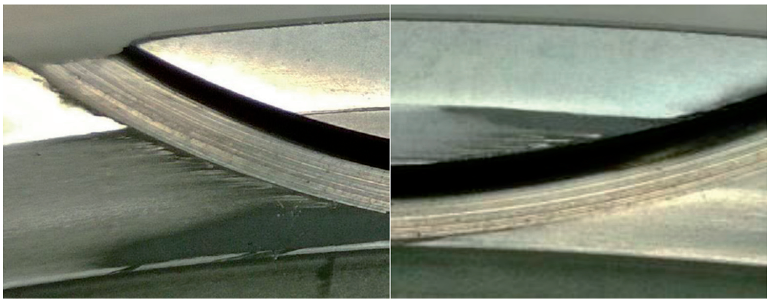

Fig. 5.
Tungsten carbide rotating seal face erosion development.

The profilometry of the silicon carbide face with PFT+PZ was virtually unchanged after 2,500 hours of testing. Although leakage initially increased slightly, it levelled off after a 1,500 hour break-in period. Visually, the silicon carbide face had only minor indications of use. Confocal laser scanning microscopy indicated that minor areas of polishing were only superficial. Seal face temperature and leakage rate were stable, indicating that the PFT + PZ silicon carbide rotating seal face is capable of increasing seal MTBR when operated in ultra-pure water conditions similar to the testing environment.

The comparison test was completed in December 2013 and final reporting was presented in February 2014. However, based on previous seal development testing conducted in a similar way, the utility had decided to install the new sealing technology in their B-pump mechanical seal during the August 2013 annual outage. The A-pump mechanical seal was refurbished, but was not yet upgraded.

Applied solution #2

After the first improvement step, the second critical focus point for the reactor system engineers involved became how to eliminate or mini-mise the destructive influences of externally induced stray currents. Operating experience had shown that with the installation of the variable frequency drives in 2010, seal face damages had suddenly increased.

Furthermore, due to the pump's design, electrically insulating the pump from the electric motor was proven to be impossible without spending vast resources on a new coupling design. The installation of a new coupling design without subjecting it to a realistic form of dynamic testing was not supported since the axial thrust forces acting on the pump shaft when changing pump speed, as well as the drive torque to be transmitted, are high. This could pose a great risk if not properly tested prior to field implementation. Also, the applicable time constraint for such a new development project proved to be challenging.

In January 2013 during the first unscheduled outage, the utility entrusted an external company to conduct shaft voltage measurements. At minimum pump speed of 400 RPM the first set of shaft voltage measurements was completed. It was noted that both pumps developed a shaft voltage with the A-pump showing a value of approx. 800 mV peak-to-peak and the B-pump a value of approx. 450 mV peak-to-peak. No shaft currents were measured at this time.

In May 2013, during the second unscheduled outage, the utility installed a temporary Rogowski coil around the spool piece of the B-pump coupling. This allowed the measurement of shaft currents whilst the station would be under full load operation. A sensor for shaft voltage measurement was not yet installed. Therefore, only potential shaft currents could be measured. In the period between May 2013 and August 2013, shaft current measurements were conducted on the B-pump.

Although at first the overall shaft current level was found to be very low, one external subject matter expert visiting the power station rec-ommended zooming in on the acquired data. Suddenly three current peaks started to appear with values up to 4.5 Amperes and occurring in a regular time sequence of 20 milliseconds (ms). It was not clear why this signal was equivalent to the net frequency of 50 Hz and not equivalent to the periodicity of the variable frequency drive. **Figure 6** shows a plot of the shaft current peaks measured with the power station under full load operation.

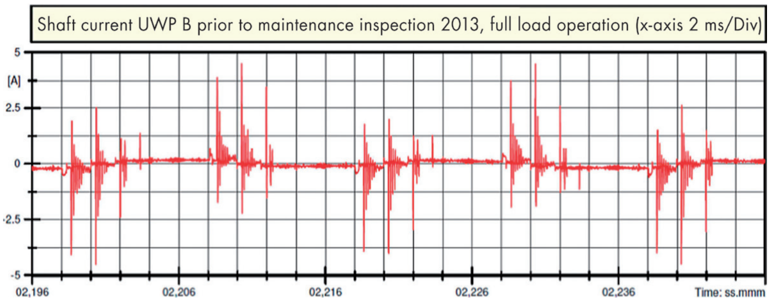

Fig. 6.
Unexplained shaft current peaks at 20 ms interval on the B-pump.

The engineers directed their attention first on how to continuously measure these external shaft currents and shaft voltages, then secondly how to prevent them flowing into the pump shaft and mechanical seal. In this process they drew from their own experiences as well as those of colleagues. Furthermore, they consulted various external subject matter experts on how to best design a robust measurement and grounding system that would allow reliable operation for a period of about 11 months in a non-accessible environment, being the reactor drywell. While valuable external input was received the station's engineers kept the responsibility of the final system design.

The following system design criteria were compiled:

- Measurement system should be able to measure shaft voltages,
- Grounding system should reduce shaft voltage to zero potential (ground),
- Measurement system should be able to measure shaft currents,
- Grounding system should lead the shaft currents safely to ground,
- Grounding system should be made redundant (non-accessible location),
- Grounding system should be designed to handle both high- and low frequency currents,
- Grounding system should be installed on both reactor recirculation pumps,
- Grounding system should be grounded separately using special strand Litzen cables,
- Total system should be robust in order to handle RRP shaft movements and vibrations under occurring plant operation.

Figure 7 shows the initial concept sketch as it was drawn up and used for discussion purposes.

The grounding system explained

Explanation of the grounding and measurement system details starts with the electric motor going downwards. This system was installed on both RRPs during the annual outage in August 2013.

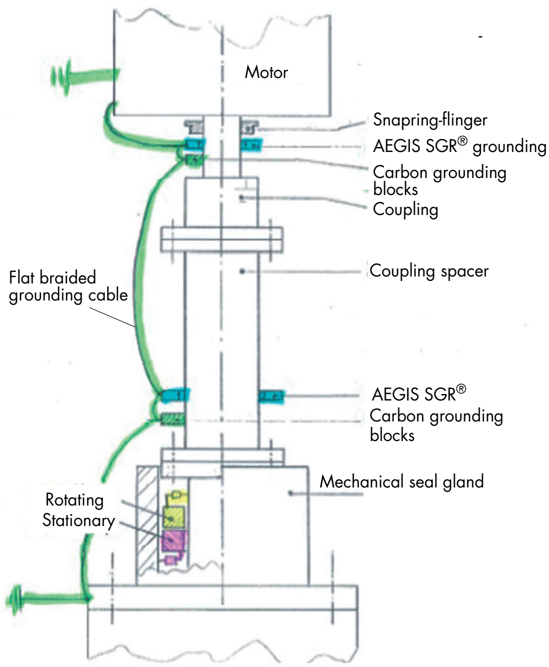

Fig. 7.
Concept sketch grounding system RRP's.

The electric motor shaft has been fitted with an AEGIS® shaft grounding ring (SGR) supplied by Morgan

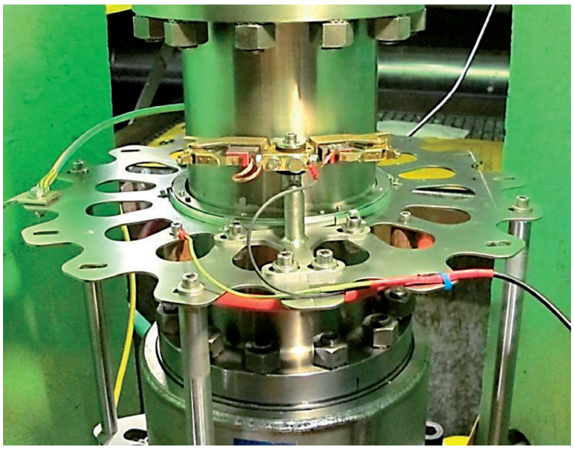

Fig. 8.
Measurement and grounding system at the coupling spool piece area.

Advanced Materials (the blue colour pieces in **Figure 7**). This is a 360 ° ring made from electrically conductive aluminum installed around the shaft. The metal ring contains rows of highly conductive microfibers, which have full 360 ° circumferential contact with the shaft. The AEGIS® SGR is mounted in an aluminum bracket to the motor housing. A colloidal silver shaft coating is applied on the shaft to ensure a good conductive path between shaft and microfibers. This particular device is used to handle potential high frequency currents, which may flow downwards from the motor. The aluminum mounting bracket is grounded to the stations grounding system by means of a new flat braided grounding cable, also made from aluminum.

Beneath the SGR, a set of two carbon grounding blocks has been installed which also ground the same motor shaft (the green colour pieces in **Figure 7**). The use of these devices is to potentially handle all low frequency currents flowing down the motor shaft. The carbon graphite grounding blocks are connected to the aluminum installation bracket of the SGR by a separate grounding cable.

Further down the coupling spool piece a similar set up is made. An aluminum installation plate is positioned around the spool piece and mounted on spacer rods connected to the seal gland below. On top of this installation plate a set of 2 carbon graphite grounding blocks have been installed. These blocks are electrically insulated from ground and serve as contact sensors for the shaft voltage measurement. A cable is fed outside the reactor drywell to allow remote measurements by station personnel during plant operation. On the opposite side a second set of carbon graphite grounding blocks are installed which are connected with a separate grounding cable to station ground. Their function is to draw off any low frequency currents that may flow downwards from the motor towards the pump.

Beneath the carbon graphite grounding blocks touching the coupling spool piece is another AEGIS® SGR clamped in the mentioned aluminum installation plate. This SGR acts as a redundant device for potential high frequency currents that may flow downwards from the motor.

Finally, located under the aluminum installation plate sits a Rogowski coil, which is used for measuring shaft currents and which has been cali-brated for a maximum value of 30 Amperes. The Rogowski coil is electrically insulated from the aluminum installation plate and its cable is fed outside the reactor drywell to allow regular measurements by station personnel.

Figure 8 shows the system set up around the coupling spool piece area.

Measurement results to date

After start-up in September 2013, measurements were made on both pumps using the newly installed shaft grounding system while the station was operating under full load.

Measurements on the A-pump showed that the shaft voltage levels were below 1 mV and thus practically zero. Prior measurements conducted in January 2013 at 400 RPM had shown shaft voltage levels up to 800 mV peak-to-peak.

Measurements of the shaft currents levels showed that these were also virtually 0 Amperes. This is an indication that the newly installed shaft grounding system is working well on the A-pump.

Measurements on the B-pump showed that shaft voltage levels were between 0.5 and 2 mV. Prior measurements conducted in January 2013 at 400 RPM had shown shaft voltage levels up to 450 mV peak-to-peak.

Measurements of shaft current levels still showed the 3 distinct peaks of around 3 Amperes, which occur at 20 ms intervals. This indicates that there is still a suspected stray current related to the net frequency for the B-pump. However, the measurement results also indicate that shaft voltage levels were lowered significantly, pointing out that the newly installed shaft grounding system is working well on the B-pump too.

Prior to the 2014 refuelling outage, another measurement campaign will be conducted on both pumps to verify if the measurement system is still in sound condition and what shaft voltage and shaft current levels are measured towards the end of the fuel cycle.

Applied solution #3

A third change was made during the refuelling outage in August 2013. In order to rule out a faulty electric motor on the B-pump, the utility decided to replace it with a spare driver. Prior to changing out the pump motor a resistance measurement was conducted. At a reduced speed of 400 RPM, electricians measured a 2 kΩ resistance value between the stator housing and the axial thrust bearing housing.

After installation of the spare electric motor this same measurement was repeated. This time the electricians measured a 30 kΩ resistance value between the stator housing and the axial thrust bearing housing when running the motor at 400 RPM. Other discrepancies between both motors could not be found.

Finally, when repeating this same measurement on the already installed motor for the A-pump, this showed a 20 kΩ resistance value between the stator housing and the axial thrust bearing housing when running this motor at 400 RPM.

Latest operating experience

The operating experience with the upgraded mechanical seal in the "B" RRP is showing a stable sealing performance since start-up in September 2013. The staged sealing pressures of the N-6000 seal have shown no decay or abnormalities. The sealing pressure is 72 barg (1,044 psig) for the lower seal stage and 34 barg (493 psig) for the upper seal stage. The seal's controlled bleed off flow is equally stable at the design value of 2.8 litre per minute (0.75 gpm). No measureable seal leakage has been observed.

Both the B-pump and its mechanical seal will continued to be monitored closely and future inspections will demonstrate the final progress made.

Concerning the upgrade for the A-pump mechanical seal this will depend on the future operating experience and seal inspection results of the B-pump mechanical seal. In due time, however, it is expected that the A-pump N-6000 mechanical seal will also be upgraded with direct sintered SiC rotating seal faces using PFT+PZ technology.

Conclusions and recommendations

Three major pump and seal reliability improvement solutions were implemented simultaneously. These measures have had a significant impact on the operating stability of this crucial pumping system.

Further investigation by subject matter experts in electric driver systems should be considered. This investigation should clarify if the measured shaft current peaks of ± 3 Amperes on the B-pump which coincide with the station's net frequency can be fully eliminated or reduced to lower levels.

A recommendation is made to check if the current insulation of the electric motors is suitable for using the new variable frequency drive systems. Insufficient resistance between stator housing and axial thrust bearing housing may lead to stray currents flowing into the motor shaft.

Recommendation is made to check the station's grounding system inside the drywell to see if further improvements may be required.

Finally, future monitoring of both RRP's should continue for developed shaft voltages and shaft currents, in order to allow assessment of the damage risk levels to both RRP mechanical seals.

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DAtF Notes

Nuclear power plants in Europe and worldwide

● Nuclear power plants currently in operation

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	NPP in operation		NPP under construction	
Country		Rated capacity gross (MWe)		Rated capacity gross (MWe)
Argentina	3	1,750	1	29
Armenia	1	408	-	-
Belgium	7	6,208	-	-
Brazil	2	1,990	1	1,300
Bulgaria	2	2,000	-	-
China	24	21,257	25	27,013
Germany	9	12,702	-	-
Finland	4	2,860	1	1,600
France	58	65,880	1	1,600
Great Britain	16	10,906	-	-
India	21	5,780	6	4,300
Iran	1	1,000	-	-
Japan	49	44,583	2	2,760
Canada	19	14,385	-	-
Republic of Korea	23	21,673	5	6,600
Mexico	2	1,640	-	-
Netherlands	1	515	-	-
Pakistan	3	787	2	680
Romania	2	1,412	-	-
Russia	34	26,253	9	8,050
Sweden	10	9,859	-	-
Switzerland	5	3,460	-	-
Slovakia	4	1,950	2	942
Slovenia	1	727	-	-
Spain	7	7,398	-	-
South Africa	2	1,940	-	-
Taiwan	6	5,213	2	2,712
Czech Republic	6	4,112	-	-
Ukraine	15	13,818	-	-
Hungary	4	2,000	-	-
USA	99	102,202	5	6,240
United Arab Emirates	-	-	3	4,200
Belarus	-	-	2	2,388
Total	**440**	**396,668**	**67**	**70,414**

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