42nd Turbomachinery
29th Pump SYMPOSIA

Proceedings of the Twenty-ninth International Pump Users Symposium
September 30 – October 3, 2013, Houston, Texas

THE EVOLUTION OF SUCCESSFUL ELIMINATION OF ELECTRO-CORROSION IN MECHANICAL SEALS FOR REACTOR- AND BOILER FEED WATER PUMPS HANDLING ULTRA-PURE WATER

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ABSTRACT

Since the introduction of mechanical seals in nuclear boiling water reactor (BWR) feed pumps operating with high drive ratings, keeping mechanical seal reliability high became a challenge. A problem also encountered in fossil feed pump applications using similar electrically low conductive feed water, referred to as Combined Water Treated (CWT) feed water operation.

After a short number of operating hours, rotating seal faces made from various kinds of silicon- or tungsten carbide materials show severe forms of edge chipping and crater type damages, while the opposing carbon graphite seal faces, may display a significant loss of seal face binder material, which inevitably results in the formation of uncontrolled radial flow channels across the seal face gap. A unique phenomenon referred to as ‘seal face generated electro corrosion’ (EC).

This tutorial discusses the pragmatic approach, which was applied to investigate what major contributing factors play a role in the development of seal face generated electro corrosion and how it can be avoided.

While satisfactorily results are achieved for applications with a water purity down to 0,5 µS/cm using more traditional seal face materials, research shows that for the very purest of water qualities (i.e. electrical conductivities $0{,}055 < X < 0{,}5$ µS/cm), a new development step is required to suppress seal face generated electro corrosion. All developments are centered around the specific nature of these applications under real world conditions, whereby resilience and performance predictability have been at the very forefront.

INTRODUCTION

With the growing demand for electric power and the subsequent increase of power station electrical output in the seventies and the eighties, feed water pumps became bigger in size and their operating speeds often exceeded 5000 revolutions per minute (RPM) or more, to generate the required head (1). Around the same time period, new seal face materials became available to seal engineers, such as silicon carbide (SiC), which were showing very promising results in many different types of challenging sealing applications, as found in the Oil & Gas or Power Generation industry.

In the mid-eighties, when the latest Generation III nuclear power stations came on line, one particular type of sealing application involving reactor feed water pumps in BWR power stations, was showing specific seal reliability problems from the beginning of plant operation. The characteristics of the seal face damage pattern revealed was one, which at the time, had never been witnessed before. Strangely, this type of damage only occurred in those mechanical seals installed in the high speed reactor feed water pumps, whereas the same type mechanical seals using identical seal face materials, but installed in the low speed booster pumps handling the same feed water, would operate reliably for many years without any signs of seal face damage. BWR power stations use demineralized neutral feed water in which small quantities of oxidizing agents are added, such as oxygen or hydrogen peroxide. The level of electrical conductivity of BWR reactor feed water measured downstream of the ion exchanger is typically less than 0.1 μS/cm.

While the use of CWT feed water treatment in fossil power stations using a Benson boiler system (once-through boiler) was first adopted in the seventies by the former Soviet Union, this technology gained popularity on a global scale as it significantly reduced overall internal boiler corrosion. Using this type of feed water chemistry also reduced usage of toxic chemicals needed for feed water conditioning. The power stations use demineralized feed water in which both alkaline and oxidizing agents (oxygen injection) are added and its pH is controlled by applying ammonia injection. The level of electrical conductivity measured downstream of the ion exchanger is typically $0.1 < X < 5.0$ μS/cm. In line with the BWR reactor feed pump seal experience, mechanical seals installed in high speed boiler feed pumps in these fossil power stations demonstrated a similar type of seal face damage with subsequent low seal- and pump Mean Time Between Maintenance (MTBM).

APPEARANCES OF SEAL FACE GENERATED EC

One of the more obvious characteristics of the seal face damage observed is believed to be caused by a special form of an electro corrosion process. The phenomenon starts with formation of small corrosion nuclei on the outer surface of a silicon carbide rotating seal face. Similar damage has also been observed on tungsten carbide rotating seal faces. With time these tiny nuclei develop into small crater shaped indentations under the continuous influence of the destructive process. As all carbide materials are brittle by nature, the erratic shape of these craters cause small chips to break off, initiating the potential of even larger chips breaking away as the damage progresses with time. Unlike chemical corrosion, this specific form of electro corrosion is not uniformly spread across the material surface, but has a tendency to start in specific locations. Predominantly in areas where manufacturing has taken place, such as milled slots and grounded edges. These locations are designated as ‘hot spots’. Once started, damage progresses from these initial hot spots, while other areas may remain completely unaffected.

Close examination of parts using Scanning Electron Microscopes (SEM) and Energy Dispersive X-ray (EDX) techniques, revealed that in this corrosion process silicon carbide is transformed into silicon oxide, which sometimes can be found as white coloured comet like trails attached to the edges of the craters. Presence of free oxygen in the chemical composition of the seal face material has become a valuable indicator to prove the presence of electro corrosion. In fact, laboratory testing in ultra-pure water demonstrated that the initial start of electro corrosion damage can be found within only a few hours into the test. Figure 1 shows the formation of electro corrosion on α-SiC rotating seal face used in a BWR reactor feed pump seal, which operated for 21 months under continuous operation.

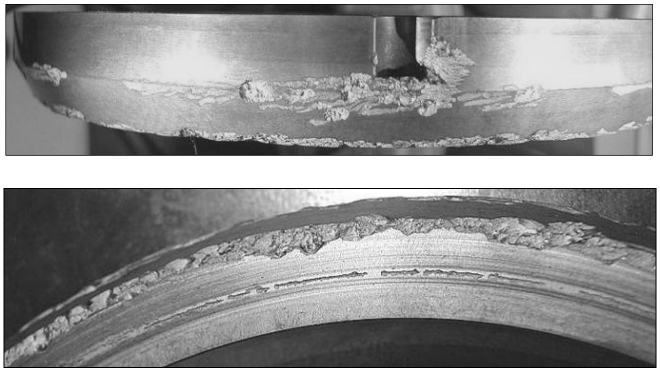

Figure 1. Electro corrosion on an α-SiC rotating seal face, used in an European reactor feed pump seal

In Figure 2 an image is shown of the same seal face using a SEM with a magnification of 20X. The formation of nuclei are clearly visible with further evidence of actual chipping damage.

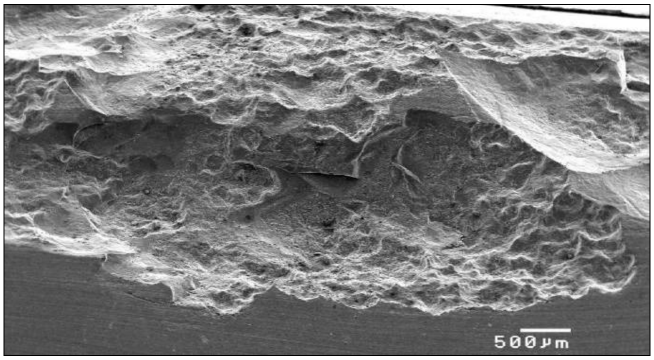

Figure 2. Corrosion nuclei with subsequent chipping of the affected areas of a α-SiC rotating seal face

During a first field trial conducted in a Scandinavian BWR between 2004 and 2006, this type of progressive EC generated seal face damage was reflected in continuous rising plan 23 seal loop temperatures. A development which was believed to be initiated by an uncontrolled hydrodynamic lubrication regime between the seal faces, resulting from erratic chipping of the rotating SiC seal face edges, whereby the EC generated damage even progressed into the seal gap itself. Typically a mechanical seal operating on plan 23 can achieve low loop temperatures if the cooling design is engineered well and merely the leakage is replaced by hot water from within the pump. In this case, during the field trail, one could observe continuously rising loop temperatures and when the installed seal cooling applied reached its limitation, the pump was taken out of service.

A second distinctive form of EC related damage is found in the opposing carbon graphite seal faces, whereby depletion of binder material from its material matrix is observed, which is believed to be related to the same electro corrosion activity within this material. One of the most optimum carbon graphite materials used in fossil (non-nuclear) feed pump seal applications is high density carbon graphite using free antimony as binder material. Another type of material used in nuclear BWR feed pump applications is carbon graphite using a resin type binder. In both seal face materials, depletion of their binder material has been observed, whereby the metal impregnated carbon materials tend to show a higher susceptibility to this type of EC phenomenon.

As the relative soft carbon graphite material is structurally weakened by this binder depletion, it leads to breaking out of small carbon graphite particles with a progressive development into formation of uncontrolled radial flow channels across the wear nose of the carbon graphite seal face. Progressive leakage flow of high velocity, degassed feed water increases the risk of material erosion damage. Figure 3 shows an example of a fully developed radial flow channel in a resin impregnated carbon graphite seal face, which was taken out of service at a European BWR power station.

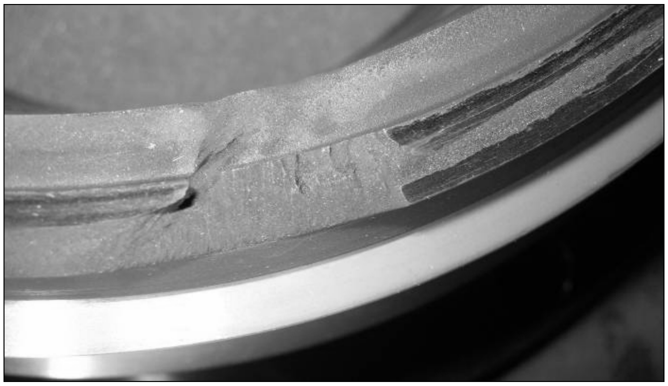

Figure 3. Radial flow channel development carbon seal face

A third indication of electrical activity in high speed feed pumps are damages observed between different pump –and seal metal parts or between a metal and a non-metallic part within the mechanical seal itself. The damages found are typically quite deep, erratic shaped lines and grooves. Figure 4 shows a close up photo of a metal seal face holder used in a fossil feed pump application operating on CWT feed water. While such damage looks severe and parts may need replacement, they seldom lead to unexpected seal failures or problems.

Figure 4. Metal part damage from electrical activity

NON-SEAL FACE GENERATED EC CAUSES

While other potential causes outside the ones which have been directly linked to seal face generated EC are not further discussed in this paper, it is worthwhile mentioning them briefly along with their potential solutions.

Within rotating equipment, 3 different types of stray current causes can be distinguished (2). They are:

1. Generator or motor induced currents
2. Electrostatic currents (DC)
3. Electromagnetically induced shaft currents

1. Generator or motor induced currents

Related to magnetic imbalances and harmonics causing dangerous shaft voltage generated in the rotor due to:

- Make-up of the steel inside the machine
- Non uniform magnetic flux path between stator and rotor
- Lack of magnetic symmetry
- Machines operated off an adjustable speed power supply

Potential solutions are:
Positive shaft grounding, use of insulated bearings and couplings and harmonic suppression.

2. Electrostatic currents

These are induced by:

- Impinging of particles or droplet atomization in the wet stages of the steam turbine
- Dry gas friction generated in high temperature piping and hot portion of the steam turbine
- Charged lubricant induced

Potential solutions are:
Almost impossible to eliminate root cause, only remedy is using suitable shaft grounding of the rotor, plus the remainder of the unit.

3. Electromagnetically induced shaft currents

These can be extremely destructive and are generated by residual magnetic fields in the stator and rotor components in the same manner as in an electric generator or eddy-current brake. Only electromagnetic induced shaft currents can build up enough current to cause the distinctive damage patterns, which reflects in the surface finish as a

result of electromagnetic discharge machining (EDM).
Potential solutions are:
Full demagnetization of the unit and shaft grounding of the rotor.

Primary damage areas identified are:
- Governor or pump drive gear
- Coupling teeth
- Thrust bearings
- Mechanical seals

The amplitude/quantity of these currents depends on:
- The strength of the residual magnetic field present in the equipment
- The relationship of residual magnetic fields towards each other
- The magnetic masses involved
- The available paths for the currents
- The insulating properties of the fluid (oil, water and gas)
- The surface speed of the rotor, which is also the velocity with which the magnetic fields interact (i.e. pump speed)

Residual magnetic fields can be created by:
- Magnetic particle inspection on rotors/stators without subsequent demagnetization
- Use of magnetic tools (i.e. lifting magnets for raw material)
- Electric arc welding done around the equipment
- Equipment running at high tip speeds and high bearing velocities
- Mechanical shock or vibrations (i.e. rotor to stator rubs, bearing failures)
- Faulty grounding of the equipment

If magnetization and generation are not detected at an early stage, self-excitation can build up (3). Magnetic and current patterns in non-electrical equipment, is typically much more complicated as self-magnetization amplifies itself from residual magnetism as the machine runs. Unfortunately the patterns of magnetism and currents arrange themselves in such a way that maximum current is generated, causing short circuited self-excitation.

Some of the EC damages observed in centrifugal pumping equipment are related to other causes than those created by seal face generated EC. Therefore, it is crucial to understand that the research and solutions discussed in this paper are restricted to 'seal face generated EC' only. While it is believed that the presented solutions against seal face generated EC will have a positive effect in reducing overall levels of EC in the pumps, other specialized techniques and solutions may be required for those causes related to non-seal face generated EC. At the same time, evidence presented through real life power plant applications have also shown that by applying specialized techniques used to solve non-seal face generated EC, such as the use of high end shaft grounding tools, are insufficient in solving genuine seal face generated EC. Seal face- and non-seal face generated EC solutions are not mutually exclusive, but complement each other.

THE PRACTICAL APPROACH

Although seal face generated EC damages had been observed since the mid-eighties in European BWR power stations, the problem became more pressing around December of 2003, when a Scandinavian utility officially requested technical support in trying to understand and solve their feed pump seal reliability problems. Up till that moment, some unsupported hypotheses had been developed and several mitigation attempts had been undertaken, but without success. While this utility's rotating SiC seal faces showed severe edge chipping damages, it never resulted in an unscheduled down power of the station due to the availability of a stand-by feed pump.

While the initial perception was that seal face generated EC problems were limited to a small number of high speed reactor feed water pumps, in 2005 it became apparent that similar problems were also observed in newly built and modernized fossil power stations using CWT feed water treatment. This fact certainly increased the overall awareness and gave additional momentum to the final solution search. The common denominator between the nuclear and fossil feed pump seal applications was the use of ultra-pure feed water with electrical conductivity of the feed water of less than 5.0 µS/cm and seal circumferential speeds in excess of 40 m/s.

In the period between 2004 – 2010, many different meetings were organized involving utilities from both Europe and the USA, different power engineering contractors, specialized companies in stray current mitigation solutions on rotating equipment, seal face material vendors with academic level capabilities in ceramic material research and development, industry knowledge centers for the nuclear- and fossil power industry with specific expertise on feed water chemistry and boiler- and reactor pressure vessel corrosion protection. At the same time, this specific problem got more widely known within the industry since more international pump- and seal industry meetings started to list this topic on their meeting agendas.

The first hypothesis on seal face generated EC

In April 2006, the previously mentioned Scandinavian utility returned a decontaminated α-SiC bi-modal rotating seal face, which had been in continuous operation for about 21 months. Reference is also made to Figures 1 and 2. This particular seal face had operated at a sealing pressure of 2.8 MPa in ultra-pure reactor feed water with an electrical conductivity less than 0.1 µS/cm at a circumferential speed of 43 m/s for the duration of 15500 hours. This specific rotating seal face material had been recommended by the vendor in 2004, based on close examination of the original used rotating seal face material, which had previously been made available for detailed inspection by the same utility. The original seal faces were made of a fine grain direct sintered SiC grade, which from initial installation back in the mid-eighties onward had displayed the famous edge chipping and crater shaped surface indentations. Furthermore, the carbon graphite stationary seal face displayed some very specific, but rather harmless lightning type lines on the radial area where it came into contact with the reactor feed water. The utility had not decontaminated the carbon graphite seal face, but provided digital pictures for review.

The α-SiC bi-modal rotating seal face was examined closely by the material vendor in June 2006. For this examination SEM and EDX techniques were used. Their preliminary conclusion was:
'The origin of damage pattern is electrical charging caused by friction between the seal faces. If a SiC seal face material is used with a relative low conductivity against a highly conductive carbon graphite seal face material, an electric potential is build up across the sealing interface. Electrical arching takes place causing pits in locations within a 'hot spot'. SiC is oxidized to SiO2 in the presence of water. Accumulation of pits produces the observed circumferential SiO2 trails. Important to note is that this electrically driven cold water corrosion progresses much faster than tribo-chemical hot water erosion'.

Interesting is the fact that presence of free oxygen in the damaged areas, whereas no oxygen is detected in the non-affected areas of the SiC seal face. Discussing this phenomenon with a leading scientist on ceramic materials, why the seal generated EC damage seems to be concentrated on the seal face edges, his hypothesis was that the discharge of electrical energy through sparking causes a local dissipation of high energy with temperature levels exceeding 5000 °C. In the core of the spark at sub-micron level, silicon carbide is oxidized to silicon oxide through the oxygen, which is present in the feed water. Further, the matrix bonding of the SiC molecules at these edges is 'damaged or broken off' as a result of manufacturing processes, such as grinding or polishing. These broken bonds may form the core of the 'hot spot'. Once a hot spot has been formed, it becomes a location for future discharging, accelerating the destruction process. As a result of the sparking activity there's suspected emission of electrons. Since the ultra-purified feed water provides a very specific environment it may even accelerate the electron emission process. In terms of mechanical seal solution searching, this scientist stated that this would likely be a three-fold process involving seal face material science, tribo-charging and tribo-emission of ceramics.

Based on the evidence collected and preliminary analyses conducted into the seal generated EC, following hypotheses were formed:

1. Friction generated between 2 seal faces operating in ultra-pure feed water or friction generated between a rotating seal face and ultra-pure feed water may cause buildup of unwanted electrical energy. 'Reduction of friction in general' is considered crucial in eliminating or minimizing the emission or transfer of electrons.
2. Relevant operating and design parameters crucial to solving seal face generated EC are: seal's circumferential speed in excess of 40 m/s, electrical conductivity of the water sealed, applied seal face materials and material combinations, water temperature and sealing pressure.
3. Use of SiC or tungsten carbide as seal face materials introduces Piëzo electrical properties that may provide super-capacitive characteristics to these seal face materials. This could result in the accumulation of an electrical charge inside the sealing interface where face friction is taking place. Altering the super-capacitive characteristics to a high conductive profile is potentially a solution to solve seal face generated EC.
4. Elimination/reduction of difference in seal face material electrical conductivity of the two pairing seal faces is considered a key element in the search for a solution.
5. Proper cooling of the mechanical seal to assist in hydrodynamic seal face lubrication lowers the seal face friction coefficient and reinforces the fluid dampening characteristics inside the sealing interface.

Converting the first hypotheses into an actual practical solution

Hydrodynamic sealing technology 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, the film thickness lies in the range of 0,4 – 1,0 µm. The film thickness, which is achieved by nature of the seal's design and operating conditions, is coupled to the specific type of application the particular mechanical seal is used for.

Sealing products such as hot water present extra challenges, as water in general is considered a very poor lubricator. Physics dictate that as the water temperature increases, its kinematic viscosity reduces and the phase transition point where liquid turns into steam (flashing) provides a tough environment for any mechanical seal, not in the least due to the huge expansion in volume when water droplets turn into steam. Steam can cause also erosion of seal face material.

Seal manufacturers in general have a strong preference for supplying the rotating seal faces out of the various hard carbides. This can be tungsten- or a silicon carbide material. Next to their critical tribological properties, these hard and stiff seal face materials also possess superior heat transfer capabilities compared to the much softer carbon graphite material, which acts as the counter seal face material. In combination with high turbulent flow of the water, both frictional heat as well as viscous drag is transferred efficiently into the cold seal water flowing around the seal.

The softer carbon graphite counter face on the other hand, provides very good dry running capabilities and adapts itself to the hard face, limiting the leakage of sealing water. For a mechanical seal facing a wide range of operating regimes and operating with thin fluid film widths, inevitably one will be exposed to some form of asperity contact between the two seal faces. Therefore, using carbon graphite material has its specific advantages and makes the so-called 'hard-soft' seal face material selection the ideal combination for poor lubricating fluids, such as hot water.

Reduction of face friction by Precision Face Topography

To enhance seal face lubrication, specific features have long been applied onto seal faces providing hydrostatic and hydrodynamic lift. Today's micro laser machining capabilities allows seal engineers to master the challenge of achieving 'low seal face friction with low seal leakage'. In contradiction to previous hydrodynamic features applied, micro laser machining provides a high degree of control in terms of the specific feature design as well as introducing an ultra-smooth surface finish, which is particularly beneficial for sealing applications handling debris. It assures a high level of refinement in the manufacturing process with a high standard of quality and repeatability. One of the products developed with such capabilities is the wavy face design, which was selected as the starting point for the required R&D into the electro corrosion solution searching.

Wavy face technology used in mechanical seals involves the use of one of the two seal faces being equipped with circumferential waviness with radial tilt and seal dam. Circumferential waviness by itself was first explored over forty years ago and was shown to be a source of hydrodynamic lubrication. The addition of radial tilt and a seal dam has also long been established in literature and practiced in a wide range of applications (4). Figure 5 displays a highly magnified graphic of a wavy face geometry.

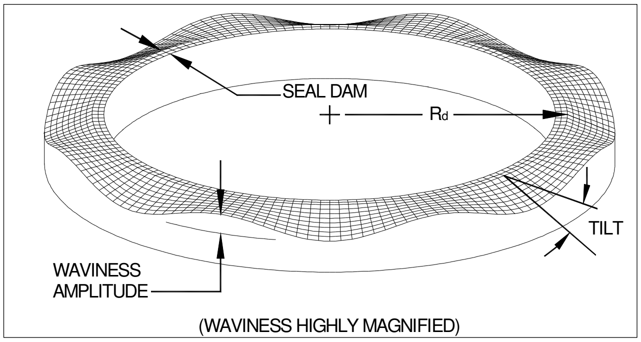

Figure 5. Wavy face geometry

When mated against a flat seal face, the waviness forms circumferentially converging and diverging regions. For a normal seal with sealing pressure on the outside diameter of this face, the circumferentially converging regions will compress the fluid (gas or liquid) under dynamic operation to develop a pressure at the wave peaks that is considerably higher than the surrounding fluid pressure. This results in hydrodynamic load support that promotes non-contact operation. Tilt at the wave valley forms a converging region in the radial direction from the outside to the inside face diameter. This promotes hydrostatic load support helping to provide lift-off during dynamic operation. Circumferential waviness also provides positive fluid film stability, just like pure radial convergence, but without the concern of preferential inner diameter wear on the soft face that would eventually cancel out the convergence, or even result in divergence.

In all seal designs, a seal balance ratio has been selected that will ensure that the faces remain in contact under static conditions, thus low leakage. During static and dynamic operation, the hydrodynamic component results in even greater film stability. The final feature of the wavy face is a seal dam that minimizes seal leakage. Depending on the required operating conditions, waviness amplitude (h) could range from 1 µm to 10 µm in amplitude. Seal faces incorporating this shape offer unique advantages over plain seal faces. The smooth wave peaks present a low wearing condition during starts and stops when the seal faces make contact. Additional positive features of the wavy shape are its bidirectional characteristic, lower leakages than groove face geometries and contamination resistance. The low leakage capability is due to two factors; waves do not pump, and wavy face mechanical seals can be designed to operate at low film thicknesses.

Figure 6 illustrates how the flow of the fluid is distributed inside a single wave feature. Under pressurized and dynamic condition, the fluid enters the (deepest) valley portion of the wave and then undergoes compression toward the wave peak due to rotational movement of the pump shaft transmitted onto the rotating seal face of the mechanical seal. At the wave peak, the fluid pressure is higher than the surrounding fluid, and so a small portion migrates across the seal dam as normal intended seal leakage. Some of the liquid travels across the wave and is ultimately responsible for the lift-off effect resulting in hydrodynamic or full lift-off lubrication. However, the majority of the fluid is circulated back into the seal chamber, which is at a lower fluid pressure. This recirculation effect of the wave profile assists in hindering debris from entering the actual sealing interface. In-house testing and examination of seals in field applications operating in debris laden applications have verified the functionality of this feature.

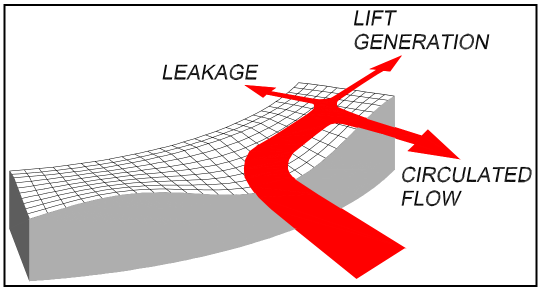

Figure 6. Fluid distribution inside a single wave

The laser process also allows a very smooth topographical surface finish, which enhances the self-cleaning effect for debris laden applications, particularly for those applications where the particulates are small enough to enter the sealing interface (i.e. solids size < 10 µm).

Equalizing seal face material's electrical conductivity by applying Preferential Surface Treatment technology

Further development of micro laser machining capabilities resulted in a proprietary laser surface treatment process, which is applied after the initial creation of the circumferential wavy profile. Using this second process specific seal face material characteristics can be physically altered. This alteration is made right at the surface level. Also the material hardness can be increased. In the case of silicon carbide the crystalline properties are altered into a more electrically conductive state. This minimizes the difference in electrical conductivity between a silicon carbide face and a seal face made from carbon graphite, whereby the electro corrosion can be suppressed.

The surface treatment process is applied on the entire area of the seal face and is done after lapping of the seal face and the manufacturing of laser micro-machined hydrodynamic features. The applied energy levels for this laser process are very low and do not remove any material, which could result in un-flatness of the seal face. Only the material's surface properties are altered. This process does not involve an overlay or coating type technology. The laser surface treatment process is an automated and repeatable process.

Another crucial step forward made with the use of this new laser surface treatment was a further reduction in the final surface roughness, which reinforces the self-cleaning effect inside the circumferential waviness pattern when dealing with tiny particulates and dirt in the fluid system. Figure 7 shows the difference in surface roughness between a traditional lapped SiC seal face and one that has been treated with the preferential surface treatment laser process. Use of the preferential surface treatment technology was integrated into the R&D program launched to solve the seal face generated EC problem.

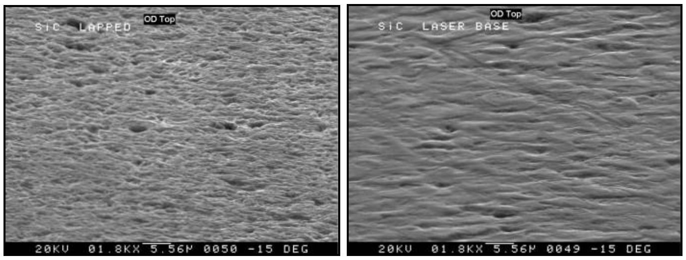

Figure 7. (Left) Lapped SiC, (right) laser processed SiC

The first reference solution in fossil power generation

In the period between 2005 – 2009, the first practical seal laboratory testing was conducted involving an actual customer application, which involved 2 different seal concepts developed for a German fossil power station. The seal technology used particular design features that were directly related to the previously developed hypotheses. The project was executed in close cooperation with the rotating equipment engineers of Jänschwalde power station in Germany, which is owned by Vattenfall Europe Generation AG. Initial development work on seal face generated EC for Vattenfall Europe Generation AG started in February 2005. The sealing application involved sealing feed water of 2.5 MPa pressure with an average electrical conductivity of 1.8 µS/cm and a seal circumferential speed of 40.3 m/s. As the power station is sometimes used for peak shaving operation to regulate wind energy on the grid, frequent slow roll of the turbine driven feed pumps is another aggravating condition the mechanical seals have to overcome.

The first sealing concept used a combination of precision face topography and preferential surface treatment ensuring the electrical conductivity of the seal faces was equal. It incorporated two seal faces made out of a high quality α-SiC bi-modal silicon carbide. While sealing hot water combined with high drive speeds as well as frequent slow roll conditions, requires reliable hydrodynamic seal face separation, a seal leakage criteria of 1,500 CC/hour under lab conditions, was agreed upon. Ensuring seal leakage could not contaminate the oil of the pump bearings, a special bushing design was integrated, normally used in dry gas seals for turbo-compressors. The bushing consisted of an engineered segmented carbon ring seal that was engineered with higher pressure capabilities than typical separation seals found in the compressor seal applications.

In March 2006, the first two mechanical seals, also known as 'the first generation Vattenfall boiler feed pump seals', were installed. These seals operated for a total of 15623 hours in continuous service. To allow a fair comparison between the original and new sealing concept, no changes were made to the pump, seal cooling system or process conditions. The specific turbo feed pump that was assigned by the power station for this field test was considered the worst 'bad actor' with an average mechanical seal life of 3000 hours when using the original seal design. Reported seal leakage of the new seals during operation was between 900 and 1200 CC/hour and average seal loop temperatures were between 40 and 45 °C. In total, this particular feed pump underwent 20 operating transients in this time frame, whereby pump speed is lowered from 5400 RPM to 103 RPM and sealing pressure is reduced from 2.5 MPa to 0.9 MPa, in line with the plant's stand-by mode conditions, using a sliding boiler pressure regime.

In February 2008, these 'first generation' mechanical seals were inspected in the presence of the Jänschwalde station personnel. The inspection revealed that approximately 95% of the previously experienced electro corrosion had disappeared and the overall condition of seal faces and supporting parts found, was excellent. Reference is made to the case study presentation made during the 2009 International Pump Users Symposium (5).

While this first field test result exceeded all expectations and demonstrated that the initial concept of equalizing the electrical conductivity of the applied seal face materials was a correct path towards a final resolution of the seal face generated EC problem, two sudden and unexpected seal failures in 2010 and 2011, demonstrated beyond any doubt, that use of a hard-hard seal face combination in this type of power plant service has little or no margin for survival or recovery, in the case of detrimental seal face contact. As a consequence, this type of sealing solution, using 2 hard faces, was abandoned.

Fortunately, seal development work from 2007 onwards, was directed in constructing a second solution using a more forgiving, resilient seal face material combination of direct sintered silicon carbide and resin impregnated carbon graphite. Also this hard-soft seal face solution involves the use of precision face topography combined with preferential surface treatment, designed to resist seal face generated EC. In agreement with Vattenfall Europe Generation AG, a second turbo feed pump was equipped with two new mechanical seals, that were identified as ‘the second generation boiler feed pump seals’.

Pump installation was conducted in May 2009 and after 15840 operating hours an opportunity came about, not related to the mechanical seals, to open up the pump and inspect the mechanical seals in the presence of the Jänschwalde station personnel. Figure 8 shows this seal design, using hard-soft seal face combination, tested at Jänschwalde power station in the period between May 2009 and July 2011. Interesting to note is that this particular feed pump underwent a total of 37 operational transients, going from normal plant operation at full speed to slow roll conditions during stand-by mode.

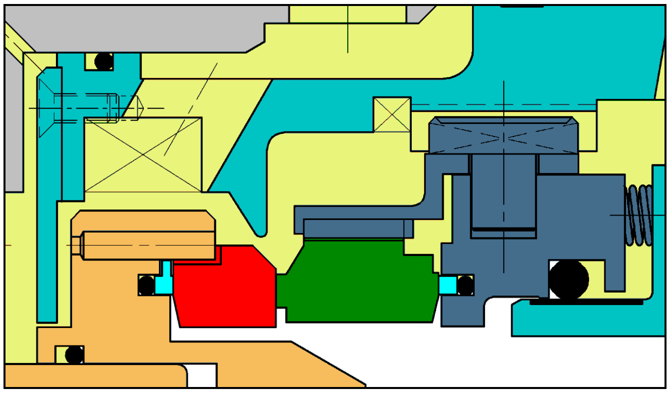

Figure 8. Mechanical seal using a resilient hard-soft seal face combination with anti-EC technology

The operational experience as well as inspection results showed:

- Both driven end and non-driven end seals demonstrated stable and reliable sealing performance under challenging conditions provided
- Use of a hard-soft seal face combination provides a high degree of resilience and more predictable sealing performance, particularly when having to meet frequently changing pump operating modes
- Close inspection of all the seal faces revealed almost no visible wear. The drive end seal faces were virtually free of any wear
- Only a few marginal signs of electro corrosion were detected in some of the metal seal components and other evidence of electrical activity was found, but their impact on the overall sealing performance was found to be negligible
- The special segmented bushing had proven effective in preventing seal leakage going into the pump bearings. It also acted as an additional grounding tool, even if the grounding effect itself could not be substantiated
- Some of the static O-rings sealing the feed water displayed evidence of rapid gas decompression. A recommendation was made to change these to a special compound elastomer, designed to withstand this particular phenomenon

In January 2012, a project closure meeting was held at Jänschwalde power station, concluding that a satisfactorily sealing solution had been developed for the plant’s feed pump operating conditions, which met all expectations (6).

The second reference solution in fossil power generation

In 2008, a new fossil power station in Wisconsin, USA, was taken into operation. This particular power station is a coal fired power plant using a Benson once through boiler system and CWT feed water. The electrical conductivity of the feed water is kept between 0.5 – 0.6 µS/cm and the mechanical seals are subjected to a sealing pressure of 2.3 MPa operating with a maximum circumferential speed of 43.8 m/s. Unfortunately, the original fitted mechanical seals did not have anti-EC features and within weeks the carbon graphite stationary seal faces got severely damaged.

An external material laboratory examined the failed seal parts. Their conclusion was that the damages detected on the outer diameter of the carbon graphite stationary seal face had been caused by multiple electrical activities and that the stationary face holder also displayed damage caused by the same electrical activities.

In January 2010, the same anti-EC technology was applied as used in the 2009 ‘second generation’ Vattenfall seals using a hard-soft seal face material combination. In December 2010, due to a cause outside of the mechanical seals, the C-pump was taken out of service and the upgraded anti-EC seals were taken out for a detailed inspection. The inspection revealed that the seal faces were in excellent condition, which confirmed that the combination technology of precision face topography and preferential surface treatment is able to withstand seal face generated EC down to a water purity of 0.5 µS/cm without sustaining any damage. Figure 9 displays one of the rotating seal faces as found after 7000 hours of operation.

Figure 9. SiC rotating seal face after 7000 hours of operation in 0.5 µS/cm electrically conductive feed water

While these practical tests in real fossil power feed pump applications had proven that the combined technology of precision face topography and preferential surface treatment suppresses seal face generated EC in feed water with an electrical conductivity down to 0.5 µS/cm, laboratory testing demonstrated that for water purities between $0.055 < X < 0.5$ µS/cm, this technology would not suffice and additional steps in material science and development would be required to offer a final solution for the ultra-pure water types. This became the starting point for the next level of R&D, starting with a feasibility study, followed by a Design of Experiment (DOE), during which more than 60 different seal laboratory tests were conducted.

THE ACADEMIC APPROACH

Conducting A Feasibility Study

In March 2008, a team of senior pump- and seal engineers was tasked to launch a research project solving ‘seal face generated EC’ problems. The team included experienced field support engineers with a pump- and mechanical seal background as well as R&D staff engineers. All laboratory testing and research was conducted under the supervision and guidance of the Director of Advanced Sealing Technology.

While some preliminary hypotheses had been developed by mechanical seal engineers in the period between 2004 - 2009, which resulted in successful sealing solutions, it was felt that an academic approach was needed in the form of a feasibility study, summarizing potential theories and root causes to allow the development of a more structured solution search path. In 2008, the Texas Institute of Science, TxIS, was requested to provide a feasibility study into this particular subject. The actual study itself (7) was conducted by a research team of the Department of Chemistry of the Technical University of Czestochowa, Poland and completed in April 2009.

After having studied the available literature, the university research team divided the possible causes for the seal face generated EC damage into the following 4 categories:

1. Mechanical determinants (cavitation – erosion)
2. Chemical / electrochemical determinants
3. Seal face material / structural determinants
4. Electrostatic determinants

1. Mechanical determinants (cavitation – erosion)

Fast moving water in the vicinity of mechanical seals and presence of obstacles for the water flow can be a reason for seal face material damage. The most violent turbulences can appear on the sharp edges of the seal faces and cavitation attack of imploding bubbles would have its greatest energy impact at the edge of the seal faces. Since most edges of SiC seal faces are initially formed through manufacturing (mechanical machining, grinding, polishing, etc.), presence of additional factors may spread erosion damages.

Cavitation may destruct seal face materials in either the sealing gap or on the outer ring surface in contact with the liquid. The latter can be caused by turbulences rotating with the ring. Discontinuous edges like lubricating grooves give rise to local degassing and cavitation. SiC has a weak ability in absorbing energy during deformation by the impact. Material removal is initiated by propagation of cracks at the grain boundaries or at the surface. Most energy is dissipated by crack formation, which leads to more frequent material removal. The absorbed energy to remove a certain volume of material by cracking is much less than when removing the same material through plastic deformation. It is the reason why brittle materials are less resistant to cavitation. Figure 10 shows damage of SiC seal ring in the vicinity of a lubricating groove.

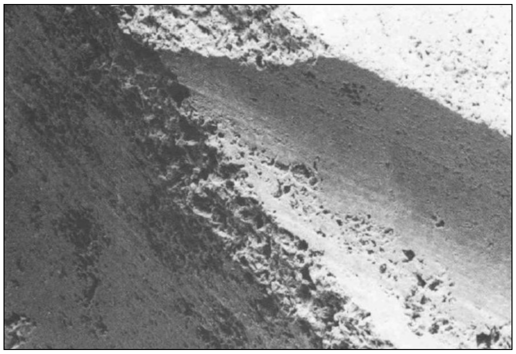

Figure 10. SiC face damage lubricating groove

2. Chemical / electrochemical determinants

In a real power station feed water application a number of solid materials come in contact with the feed water. Dissolved oxygen is considered to be the strongest oxidizer that causes electrochemical corrosion processes. Electrochemical corrosion rate depends on many parameters, such as temperature, pressure, solution conductivity, presence of corrosion stimulators/inhibitors, etc. Generally, contact of two or more different metals in an electrolyte solution is prone to formation of galvanic cells. The corrosion processes in such galvanic cells are usually very fast because of direct contact of the electrodes and these processes are faster the greater the conductivity of the solution.

In case of ultra-pure water the electrochemical corrosion process strongly decreases due to low water conductivity, but in practice for air-saturated solutions the reduction of oxygen molecules is controlled by their diffusion towards a metal surface. The transport of oxygen molecules is much faster when the water is moving fast and this may cause serious corrosion damage of most metals/alloys. Reduction of oxygen molecules is very fast on conducting surfaces. If we assume that a SiC seal surface becomes electrically charged, it may reduce oxygen with pH increase and simultaneously the seal constituents may oxidize themselves. For instance, the production of silicon oxide.

White silicon oxide trails have been identified on surfaces of SiC seal faces, which were installed in mechanical seals used for long periods in fast flowing ultra-pure feed water. Electrical sparks that appear between silicon carbide and carbon graphite seal faces applied in ultra-pure water prompt local temperature jumps and one may expect very high local temperatures in the center of the material hit by such a spark. The possibility of many both exo- and endothermic reactions may occur in such spots, which are or become spontaneous at very high temperatures.

The role of hydrogen as a cause for seal face deterioration seems to be serious and should be carefully examined. Three different sources for hydrogen gas development in feed water systems are identified:

- High temperature water – steam reaction with the steel walls of the boiler and piping
- Reactions of carbon graphite with ultra-pure water in the core of the developed sparks
- Reactions of SiC, or alternatively tungsten carbide, with ultra-pure water in the core of the developed sparks

3. *Seal face material / structural determinants*

Silicon carbide is frequently used as seal face material due to its natural hardness, chemical inertness, high temperature stability, high thermal conductivity and high maximum current density. In combination with a soft carbon graphite seal face it shows excellent tribological properties, particularly for those applications where asperity contact between the seal faces needs to be expected and momentarily contact during transient conditions may occur. Silicon carbide is a hard crystalline material. While there are significant differences in the different grades available on the market today, when comparing SiC to carbon graphite material, SiC has a low electrical conductivity. Also, it is brittle and can fail by brittle fracture easily. While SiC has some material characteristics that require detailed attention during seal engineering phase, overall it is considered still one of the most optimum seal face materials available today.

Use of tungsten carbide with nickel based binder has been used in nuclear and fossil feed pump applications for many years. When used in a neutral water applications these materials have demonstrated leaching of the nickel binder located in between the hard tungsten carbide crystals. This leaves behind an abrasive tungsten carbide surface that can damage the counter carbon graphite seal face. Figure 11 shows a close up of a tungsten seal face where the nickel has disappeared leaving behind the tungsten carbide crystals. If left in this state, also the base material would be attacked.

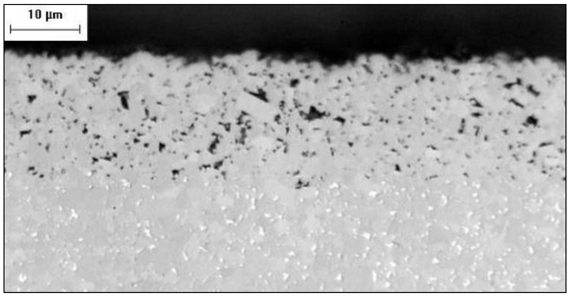

Figure 11. Removal of the white nickel binder in a tungsten carbide seal face, used in neutral water

Experiments held to study the oxidization and dissolution of tungsten carbide in water (8) has shown that this material can suffer from ultra-pure water corrosion, as can be seen in Figure 12. Laboratory testing of nickel impregnated tungsten carbide conducted has also revealed the formation of what at first are small radial flow channels. These flow channels can grow from the seal face inner- or outer diameter and then develop into the sealing interface area where they will cause an uncontrolled hydrodynamic lift off effect raising seal leakage. Using a scanning microscope, these flow channels can be visualized and even measured. Actual field experience has shown that significant formation of radial flow channels can develop even after a few months into operation.

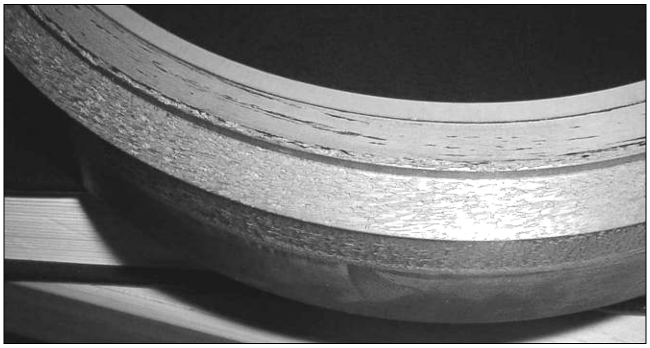

Figure 12. Tungsten carbide seal face with severe corrosion damage, fossil feed pump application

Figure 13 is a set of 3 images showing the formation of radial flow channel developed from the outer diameter into the sealing interface of the seal ring of a rotating tungsten carbide seal face subjected to ultra-pure water testing. Test run was for 168 hours with a maximum water conductivity of 0.15 µS/cm, water temperature of 38 °C, sealing pressure of 4.0 MPa and seal’s circumferential speed around 48.3 m/s.

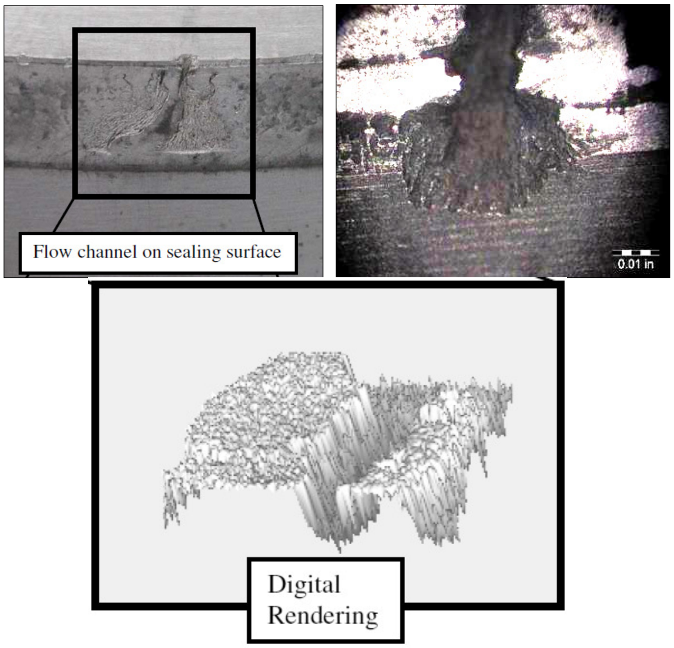

Figure 13. Radial flow channel development on the outer diameter of a tungsten carbide rotating seal face

Figure 14 is an image of radial flow channel development on the inner diameter of a tungsten carbide rotating seal face tested in ultra-pure water for 200 hours, whereby severe pitting and erosion type flow channels have been developed. The depth of the flow channels measured in this tested seal face were 0.001” or 0.025 mm deep and these were observed around the entire circumference of the ring. While the radial flow channels were not yet protruding into the wear track of the seal face, in time they could lead to a premature failure of the mechanical seal due to uncontrolled hydrodynamic lift off effects created by these same channels.

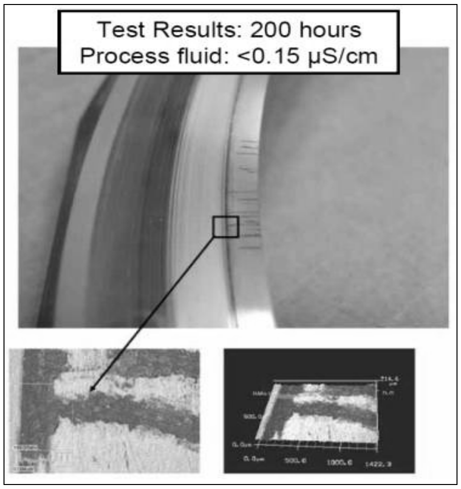

Figure 14. Radial flow channel development inner diameter of a tungsten carbide rotating seal face

Rotating seal faces made from tungsten carbide, which have been designed using sharp edges, such as the ones used as for lubrication grooves, seem to be particularly prone to this damage mechanism. With reference to the hypothesis that this damage could be the result of an accumulation of high amounts of static electricity stored into the tungsten carbide material, it appears that the presence of sharp edges may promote the accumulation of the static charge, much like the tip of a spark plug, until the limit of material’s capacitive energy storage has been reached and the charge is suddenly discharged. Damage as shown in Figure 15 can occur within months of operation and has resulted in unscheduled outages of power stations not being able to maintain system pressure due to high seal leakages.

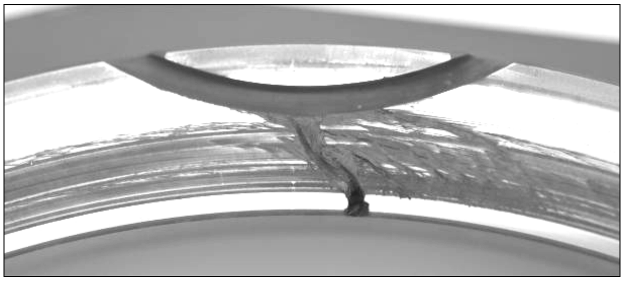

Figure 15. Developed radial flow channel with erosion in a tungsten carbide rotating seal face using Mayer lubrication groove technology

4. *Electrostatic determinants*

Although water has no overall electric charge it is normally full of moveable electric charges (ions). In case of ultra-pure water half of the water’s charges are positive and half are negative. It is not hard to separate these charges. As conducted by Kelvin in 1867 in an experiment to proof the phenomenon of voltage generation using an electrostatic generator (9), an electrified object will attract the unlike charges to the water’s surface. A positive charged object will attract the water’s negative ions, while repelling an equal amount of positive ions. If we would compare Kelvin’s water-drop electrostatic generator an analogy could be made between the different parts used, being:

Kelvin’s electrostatic generator ←→ mechanical seal
gravity force ← → pressure gradient + rotational friction
rings ← → SiC and carbon graphite seal faces

The sealing conditions imply that the physical distance between the seal faces can be very small (i.e. 0.5 micron or less), water conductivity is very low and the electrical conductivity of seal face materials used, such as SiC, can also be low compared to carbon graphite. The combination of these facts imply that high force fields may be created.

Following intermediate conclusions were made on the influence of electrostatic determinants:

- The ionic fluxes entering or leaving the ultra-pure water are different for the seal face materials used
- The interface fluxes depend on ion concentrations in the flowing ultra-pure water. Concentrations of

impurities depend on materials, dimensions, flow rate, wall roughness, etc.

- Both water and seal faces can become electrically charged and consequently:
    - Rotational movement of the charged water and flow in an axial direction may imply a current
    - Currents generate a magnetic field and parts may become magnetized during operation. A phenomenon which has been observed in practice
    - Surface charge density on a moving surface depends on its position and consequently an electrical field is generated in radial and tangential direction
    - High value electric fields will be present at the edges and macro defects on the SiC surface
    - Friction generated can generate extremely high electrical fields. Recently X-ray flashes have been observed as a result of friction
    - Recent data suggests that interaction between hydrogen and carbon graphite can turn the carbon graphite into an insulator
    - Even weak magnetic fields (in the order of mill gauss) applied in ultra-pure water, affects electrochemical processes
    - Use of ultra-pure water implies a complex electro-mechano-chemical phenomenon

The university's research team concluded that most probably all listed determinants are included in the resulting EC damage effect. However, electrostatic charges releasing a flow of electrons in the form of sparks concentrated at the outer edges of the SiC seal rings seemed to be the most important candidate for the damages observed. The possibility of high temperature spots caused by sparking, which in turn favours and accelerates a number of chemical redox processes, including the oxidization of silicon carbide into silicon oxide when subjected to an ultra-pure water environment, was seen as a major potential root cause. Also, diffusion of hydrogen atoms into the depth of the seal ring's structure and their recombination within SiC structural defects were considered prone to the mechanical degradation of the seal rings, owing to high hydrogen pressure in the structural traps.

In the final concluding remarks of the university's research team the most important conclusions and recommendations were:

- Reduction of frictional losses at the seal faces by the use of modified SiC materials is to be considered
- Proper modification of the electrical parameters of the SiC materials should allow the charge accumulation to be limited
- Decreasing the charge accumulation within the sealing interface seems to be of great importance as charge accumulation can induce redox chemical reactions, but also create electrical spark jumps within the mechanical seal itself. In local, high temperature spark centers' many physic-chemical processes become spontaneous and extraordinarily fast
- Role of hydrogen production (especially during sparking) for seal face deterioration seems to be very serious and should be examined carefully.

These conclusions and recommendations together with the experiences gathered from previously conducted laboratory- as well as field testing, then became the starting point for an elaborate program involving experimental R&D in developing the final solution against seal face generated EC damage presented further on in this document.

EXPERIMENTAL SEAL LABORATORY TESTING

Using a methodology known as Design of Experiments (DOE), in 2008 a seal laboratory test program was started to investigate potential solutions for seal face generated EC. DOE is defined as information-gathering exercises where variation is present, whether under the full control of the experimenter or not. When using DOE, the experimenter is often interested in the effect of a process or intervention (i.e. treatment) on a specific object, such as a seal face. It is a well-known methodology which is frequently applied in engineering studies.

The first step was to identify what specific sealing conditions would seem appropriate to investigate the seal face generated EC phenomenon. Based on literature and feedback received from actual power generation utilities, the following sealing parameters were selected as the benchmark system settings for seal laboratory testing:

- Sealing pressure: 4 MPa
- Seal circumferential speed: 48.3 m/s
- Ultra-pure water temperature: 38 – 65 °C
- Water purity: 0.15 – 30 µS/cm
- Carbon graphite seal face materials with resin binder
- No use of any materials which may become activated in nuclear service (i.e. BWR reactor feed applications)

To rule out influences from external electrical sources, the two seal test units used for this experimental testing were designed in such a way that they were electrically isolated from ground, including the interconnecting seal system piping. Using tester hardware made from AISI 316 stainless steel, residual magnetic influences were minimized, which may have affected testing. Figure 16 shows one of two seal test units used for these experiments.

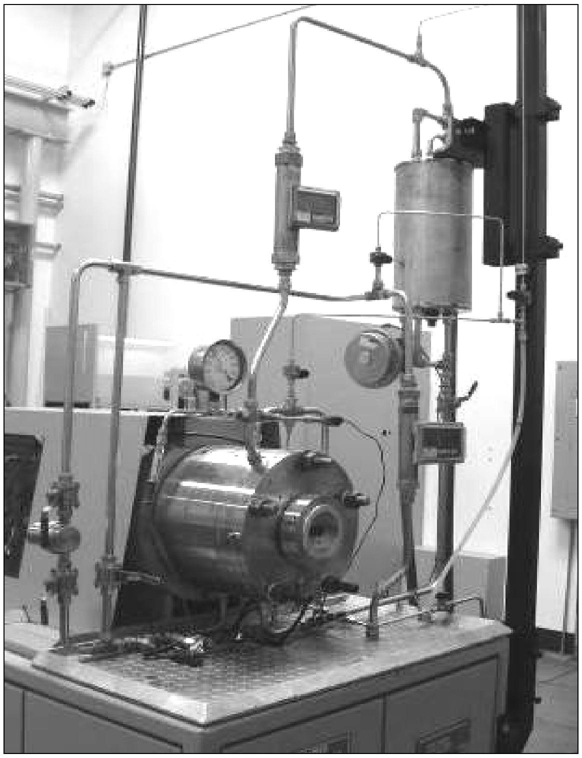

Figure 16. Seal test unit used for EC testing

At the start of the DOE, a number of potential process influencing factors were identified that needed to be examined in greater detail. These factors were:

1. Influence of seal water's electrical conductivity
2. Influence of (circumferential) speed
3. Influence of seal water's temperature
4. Influence of sealing pressure
5. Influence on seal face part geometry and specific design features
6. Influence of seal face materials and material combinations

The standard test set up used for the DOE is displayed in Figure 17. It consists of a so-called plug seal and a primary- or test seal.

During some tests, a single ceramic rotating seal face was placed in between the plug- and test seal. This separate rotating seal face was installed using electrically insulated materials to ensure it would not be influenced by the plug- or test seals. The purpose of these specific separate spinning seal face tests was to investigate the friction effect between a rotating hard face and the ultra-pure water, without this part being subjected to other types of friction, such as potentially created through asperity contact with a carbon graphite counter face. These single ceramic seal face spin tests proved to be very enlightening as they too revealed formation of EC on the ceramic ring's surface, although the EC effect was less strong compared to EC damage observed in a traditional two seal face system being tested under the same conditions.

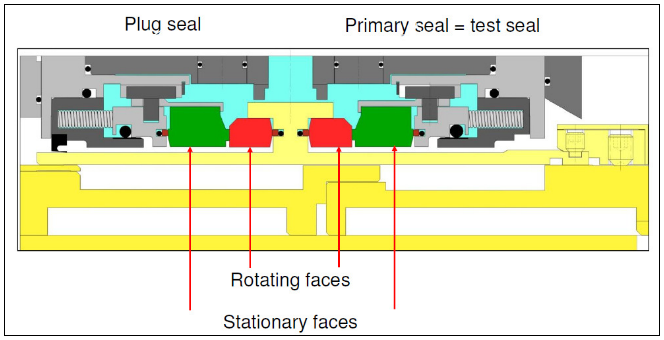

Figure 17. Test seal set up

The second step was to verify if the specific rotating seal face damage as observed in actual BWR feed pump seal applications, could be repeated under controlled laboratory conditions. This appeared to be the case. Figure 18 shows a fine grain direct sintered SiC rotating seal face after 12 months of operation in a BWR feed pump. Figure 19 shows the same SiC material but tested for a period of merely 184 hours under the test conditions as previously defined. The damage observed is very similar and demonstrates that the benchmark laboratory test conditions, plus the design of the test unit are comparable to actual field conditions in BWR reactor feed service. BWR reactor feed service being identified as one of the most challenging high speed ultra-pure water applications to be sealed. Interesting to note is that the drive notches which are made in the back of the rotating seal face to drive the ring tend to be susceptible to seal face generated EC damage. Something often observed during the duration of this development program.

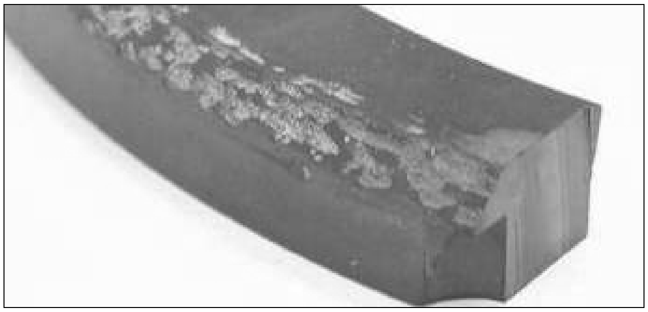

Figure 18. Rotating SiC seal face after 12 months in BWR operation

Figure 19. Same SiC seal face material tested 184 hours under benchmark laboratory conditions

Influence of seal water's electrical conductivity

The first 2 seal tests conducted after verification was made that the test system set up was able to generate seal face generated EC, was to investigate the influence of water conductivity. Even if there was already sufficient literature and field test evidence available suggesting that water conductivity has a major influence on the phenomenon it was tested as part of the DOE.

The first test used a plug seal using a specific α-SiC bi-modal flat rotating seal face against a standard grade resin impregnated stationary face. This particular rotating seal face material had proven to be resistant against seal generated EC in the previous field tests conducted in Europe and the USA on a fossil feed water application. A flat rotating seal face was used to verify if a more traditional contacting feed pump seal design would be affected or not. The test seal used the same α-SiC bi-modal wavy face versus an iso-statically molded resin carbon graphite stationary seal face. After 287 hours of testing this set up under ultra-pure water conditions, electrical type damage was observed on the interference fit of the metal shaft sleeve with the tester shaft, as can be seen in Figure 20. Also pitting damage by classic EC was found on both SiC seal faces upon inspection.

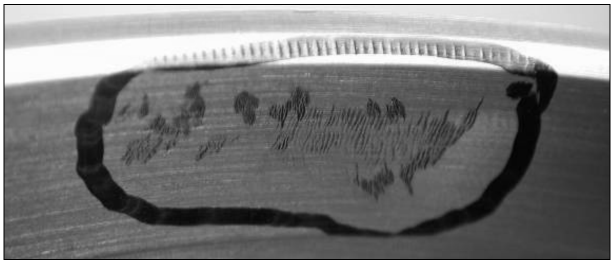

Figure 20. Electrical activity, damage of sleeve interference fit

The second test used exactly the same test set up and materials as in the first test, except now the water's electrical conductivity was kept between 20 – 30 µS/cm and the seals were tested for 300 hours. Upon inspection, no signs of seal face generated EC were found on either of the 2 rotating SiC seal faces, nor any other type of electrically induced damage was observed. The seal faces looked in pristine condition as can be seen in Figure 21.

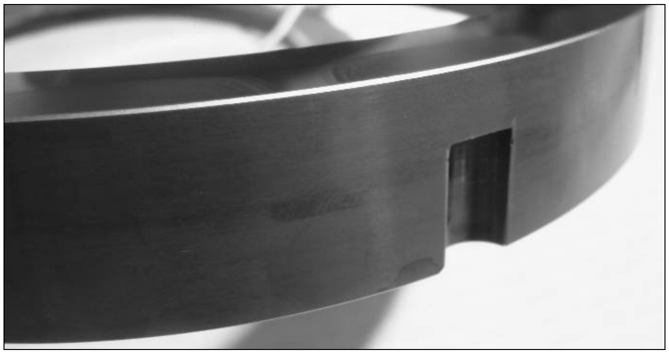

Figure 21. Rotating SiC seal face after 168 hours in 20 – 30 µS/cm electrically conductive water

Additional seal tests were conducted to see if a more gradual and localized increase of the seal water's conductivity in the seal plan 23 could be realized. Up until April 2011, there had been only one BWR power station in the world, ISAR-1 in Germany, which had actually used complex ammonia dosing systems feeding small quantities of ammonia into the plan 23 seal loops through sensor monitoring of the water conductivity. While the actual monitoring and regulation of this dosing system was quite labour intensive, reasonable sealing performance had been achieved by the power station.

The additional laboratory tests were designed around developing a fool proof method whereby specific substances were added to the seal loop without the use of an active, complicated system. The outcome of these tests showed that seal face generated EC could be not solved effectively in this way. Also, discussions with feed water chemists of BWR power stations learned that the risk of external agents or particles potentially damaging the nuclear fuel in the reactor pressure vessel outweighed the problems with premature failing mechanical seals due to seal face generated EC. As such, this solution path was abandoned.

Preliminary conclusion: water conductivity is a major contributor to seal face generated EC.

Influence of (circumferential) speed

A test was set up using a specific α-SiC rotating face material specifically recommended by a vendor incorporating the precision face topography and preferential surface treatment technology as field tested versus an iso-statically molded resin carbon graphite stationary seal face. These seal face materials were used for both the plug- and test seal. A test was run for 168 hours under the benchmark conditions and upon inspection of both rotating seal faces, significant seal face generated EC damage was found on the chamfered area of the rings, as can be observed in Figure 22.

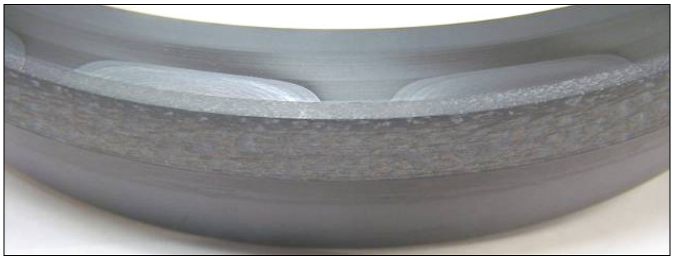

Figure 22. Seal face generated EC damage when tested at 48.3 m/s circumferential speed

A second test was conducted using exactly the same test set up as the first test. It used the same seal face features and materials. However, the differentiator this time being the seal's circumferential speed being lowered from 48.3 to 15.8 m/s. The test was conducted for 168 hours with the remaining conditions as per benchmark parameters using the ultra-pure water conditions.

Upon detailed inspection, no seal face generated EC was found on both rotating seal faces tested, nor was there any other electrically induced damage found in the remainder of the hardware. Figures 23 and 24 show one of the α-SiC rotating seal faces after testing, appearing to be in excellent condition.

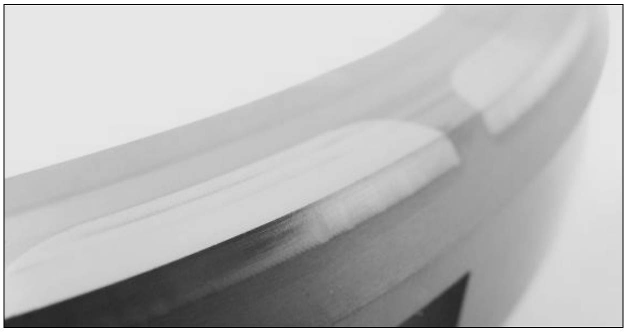
Figure 23. Rotating SiC seal face after
a 168 hour test at 15.8 m/s circumferential speed

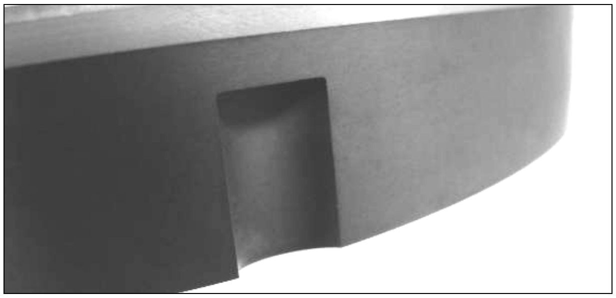
Figure 24. No seal face generated EC damage observed
at seal face drive notches

This test demonstrated that the energy levels inside the sealing interface responsible for seal face generated EC are directly related to the circumferential speed of the mechanical seal when sealing ultra-pure water. It explained the fact why similar design mechanical seals using similar seal face materials, but operated at lower pump speeds are not affected by this phenomenon. Mechanical seals installed in booster feed water pumps used in BWR service achieve satisfactorily MTBM intervals, compared to the same mechanical seals installed in the high speed reactor feed pumps.

Within the sealing industry there seems to be a consensus that for those ultra-pure water applications where the seal's circumferential speed exceeds 40 m/s, risk of seal face generated EC has to be anticipated and special precautions may be required for protection of the seal faces.

Preliminary conclusion: the seal's circumferential speed is a major contributor to seal face generated EC.

Influence of seal water's temperature

In order to investigate if water temperature has an effect on seal face generate EC, two tests were conducted whereby the first test was conducted at 55 °C average seal loop temperature and the second test at 30 °C average seal loop temperature. Both tests were run for 168 hours on the ultra-pure water benchmark conditions specified previously.

For these tests a rotating seal face design was used with a smooth outer diameter and a fillet instead of a chamfer. The drive notches, usually prone to seal face generated EC, were located at the inner diameter to minimize water turbulence at the outer diameter. The principle of this design is shown in Figure 25. The plug seal used a α-SiC bi-modal SiC rotating face, whereas the test seal used a fine grain self-sintered SiC. Both these rotating faces ran against the same resin impregnated carbon graphite material, both of which were equipped with a wire to ground.

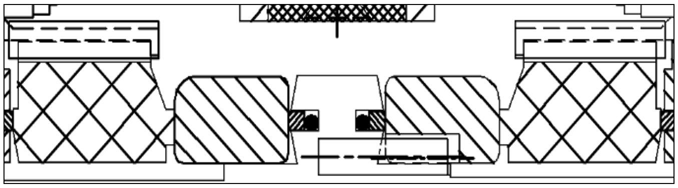
Figure 25. Fillet design rotating face with internal drive pins

While the fine grain self-sintered SiC appeared to have a higher resistance to seal face generated EC compared to the α-SiC bi-modal SiC, it was concluded that by merely lowering the seal water temperature has no significant effect on minimizing seal face generated EC.

Needless to say, having water in the sealing gap at lower temperatures does improve the state of lubrication for the mechanical seal as the asperity contact is lowered by an increased film stiffness between the faces due to the water's increased kinematic viscosity. Therefore, having colder seal water between the faces will have a beneficial effect on sealing performance, but it is not considered a major contributing factor in eliminating or minimizing seal face generated EC.

Figure 26 shows the fine grain self-sintered SiC tested for 168 hours under ultra-pure water conditions at 30 °C. Figure 27 shows the same seal face material tested for 168 hours under ultra-pure water conditions at 55 °C.

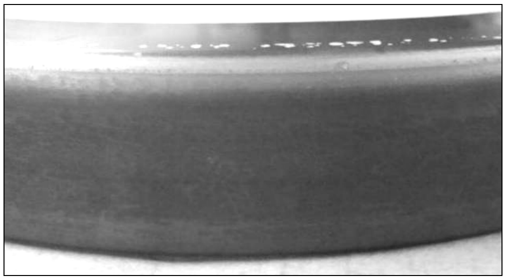
Figure 26. Fine grain SiC rotating face tested at 30 °C

Figure 27. Fine grain SiC rotating face tested at 55 °C

Figure 28 shows the α-SiC bi-modal SiC tested for 168 hours under ultra-pure water conditions at 30 °C. Figure 29 shows the same seal face material tested for 168 hours under ultra-pure water conditions at 55 °C.

Figure 28. α-SiC bi-modal SiC rotating face tested at 30 °C

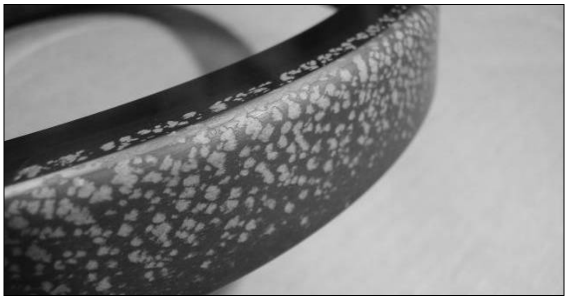

Figure 29. α-SiC bi-modal SiC rotating face tested at 55 °C

Preliminary conclusion: the seal water's temperature is not a significant contributor to seal face generated EC.

Influence of sealing pressure

While the vast majority of the ultra-pure water tests executed under this development program were conducted at a sealing pressure of 4 MPa, in 2010 a reactor feed pump seal test was conducted on behalf of an European BWR utility. This particular test was made on the same test bench as used for the ultra-pure water development program. The test results of this utility ordered test, were integrated into the development program.

Main objective of the test was to demonstrate a new sealing solution for ultra-pure water conditions as used in the actual power station. This meant all conditions, including the sealing pressure would have to meet actual plant conditions.

A plug seal was used with a traditional seal face design and materials to demonstrate to the utility that seal face generated EC would develop allowing a direct comparison to be made with the special test seal installed. The rotating seal face material used was a reaction bonded SiC, known for developing seal face generated EC when subjected to ultra-pure water conditions.

The test seal used the latest anti-EC technology features and seal face materials. The rotating seal face used was equipped with a highly electrically conductive coating using a so-called 'pure-phase crystalline nano-sized diamond grains'. The seal ring's substrate material was the same reaction bonded SiC as used for the plug seal. Furthermore, this rotating seal face used the precision face topography features (waves). Both rotating faces would operate against a flat iso-statically molded resin impregnated carbon graphite stationary seal face.

Seal conditions for the customer test were:

- Medium; ultra-pure water, guaranteed electrical conductivity less than 0.15 µS/cm
- Sealing pressure: 2.5 MPa
- Seal water temperature: 42 °C
- Seal's circumferential speed: 51.8 m/s
- Test duration: 1550 hours

Upon inspection of the test parts, multiple damages were found in the seal's metal parts that suggested a strong presence of electrical activity, including damage between the anti-rotation pin heads and their axial slots in the seal gland, used to retain the stationary seal face holder. Also, corroded stainless steel (AISI 316) coil springs were found with similar corrosion damage in the bottom of the spring pockets located in the seal gland. The latter was likely caused by damage of the protecting oxide layer of the stainless steel through electrical (spark) activity.

Visual inspection presented clear evidence of seal face generated EC on the plug seal's rotating seal face. A portion of each rotating face was then sectioned, solidified, and polished. After reviewing multiple locations on the ring's cross section under a microscope, it became evident that despite being made of the same substrate material, the standard rotating seal face used in the plug seal showed an increasing amount of holes whereby the concentrations of the holes increased the closer its proximity to the corroded surface locations. The OD showed the most damage with SiC material loss. In the case of the test seal face using the coating protection technology the core material was consistent throughout and showed no changes whatsoever.

While the newly developed coated rotating seal face of the test seal did not show the typical spots as seen with seal face generated EC, there were a few spots found on this seal face that through detailed analyses using SEM and EDX techniques were identified as potential delamination locations of the coating with its base substrate material. Apparently, reaction bonded SiC having free silicon in between the SiC crystals does not form a solid basis for the coating, applied through a patented chemical vapor deposition process, to adhere itself to.

All subsequent tests conducted with this same diamond coating technology used a direct sintered SiC substrate material from there on. While delamination of diamond coatings is one concern, the other concern is the relatively high surface roughness obtained on diamond coated seal faces, particularly when it has to be mated with a soft carbon graphite seal face to create a resilient seal face material combination. This concern remains valid even if the diamond crystals are produced on a true nano scale. The actual challenge for seal engineers when using diamond coated seal face technology, is to assure both seal faces will operate consistently and reliably at a minimum seal gap width, in order to minimize asperity contact and subsequent face wear.

Seal leak rate is roughly proportional to the cube of the film gap width. Testing has demonstrated that in order to achieve non-contacting seal face operation the required film gap width needs to be greater than 0.5 micron, but in order to realize low leakage operation, film gap widths should be kept less than 1 micron. For a perspective on how tightly seal face deflection and film gap width dimensions need to be controlled, consider that a single sheet of A4 printer paper is about 100 microns thick.

This specific test was one of the first tests conducted that supported the initial hypothesis that by electrically equalizing both opposing seal faces, one could minimize seal face generated EC. The fact that this customer test was conducted at 2.5 MPa sealing pressure instead of 4 MPa, did not seem to make any difference whatsoever in the appearance of the actual phenomenon.

Naturally, as far as the seal face friction regime and overall seal face distortions are concerned, sealing pressure always remains a critical parameter for high end mechanical sealing solutions. Fortunately, today's sophisticated computer modeling techniques and state-of-the-art finite element programs available on the market are powerful tools for the seal engineers to ensure each mechanical seal is designed in the most optimum way for its specific task given.

Preliminary conclusion: variation in actual sealing pressures as found in today's boiler- or reactor feed pump applications, does not seem to have a significant effect on seal face generated EC.

Influence of seal face part geometry and specific design features

Observations made of actual seal parts used in mechanical seals, which had been field tested for extensive periods in fossil applications using low conductive CWT feed water, use of low seal face friction technology in the form of precision face topography (wavy faces) and preferential surface treatment had proven to be beneficial for feed water's with an electrical conductivity down to 0,5 μS/cm. This demonstrated that specific seal face part geometries and design features may provide a partial solution to the seal face generated EC phenomenon. In light of this experience, many different seal part geometries and design features were tested under this development program. Some of which have already been discussed earlier in this document.

This test conducted was to investigate the resistance against seal face generated EC using the same seal part geometry and features successfully used in water conductivities above 0,5 μS/cm. Both the plug- and test seal were equipped with the same α-SiC bi-modal rotating seal faces using precision face topography and preferential surface treatment technology and operated against a flat iso-statically molded resin impregnated carbon graphite. The sealing conditions were the ones as per benchmark values stated and this test ran for about 173 hours.

While seal face generated EC was found to be significantly less compared to traditional sealing technology used in boiler feed pump seals, EC concentrations were found around the drive slots of both rotating seal faces. Figure 30 shows the plug seal rotating face on the left and the test seal rotating face on the right. Both show signs of seal face generated EC.

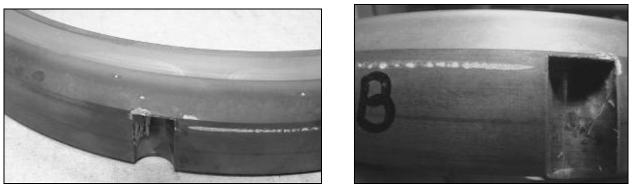

Figure 30. EC at the ring drive slots mainly

Full electrically isolated- or a full conductive tester set up

While the seal face generated EC phenomenon was suspected to have electrical links or causes, explorations were made in design features, which included the use of full electrical isolation of the opposing seal faces as well as using full conductive set ups of the tester hardware. Both these tests were operated under the benchmark test conditions with the electrically isolated set up running for 168 hours and the full conductive test for 160 hours.

The full electrically isolated test used a α-SiC bi-modal rotating seal face with precision face topography and preferential surface treatment technology and operated against a flat iso-statically molded resin impregnated carbon graphite. Tester design was made in such a way that no direct conductive path was present.

The full electrically conductive test used a reaction bonded SiC with precision face topography and preferential surface treatment technology and operated against a flat iso-statically molded resin impregnated carbon graphite. The reason for using the reaction bonded SiC instead of the α-SiC bi-modal material, was the low electrical resistance of the reaction bonded SiC in comparison to the α-SiC bi-modal material. In order to maximize conductance, an additional centering ring was placed under the inner diameter of the rotating seal faces.

Upon inspection of the rotating seal faces, both from the full electrically isolated set up and the full conductive set up, signs of seal generated EC were detected. For the isolated faces, damage was found at the drive slots, whereas for the conductive seal faces, EC damage was found around the OD and chamfer areas of the rotating seal faces. Figure 31 shows the parts of the electrically isolated seal faces. Figure 32 shows the parts of the full conductive seal faces.

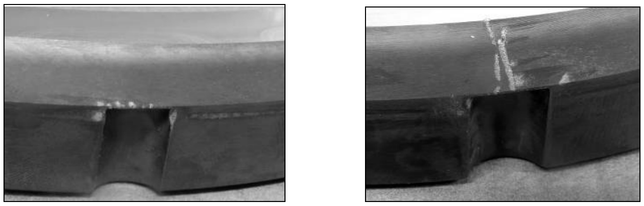

Figure 31. EC damage using full electrically isolated set up

Figure 32. EC damage using full electrically conductive set up

Preliminary conclusion: seal face generated EC damage is created very locally within the sealing gap. A solution needs to be applied inside the sealing gap rather than relying on dissipation of electrical energy through external solutions.

Grounding the carbon graphite stationary seal face

While there have been some hypotheses stating that actual grounding of the seal faces could minimize or eliminate seal face generated EC, a number of tests were conducted using a ground wire connected to the stationary seal faces. In most cases these seal faces would be made from an iso-statically molded resin impregnated carbon graphite material as used in many of the +60 different tests conducted under this development program.

Experience with using special carbon graphite made floating ring bushings installed on the atmospheric side of mechanical seals used in low conductive fossil feed water applications had previously shown evidence of grounding activity with imprints made on the supporting metal hardware (6).

In two particular ultra-pure tests, it was demonstrated that depending on the specific type of rotating SiC seal face material used and whether or not its opposing stationary carbon graphite face would have a ground wire, significant differences in EC damage could be observed, which may suggest that specific seal face materials may benefit from having a grounding wire installed.

The first test used a plug seal with a fine grain self-sintered SiC using seal face topography and preferential surface treatment technology versus a iso-statically molded resin impregnated carbon graphite. The stationary face had a ground wire attached. The test seal used 2 seal faces made from the same α-SiC bi-modal material with no ground wire attached. The tested was conducted for 186 hours under the benchmark ultra-pure water conditions.

Upon inspection the fine grain self-sintered SiC showed a very good resistance to seal face generated EC, while the α-SiC bi-modal material of the test seal rotating face showed pitting on the edges of the face and in the wave region of the stationary face. Figure 33 shows the result of the grounded SiC face while Figure 34 shows the EC damage found on the seal face with no grounding wire.

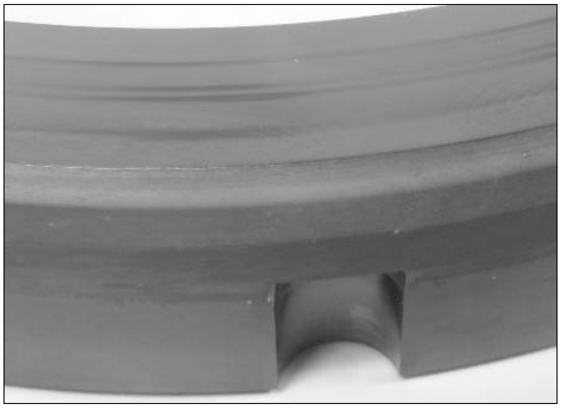

Figure 33. No apparent EC damage on fine grain self-sintered SiC rotating face, operated with a ground wire

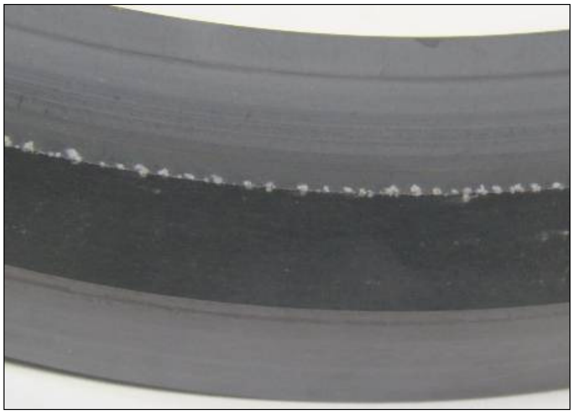

Figure 34. EC damage on α-SiC bi-modal rotating face edge, operated without a ground wire

For the second test, operated for 168 hours under the benchmark test conditions, the plug seal used the same rotating seal face design made from a fine grain self-sintered SiC materials, except this time the ground wire was not applied. The opposing stationary face was an iso-statically molded resin impregnated carbon graphite. For the test seal, a α-SiC bi-modal rotating face was applied running against an iso-statically molded resin impregnated carbon graphite stationary face connected to a ground wire. Both rotating faces used the precision face topography and preferential surface treatment technology.

Upon inspection, it became evident that while the fine grain self-sintered SiC had not shown any seal face generated EC in the first test using a ground wire, this time it did show significant EC damage. Also the test seal rotating face, despite connected to a ground wire, displayed a significant amount of EC damage. Figure 35 shows the ungrounded fine grain self-sintered SiC seal face from the plug seal, while Figure 36 shows the α-SiC bi-modal rotating face from the test seal equipped with a ground wire to its stationary seal face.

Figure 35. EC damage on fine grain self-sintered SiC rotating face, operated without a ground wire

Figure 36. EC damage on α-SiC bi-modal rotating face, operated with a ground wire

During both tests a series of voltage measurements were conducted from the carbon graphite stationary face to ground. Figure 37 shows the graph made from these shaft voltage measurements. The blue dots are measurement results obtained during the first test and the pink dots are the result from the second test.

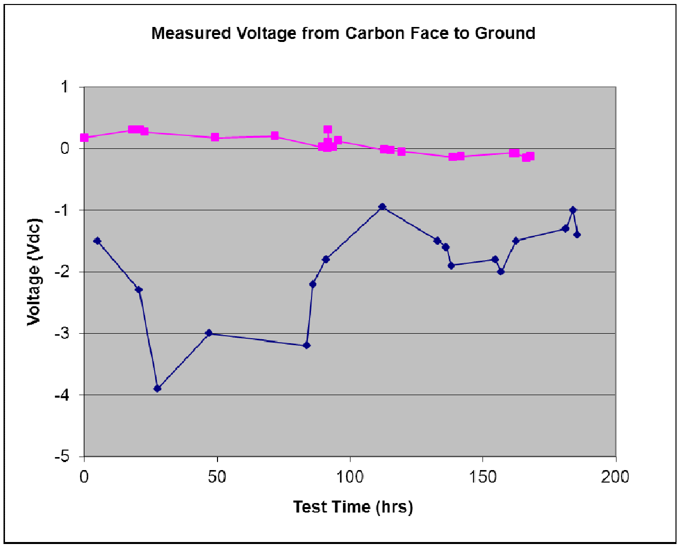

Figure 37. Shaft voltage results ground wire tests

Preliminary conclusion: depending on the type of seal face technology and material combination used, grounding of the seal faces seems to have some benefit in minimizing seal face generated EC, but the practical implementation in real life feed pump applications may prove complicated.

Protection of seal faces by an external cover

Since most of the seal face generated EC appeared to be located on the rotating seal face area, which is in direct contact with the highly turbulent surrounding liquid, tests were conducted with a protective shroud covering the EC damage prone areas to see if this would bring a possible solution. Typically seal engineers have a strong preference to use highly thermal conductive ceramics as rotating seal face material to allow an efficient transfer of frictional heat into the surrounding seal water. Putting a shroud over this area of the rotating seal face could hinder this transfer of heat and may generate hotter interface temperatures in the sealing gap. Therefore, not the entire area of where the rotating seal face is exposed to the seal water can be closed off by such a device, leaving some of the area exposed to the high turbulent, ultra-pure water. A first of several tests were set up using a shroud to partially cover the rotating seal faces.

This first test used a plug seal with a fine grain self-sintered SiC rotating seal face in combination with an iso-statically molded resin impregnated carbon graphite stationary face connected to a ground wire. The same set up as was successfully tested during the previous grounding test series. The plug seal did not have a shroud protecting the rotating seal face.

The test seal used a rotating seal face made from a α-SiC bi-modal material operating against an iso-statically molded resin impregnated carbon graphite stationary face. The rotating seal face was equipped with a protective metal shroud limiting the amount of exposed SiC face area with the ultra-pure water.

After 170 hours of operation, inspection of the parts showed presence of EC in those areas of the test seal rotating seal face, which had been directly exposed to the highly turbulent water. Also in other tests conducted under this development program that incorporated a shroud for protection, seal face generated EC was continued to be witnessed.

Preliminary conclusion: applying protective hardware to seal face areas exposed to high turbulent ultra-pure water can reduce seal face generated EC, but is not considered a feasible option as some areas of the same seal face are still affected by the phenomenon.

Reversal of seal face materials

Some years ago a field test was conducted at a European BWR utility by a vendor under the hypothesis that by reversing the seal face materials, seal generated EC could minimized or eliminated. While seal engineers usually have a strong preference using high thermal conductive ceramics as rotating seal face material in order to transfer frictional heat into the surrounding seal water, this hypothesis was investigated by a separate test.

A specific test was set up using a iso-statically molded resin impregnated carbon graphite as rotating seal face material. The stationary seal face was made from a fine-grain self-sintered SiC equipped with precision face topography and preferential surface treatment technology. This test was conducted for 168 hours under the benchmark ultra-pure water conditions.

Inspection of the rotating carbon graphite seal face showed a grainy texture of the wear nose towards the outer diameter, which was likely caused by material pull out due to high shear. While the fine grain self-sintered SiC appeared to be in excellent condition, seal face generated EC was found in the middle of the features lasered resembling the deepest part of the valley inside the wavy profile. Figure 38 shows the grainy texture found on the wear nose of the rotating carbon graphite seal face. Figure 39 shows the fine grain self-sintered SiC stationary seal face with EC damage in the middle of the lasered features. The polishing effect of the carbon rotating face can be well observed and EC damage seems to coincide with the outer diameter of the carbon wear nose.

Figure 38. Grainy texture rotating carbon graphite seal face

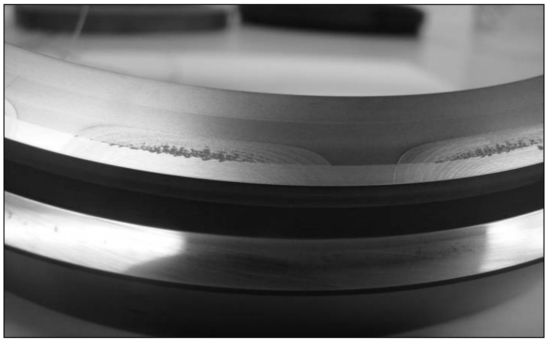

Figure 39. EC damage inside lasered feature of stationary seal face coinciding with wear nose OD of rotating seal face

Preliminary conclusion: merely reversing the seal face materials does not seem to be effective against seal face generated EC. Grainy texture of the carbon graphite suggests a mechanical overload of this material by pull out through high shear even when supported by hydrodynamic lubrication enhancing sealing technology.

Using different seal face friction reducing techniques

While it was assumed that seal face friction, either between 2 opposing seal faces or between the rotating seal face and the ultra-pure water, may cause an accumulation of electrostatic energy, reduction of friction was seen as a major factor for this phenomenon. In fact, the 2 practical field tests conducted for the fossil power stations in Europe and USA had demonstrated that use of precision face topography (waves) in combination with the preferential surface treatment technology had significantly reduced seal face generated EC.

Having the capability of today’s micro-laser machining allows seal engineers to develop tribological systems where seal face surface friction can be significantly reduced using true nano-scale features. In fact, these recently developed micro-laser machining capabilities are so powerful that the geometry and size of these surface lubrication features are only limited by the imagination of the seal’s designer. Laboratory- and field tests have been conducted on single mechanical seals used in light hydrocarbon applications, where the seal face friction coefficient can be lowered by approximately 60% compared to traditional sealing technology, while maintaining low leakages.

A test was set up where the plug seal used a fine grain self-sintered SiC rotating seal face using a shroud for protection equipped with newly developed face features operating against a iso-statically molded resin impregnated carbon graphite seal face. The test seal used a rotating seal face made from a proprietary material protected with a highly conductive coating also operating against a iso-statically molded resin impregnated carbon graphite seal face. Seal face friction for the test seal was reduced by using precision face topography technology (waves). The plug seal face materials were tested for 212 hours under the benchmark ultra-pure water conditions, while the seal face materials for the test seal had been operated for a total of 397 hours under the same conditions.

During testing, it was noticed that the plug seal using the low friction features ran very well with low leakages. Upon disassembly however, EC was detected on the outer diameter of the rotating seal face. The test seal using the new proprietary seal face material had shown higher leakages, but inspection revealed that no EC damage could be found. As more tests were conducted with the new seal face material, it became apparent that this seal face material would become crucial in the search for a final sealing solution against seal face generated EC.

Figure 40 shows the plug seal rotating seal face with signs of EC on the outer, unprotected area of the fine grain self-sintered seal face.

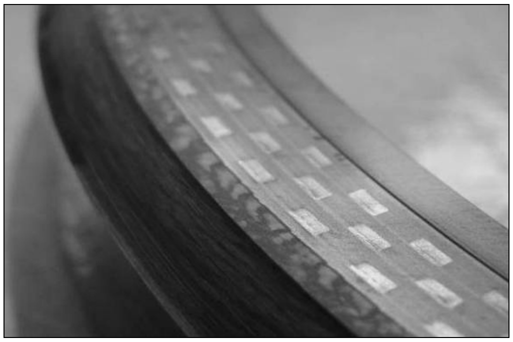

Figure 40. Use of special friction reduction features on a fine grain self-sintered SiC rotating seal face

Figure 41 shows the new proprietary seal face material which operated for 397 hours under the ultra-pure water regime without developing any EC damage whatsoever.

Figure 41. Proprietary rotating seal face material using wavy face technology to reduce face friction

As previously discussed in paragraph ‘Experimental Seal Laboratory Testing’, it became apparent that friction in general is a factor in the phenomenon of seal face generated EC. This includes friction generated by a single rotating ring when subjected to the benchmark ultra-pure water test conditions.

Several tests were conducted during which a single seal face was installed on the test unit using electrically isolated PTFE parts allowed to rotate freely in ultra-pure water with no additional frictional contact from a secondary part. The seal face was mounted on a PTFE sleeve and clamped in axial direction between two PTFE discs.

The first test used a α-SiC material. It was operated for 165 hours under the benchmark ultra-pure water conditions. Upon inspection EC damage was found on the drive notches with circumferential erosion/corrosion damage starting from these drive notches. Damage was also observed on the SiC seal face at the outer diameter boundary where both PTFE rings are situated on both sides of the ring. The damage seen appeared to have some periodicity to it. Figure 42 shows the observed damage found at this specific location.

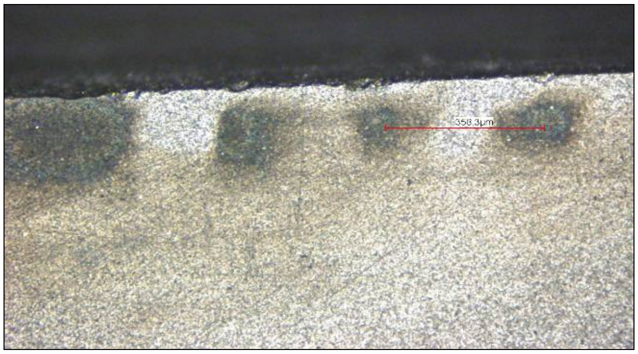

Figure 42. EC damage SiC face at OD boundary with PTFE clamp ring

A second test was conducted using a similar set up as the first one. This time the free rotor material was a silicon nitride material that was tested for 168 hours under the benchmark ultra-pure water conditions. Upon inspection, this material did not reveal any EC related damage.

Finally, a third test was conducted. The free rotor material used was a self-sintered SiC was tested designed with a special porosity. The rotor was operated for 168 hours in the ultra-pure water. Upon inspection the rotor displayed some very light EC type markings on the OD, but no measurable wear could be found. Figure 43 shows a picture of this particular rotor tested.

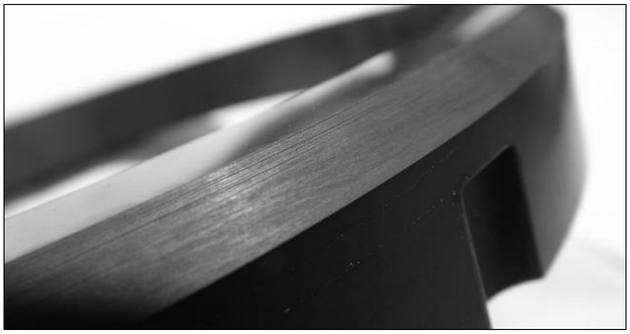

Figure 43. Very light EC markings, no measurable wear

Preliminary conclusion: reduction of seal face friction through the use of micro-lasered features has proven to contribute in lowering seal face generated EC, but its combination with the type of seal face material used, seems crucial.

Influence of seal face materials and material combinations

From the very beginning of this development program it was clear to all individuals involved that seal face materials and their possible combinations, would play a critical role in solving the phenomenon of seal face generated EC. While some first successes were achieved for feed pump seal applications using low conductive water with an electrical conductivity down to 0,5 μS/cm, making the final step for ultra-pure water conductivities between 0.055 < X < 0.5 μS/cm, proved to be a challenge.

Under the development program, which incorporated more than 60 different tests, many different seal face materials and seal face material combinations were tested. The seal face materials tested include, but are not limited to:

- Reaction bonded fine-grain SiC
- Fine grain self-sintered SiC
- Medium grain self-sintered SiC
- Coarse grain self-sintered SiC
- Bi-modal α-SiC
- Nickel bound tungsten carbide
- Aluminum oxide
- Conductive silicon nitride
- Non-conductive silicon nitride
- Conductive ultra-nano diamond crystal coating on a direct sintered SiC substrate
- Non-conductive ultra-nano diamond crystal coating on a direct sintered SiC substrate
- Conductive ultra-nano diamond crystal coating on a reaction bonded fine grain SiC substrate
- Non-conductive diamond like coating
- Iso-statically molded resin impregnated carbon graphite

One of the prime objectives under this development program has been to develop a resilient sealing solution using a combination of a rotating hard face for critical heat transfer capabilities and a soft stationary carbon graphite face being the forgiving material in this complex tribological system.

To date, two rotating seal face materials have been tested that have demonstrated to fully resist 'seal face generated EC' under the benchmark ultra-pure water conditions. Both seal face materials are based on the principle of applying a highly conductive surface coating on a highly conductive substrate material. Their resistance has been proven under laboratory testing, with one particular material tested more than 850 hours.

In line with the very first hypotheses stated in this document, the actual solution seems to come from equalizing the electrical conductivities of both opposing seal face materials. While stationary face carbon graphite materials by nature have a high electrical conductivity, the main goal is to assure that the opposing, rotating hard face has the same electrical conductivity level. It is evident that such a solution has to be developed in close cooperation with highly skilled material technologists having the capabilities to engineer a suitable rotating hard face material with required characteristics.

Both developed hard seal face material solutions are based on experimental design and require the use of newly developed manufacturing techniques. Therefore, obtaining the required consistency in coating uniformity, coating adhesion as well as determining the optimum seal gap width to allow operation against a soft carbon graphite seal face, has become the final step in the process of finalizing the sealing solution. As a result of this, more testing will be conducted under this development program, although it is expected that the actual program will be completed towards the end of 2013, allowing the introduction of several final anti-EC sealing solutions to the market.

Preliminary conclusion: seal face materials are a key factor in eliminating seal face generated EC. Tests have shown that using highly conductive rotating hard seal face materials operated against a soft carbon graphite stationary seal face can fully eliminate seal face generated EC damage under the presented benchmark ultra-pure water conditions.

CONCLUSIONS

Seal face generated electrical corrosion damage is closely related to the applied seal water conductivity, seal's circumferential speed, applied seal face materials as well as their combinations. Variation in seal water temperature or sealing pressure do not seem to be a major factor in the development of the phenomenon. Seal face generated EC seems to be created locally at the sealing interface, whereby external solutions, such as use of a ground wire or the use of protective covers across the rotating seal faces, do not seem highly effective in minimizing or eliminating the phenomenon. Use of seal face friction reducing features involving precision face topography and preferential surface treatment technology present a partial solution to the problem. The most crucial part of the 'seal face generated EC' sealing solution is to apply a rotating hard face material that possesses an equally high electrical conductivity than the opposing carbon graphite stationary seal face, effectively stopping the flow of electrons across the seal gap.

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ACKNOWLEDGEMENTS

The authors would like to thank the management of Flowserve Corporation for their support and the opportunity to present this tutorial.