GE Power

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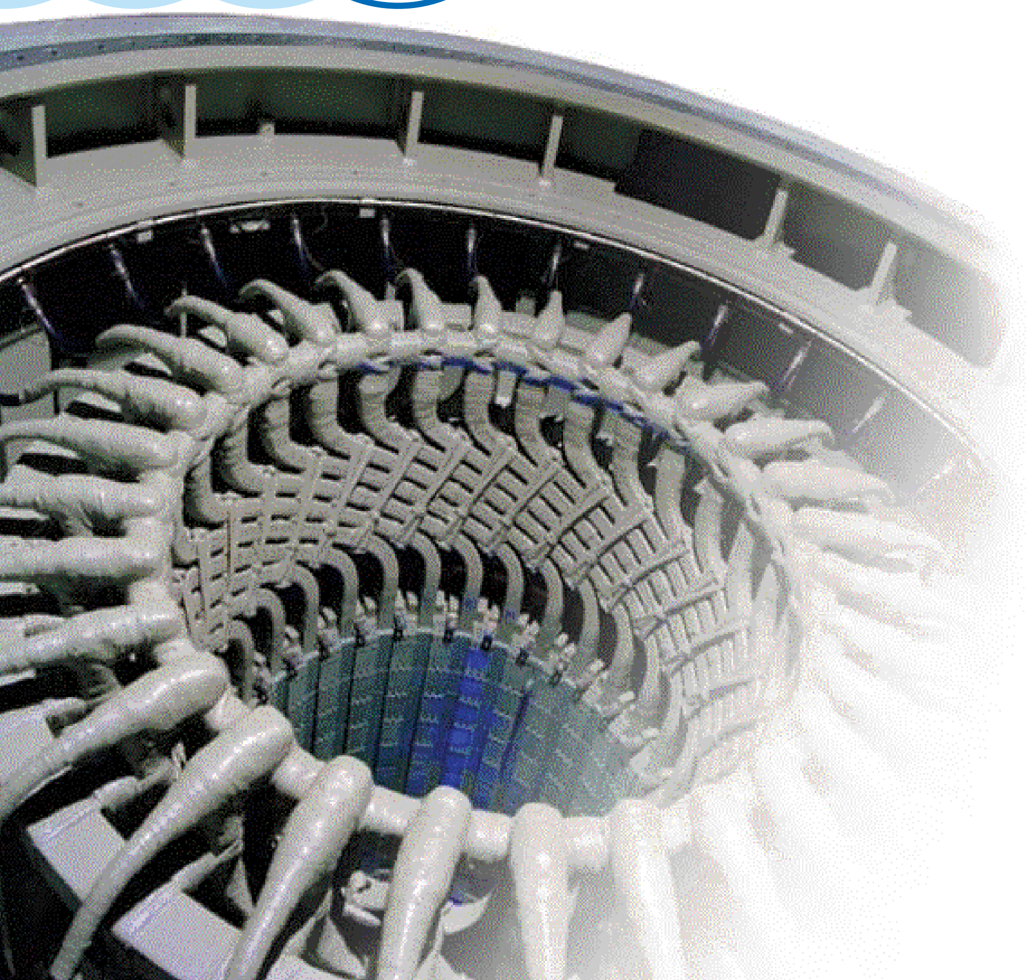
Liquid Cooled Generator – Stator Winding Connection Ring Test, Repair and Upgrades



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Introduction

The average age of a large liquid cooled GE generator is now over 35 years and many owners plan to run them for many more years. Large liquid cooled generators were designed for decades of life with expected periodic inspection, maintenance and repairs. For example, field rewinds and stator rewinds have been routine refurbishments over the years.

One large subcomponent commonly overlooked has been the Liquid Cooled Connection Ring (LCCR) system as most stator rewinds up to now reused the existing connection rings since in many cases they were in good operating condition.

The LCCR system consists of various quantity and sizes of stator winding connection rings along with the Tetra-loc end winding basket that support the stator end winding and connection rings.

However, older stator winding connection ring system can develop reliability issues due to gradual thermal ageing of the ground wall insulation, gradual deterioration and loosening of the end winding basket and there is evidence of crevice corrosion in the brazes of the connection rings similar to what we have seen on stator bar clips.

For these reasons GE is now recommending testing and potential refurbishment or replacement of connection rings. This document will provide more information on this subject including;

- Recent fleet leak data and recommended inspections and monitoring
- Function of Connection Rings and recommended repairs and upgrades
- More detailed description of the Connection Ring and End Winding Basket hardware
- Recent new development of Phos-Free braze upgrades for Connection Rings. Phos-Free refers to a non-phosphorus containing braze material.

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1. Fleet Experience on Connection Ring Leaks, Monitoring, Inspections and Repairs

A. Background

Over the past few years GE has seen systemic leaks in the Liquid Cooled Connection Ring (LCCR) System which has affected reliability and availability. The word 'System' refers to the connection rings and end winding basket described in more detail in Section 3. Recent lab analysis has identified crevice corrosion is occurring similar to what has been experienced in the stator bar clip to strand braze joint. Though the LCCR has not seen the quantity of leaks compared to bar clip to strand leaks and they typically occur later in the life of the unit. GE believes the cause of most of these leaks to be due to crevice corrosion. The mechanism switches back and forth from crevice corrosion of the braze alloy to acid attack of copper which leads to a development of a leak path as referenced in GE TIL 1098. The discovery of these leaks is either in service or during an outage or stator rewind and depending on the size of the leak, the LCCR may require urgent repair and/or continuous monitoring and/or replacement.

The life of a GE generator was expected to be decades with periodic inspection, maintenance and repairs. Stator bar and rotor rewinds have been typical in the industry but the LCCR System has typically not been replaced in stator bar rewinds due to good material condition. But that is changing, the average age of these liquid cooled connection rings is now over 35 years based on the number of units in service since commercial operation as shown in Figure 1. So Connection Rings and Tetra-loc end winding baskets are expected to show more wear as they continue to age. Some customers have now chosen to replace the LCCR System based upon leaks, and/or gradual thermal degradation and mechanical wear of the LCCR electrical ground insulation and/or gradual thermal degradation and mechanical wear of the end winding basket.

B. Leak Data

To help customers perform risk assessment GE has compiled data on the connection ring leaks, as shown in Figure 2. This shows the number and location of leaks. This is data we are aware of at the time of this document and it is reasonable to expect this number will continue to grow.

Thus, GE now recommends performing actions on connection rings at outages or during a stator rewind to address potential leaks and wear. Figure 3 shows leaks identified at an outage or at a stator rewind.

C. Testing

Testing of the LCCR system should be part of an overall generator test plan. GE recommends an overall Test and Inspection Plan per GEK 103566J but below are some specific highlights from the overall testing plan.

Offline Leak Testing Methods

Offline leak testing is the best way to determine and quantify the leak at connection rings. The typical recommendations from GE have been to perform a periodic off-line stator leak maintenance test program at every minor and major outage. In order to perform offline leak testing, stator preparation is the key as presence of moisture within the winding can conceal a small leak making it undetectable to some leak tests. The most efficient method of removing water is to perform a "Stator Blowdown" using very dry air. There are situations where the last remaining moisture trace within the winding must be removed by pulling a vacuum on the system, which will "boil off" the water. This is a time consuming process and can be minimized by performing a thorough blowdown prior to vacuum drying. This process is slow in relation to blowdown, but is necessary. Typically, if a winding has been dried well by blowdown, vacuum must be pulled on the winding until it is dry, which can take approximately 24 to 36 hours.

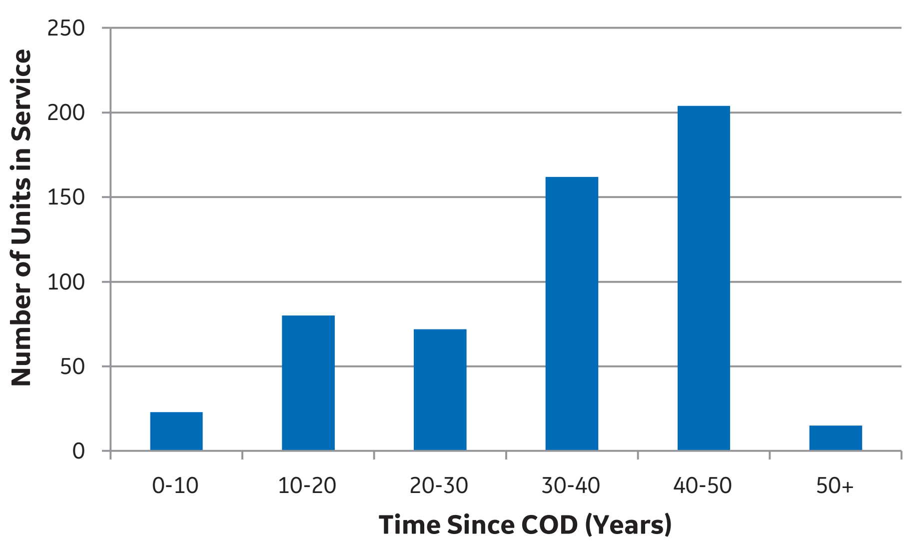


Figure 1 Generator Age

Hydraulic Integrity Test (HIT) Skid

To facilitate and expedite the dry out of the water-cooled stator windings, as well as the Vacuum and Pressure Decay Tests, GE has developed a self-contained, skid-mounted equipment, called a "HIT Skid" (Hydraulic Integrity Test Skid). Hoses from the skid are connected to the generator at specified flanges of the stator.

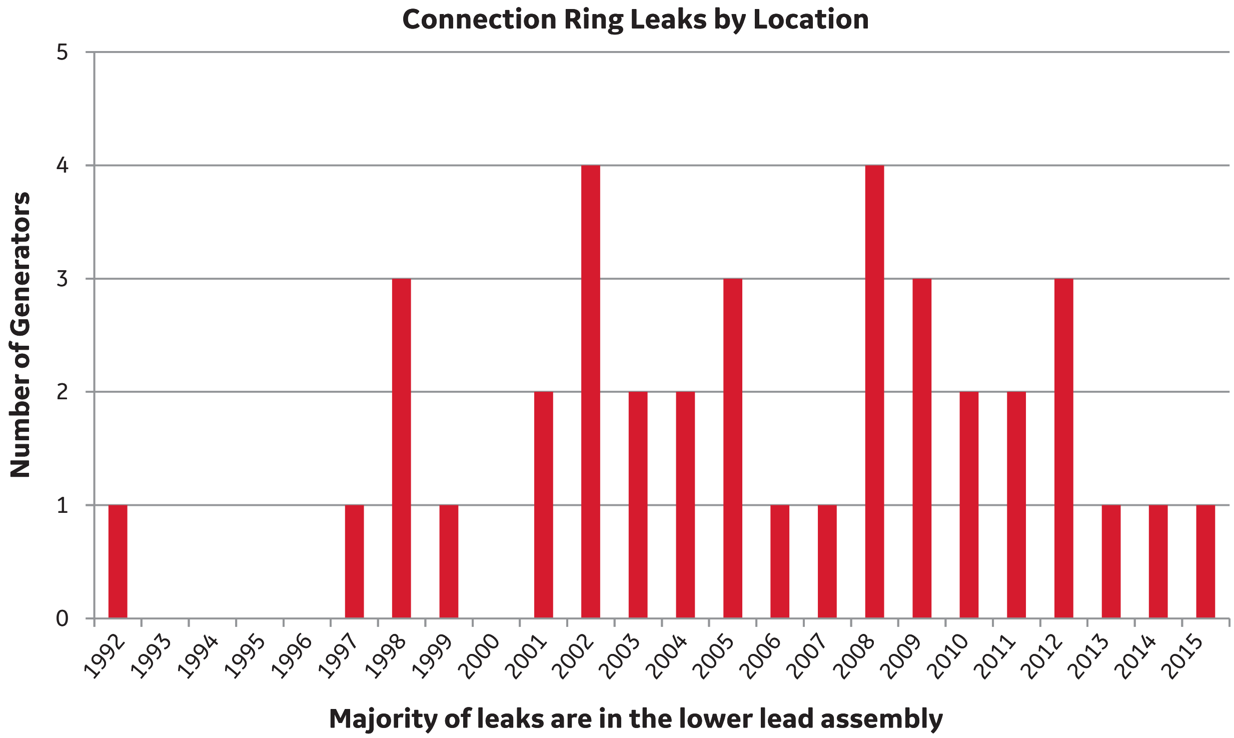


Figure 2 Connection Ring Leaks by Location

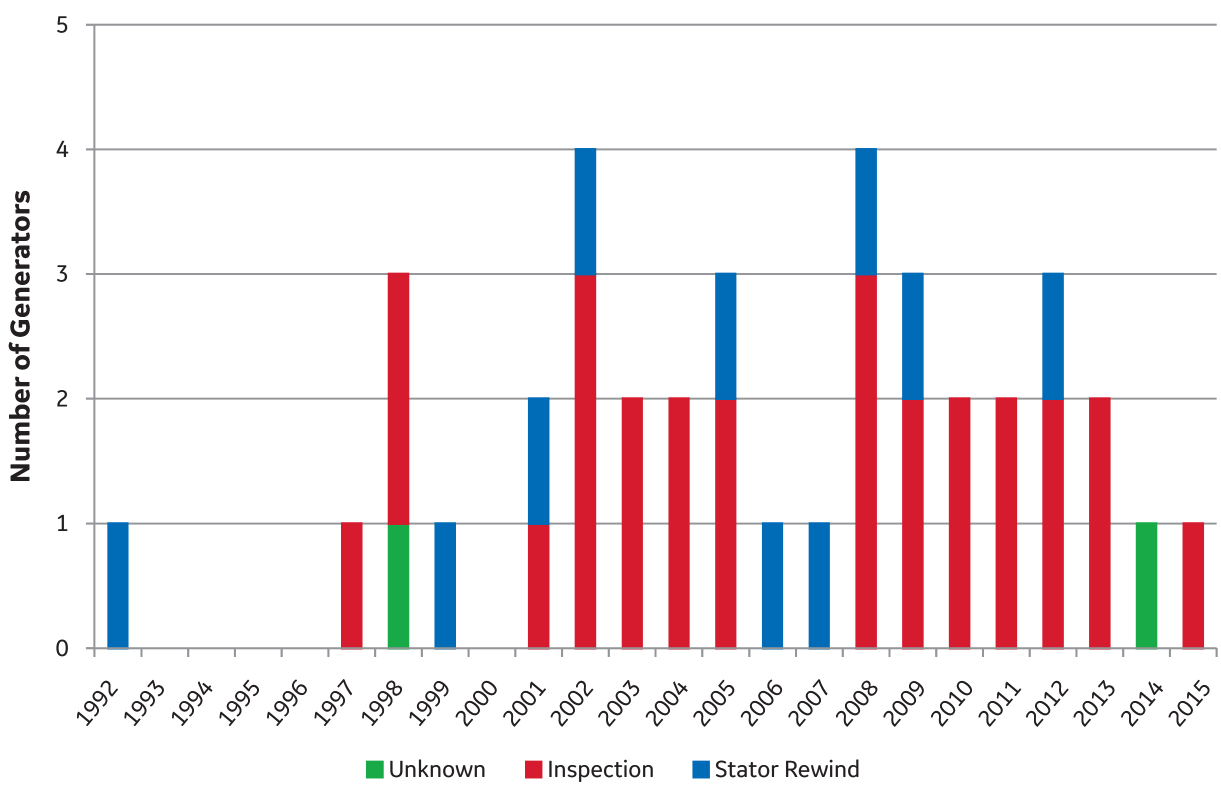


Figure 3. Leaks Identified at Outage Inspection or at Rewind

Helium Tracer Gas Testing

Helium Tracer Gas Testing is a method of leak detection where the generator is pressurized with a helium gas so that possible leak points can be detected using a helium gas detector. There is a wide range of tracer gases and tracer gas detectors on the market. The Mass Spectrometry technology used by GE employs helium as the tracer gas because it is the lightest inert gas, nontoxic, and non-hazardous. Other gases do not provide the level of sensitivity of helium, and some of them can combine with any residual water in the winding to form acidic solutions. Tracer gas detector sensitivity is very important in finding leaks in the LCCR system. Leak sources can be buried beneath several layers of glass, mica, and resin within the LCCR system. This can make detection difficult. A process of bagging the local braze locations (the source of most leaks) has greatly improved the ability to locate very small leaks. Helium pressure is maintained on the system for a period of time to allow helium from a buried leak to migrate through the insulation and become concentrated in the bag.

Leaks that could have been found with the tracer gas will be missed if LCCR System only had been Vacuum Decay Tested and Pressure Decay Tested based on experience. Early detection provides the opportunity to make repairs before more extensive damage can occur to the ground insulation. To detect small leaks, the sniffer detector must be brought within 2 to 3 inches of the leak. Since it is nearly impossible to cover every square inch of the connection rings, tracer test techniques such as bagging the lower lead area are recommended as it provides better test data at higher risk areas of leaks.

D. Online Monitoring and Repairs

On-line testing allows for monitoring of the winding condition over the period between maintenance tests, but is not capable of isolating individual leaks. However, on-line testing is still an important part of proper stator maintenance. Early detection and repair are crucial to minimizing the damage that can result from water within the generator. Periodic monitoring of these indicators should be a fundamental part of operating all generators with water-cooled stator windings.

Stator Leak Monitoring System (SLMS – HP)

GE has developed a Stator Leak Monitoring System (SLMS-HP) which is highly recommended for:

- Oxygenating stator cooling water to the recommended level
- Monitoring the level of hydrogen escaping out of the YTV vent

The system consists of a flow meter, gas analyzer, data acquisition and control system and a system piping modification package. The SLMS-HP module is mounted at the hydrogen detraining tank and connects to a gas analyzer and a flow meter which are added to the existing piping. The system brings fresh filtered air into the cooling water to provide a measurable gas flow and to maintain the proper water oxygen content (2 to 8 ppm). Figure below shows the typical configuration of the SLMS-HP system. Measurement of the hydrogen content and gas flow provides an accurate measurement of hydrogen leakage through the stator winding. The level of hydrogen leakage is directly related to leaks in the water-cooled stator winding and connection rings. Additionally, SLMS-HP aids in minimizing stator bar copper erosion, resin bed damage, rectifier grounds, and stator winding strand blockage.

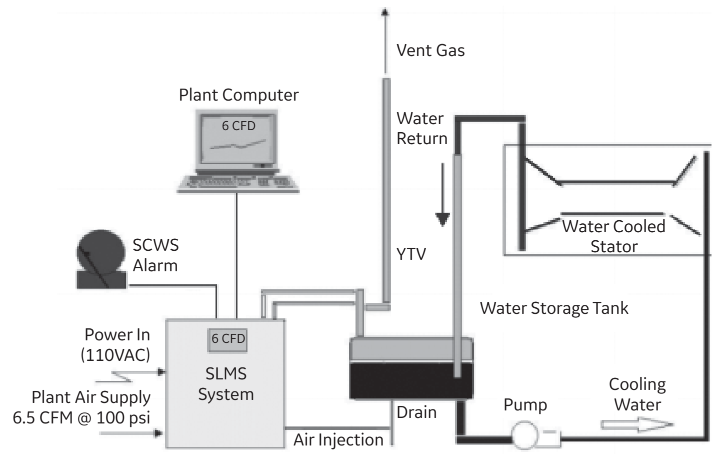


Figure 4

ePDA

Like the main stator winding, the use of partial discharge couplers can detect long term trending of gradual electrical degradation of the LCCR ground insulation system. So this is a recommended on-line monitoring system.

Summary of Recommended Tests if a Leak on LCCR Develops

- Continuous on-line monitoring of the connection rings (and rest of the stator winding circuit) using SLMS-HP is recommended to determine development of in-service leaks.
- Performing periodic HIT skid with Helium Tracer Gas Testing (per GEK103556J) focused on connection rings at the beginning of an outage can help identify a possible leak early in the outage cycle and an extended outage can be minimized.
- ePDA can be a useful on line trending tool to detect deterioration of the ground wall insulation.
- Remember to leverage existing RTD and Thermocouple Monitoring. Knowing trends in stator bar temperatures can be useful in overall condition assessment of the connection rings if a leak is present. For example a high reading thermocouple and/or RTD (caused by a gas bubble) at a phase bar compared to normal temperatures can indicate a local leak.

2. Recommended Repairs and Upgrades

A. Function of and Duty on the LCCR System

GE Water-Cooled Connection Rings are a distinct subsystem of the stator winding and are fully contained in the hydrogen boundary within the generator end winding and lower frame extension space. The Connection Rings conduct the stator (armature) current from the stator winding to the high voltage bushings and further downstream to the iso-phase bus/neutral compartment. The Connection Rings operate at full winding voltage and experience significant magnetic forces in both steady state operation and during transient events (e.g. close in fault, out of phase synchronization).

As previously mentioned, the Connection Rings are water-cooled and are subject to corrosive action in the assembly braze joints. The first GE Water-Cooled Connection Ring units were shipped in the early 1960's and GE has used similar design and manufacturing technology on both new Water-Cooled generators and Connection Ring Replacements until 2014. The GE Water-Cooled Connection Ring fleet has shown to be very reliable overall.

Connections Rings are highly stressed components and GE recommends regular test and inspections of the Generator System including the Connection Rings per GEK 103566J. This includes visual inspection, electrical test (hi-pot) and hydraulic integrity tests. This regimen of testing provides a complete assessment of the Connection Rings and the results of these tests and inspections has typically been the driver for maintenance activities on Connection Rings.

B. Failure modes

Typical adverse conditions on Connection Rings that require maintenance/repair activity include loose and "greasing" blocking, electrical insulation failures and hydraulic leaks. Repairs to loose and "greasing" blocking typically entails replacement of the loose block, re-tying or application of epoxy (e.g. "red-eye).

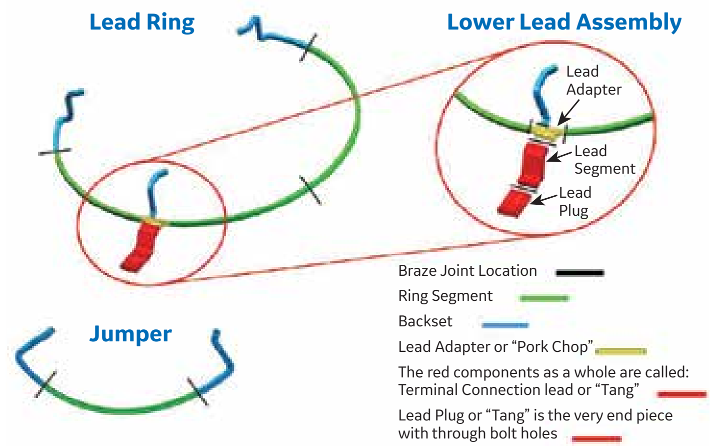
These repairs are considered routine, long term repairs and generally do not present future operating risk. Insulation failures, either in-service or during hi-pot testing, are extremely rare to non-existent. GE has no actual documented cases of a Water-Cooled Connection Ring hi-pot failure. Therefore, currently, GE has no actual repair experience for this type of failure. But this may change in the future.

The failure of key concern is hydraulic leaks and as documented in Section 1, Water-Cooled Connection Rings leaks present significant reliability risk.

The vast majority of Water-Cooled Connection Ring Leaks have been found in the Lead Plug (commonly referred to as the "Tang" or the "Lower Lead ') or Lead Adapter (commonly referred to as the "Pork Chop") regions of the Connection Ring Assembly. The tongue and groove braze joint is at particularly high risk for leaks. Reference Figure 5 and Figure 6.

Terminology of Connection Rings

There are two types of rings. A Lead Ring which makes an external connection outside of the generator and a Jumper which connects circuits within the generator. The black lines between the different components indicates a braze joint location



All Connection Ring Braze Joints contain phosphorus and are susceptible to Crevice Corrosion

Figure 5. Connection Ring Terminology

Collector End Set of Connection Rings

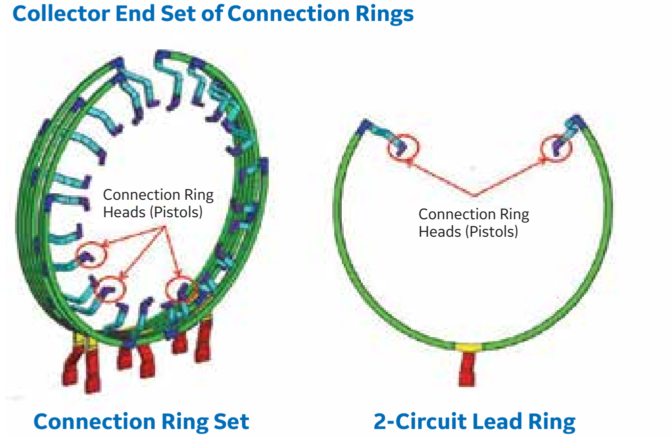


Figure 6. Collector End Set of Connection RIngs

Typically only about 50% of the linear braze distance in the connection ring tang (pork chop) is accessible due to the proximity of the adjacent connection rings (even with stripping insulation). The mid arc segments are not accessible due to the proximity of adjacent rings.

Based on typical GE Water-Cooled Connection Ring design, approximately 50% of the brazes are accessible. When you take into account the size of a modified TIG torch and length of a human arm, and the ability for someone to braze using a mirror, GE estimated that typically ~40% of the linear braze distance is repairable without disassembly of the connection rings.

C. Repair Experience

The recommended repair process for an accessible Connection Ring Leak is a TIG Braze repair at the leak site.

GE has had good experience with successful TIG Braze repairs to accessible Connection Ring leak sites. Reference Figure 7 for a typical accessible leak and Figure 8 of a TIG repair.

However, GE has a case (2013) of a connection ring leak location in the “tang” / “pork chop” tongue and groove joint that was non-repairable using the TIG Braze process. The leak rate was reduced and the unit was returned to service. However, a leak is still present in the connection ring.

Anaerobic Cement has been used in the past for short term repairs but is not a recommended repair as it is water soluble and requires a vacuum on the water side to draw it into the leak. This can result in a material being drawn into the connection ring and into the water system. Any foreign material in the water side can potentially plug a water passage.

Epoxy Injection (external) is a repair option for connection ring leaks that are inaccessible or non-repairable using TIG brazing. This repair would be considered temporary. The epoxy material is not water soluble and would be expected to last longer than anaerobic cement.

GE has recently experienced two forced outages (a nuclear unit and a fossil unit) since October 2013 due to connection ring leaks. Both units were repaired to an extent that allowed a return to service.

The Connection Ring leak on the nuclear unit was initially identified by a large magnitude step change in the hydrogen leakage rate into the Stator Cooling Water System and detected by the GE Stator Leak Monitoring System (SLMS HP). This leak also resulted in a high Stator Cooling Water thermocouple (TC) indication and high Stator Slot resistance temperature detector (RTD) indication. These high temperatures were consistent with extensive hydrogen gas ingress into the phase stator bar connected electrically and hydraulically to the leaking connection ring. This occurrence demonstrates the high risk associated with a Connection Ring leak.

GE has experienced a case (2012) of a Connection Ring Leak that was not accessible for repair. See Figure 9 for a typical view. This type of leak presents a difficult customer risk decision in regards to pursuing a repair solution or operating the unit as is and monitoring the leak. A repair solution for an inaccessible leak would entail removal of the connection ring from the end winding with the stator winding in-place. This removal process would be highly intrusive and would require disassembly of the hose, phase connections, connection ring support system and flexible leads.

In this section, in- situ repairs have been discussed but what about replacement of connection rings with the winding in place?

There are technical risks associated with removal and installation of the connection rings with the stator winding in-place. In some cases certain connection rings need to be installed before the

Figure 7. Typical accessible leak location in Connection Ring “tang” / “pork chop” tongue and groove joint

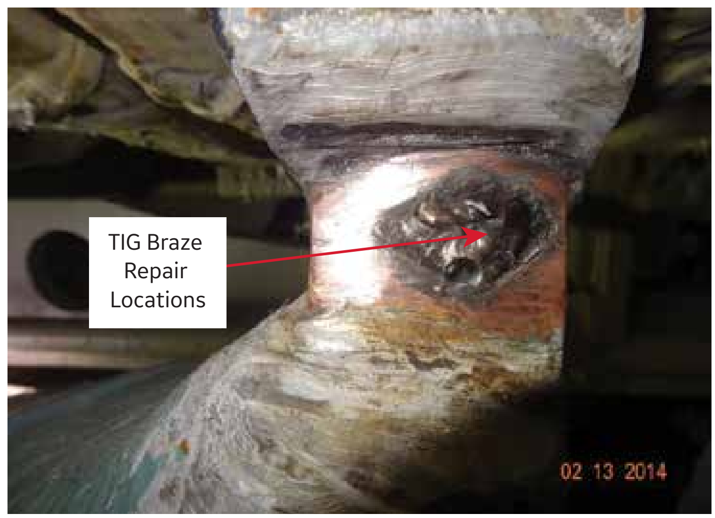


Figure 8. Successful TIG braze repair

Figure 9. Inaccessible Connection Ring Leak

stator bars are installed. So, a connection ring replacement with the winding in place could require a full lay-out and 3D model to determine if there would be interferences.

GE has not had to perform such a repair yet on the Water-Cooled Connection Ring fleet, but has performed 3D modeling on several high risk generators in the fleet to ascertain feasibility of removal and installation of the connection rings with the stator winding in-place. Positive results have been determined from the 3D modeling, but each unique generator family will require this same 3D modeling effort.

GE expects to continue to find more connection ring leaks both in-service from SLMS and during HIT Skid testing due to normal aging and the susceptibility of the connection ring braze joints to the crevice corrosion phenomenon.

D. Repair Recommendations

Consequently, GE is recommending that Water-Cooled Connection Ring users consider long term reliability in their maintenance planning.

A Liquid Cooled Stator Rewind presents the optimal opportunity to address long term connection ring reliability as the connection rings are fully accessible for removal and installation with the winding removed. GE can provide new connection rings utilizing a phosphorus free manufacturing assembly brazing process and can optimize schedule activities during the stator rewind process to minimize schedule impact. New connection rings with phos-free manufacturing assembly brazes eliminate concerns with crevice corrosion and dramatically reduces future leak risk.

GE also can remove the existing connection rings and refurbish them by stripping the existing insulation, re-flowing the manufacturing assembly brazes and re-insulating at the GE Schenectady manufacturing plant. Reference Figure 10. This refurbishment process resets the insulation and braze integrity

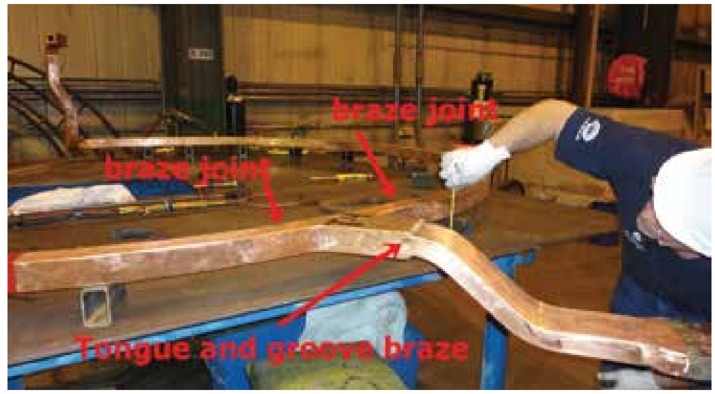


Figure 10. Typical Connection Ring Refurbishment

for years of expected high reliability. This refurbishment process does not eliminate the risk of crevice corrosion as the braze reflow must be done with the original phosphorous containing braze alloy. Refurbishment can provide outage duration challenges for reduced cycle stator rewind outages. (See Pros and Cons table below.)

E. Replacement of the Connection Rings with the winding in-place

Replacement of the Connection Rings with the winding in-place can also be considered as a proactive approach or when leaks have been incurred to eliminate reliability concerns with Connection Ring leaks. GE has not performed a replacement of the Connection Rings with the winding in-place on the GE Water-Cooled Connection Ring fleet, but has performed 3D modeling on several high risk generators in the fleet to ascertain feasibility of removal and installation of the connection rings with the stator winding in-place. Positive results have been determined from the 3D modeling analysis, but each unique generator family will require this same 3D modeling effort. GE anticipates that this scope will be performed at some point in the future.

Summary of Recommended Repairs		**Pros**	**Cons**
A.	TIG braze for spot repair	• Quick planning and execution	• Limited to specific leak • Still have other potential leak sites • Retain older, original end winding basket and other connection rings • Braze repair location may be inaccessible
B.	Strip insulation, un-braze/re-braze with original type braze material, re-insulate during rewind outage	• May be possible to do during an outage with little up front planning	• Uses in kind phos-containing braze • Risk of extending outage • Retain older, original end winding basket
C.	New phos-free replacement connection rings – this is the preferred option.	• New phos-free brazes - planned execution - new end winding basket	

3. Connection Ring and End Winding Basket Hardware Description

The majority of the GE Large Steam Turbine Generator fleet was manufactured in an era when custom designed generators were produced to match specific turbine output and grid requirements. As a result, there are approximately 600 units in this fleet, many are similar in design but few have identical LCCR systems. Each new replacement order involves a substantial engineering effort which requires a full 3-D model of the end-winding basket and connection rings in order to upgrade these critical components to current design standards. This comprehensive redesign is one of the many steps completed to ensure the new connection rings fit up correctly to the rest of the generator during an outage.

A. Connection Ring Design

The number of braze joints has been minimized to produce each connection ring. The necessity of the braze joints may be understood with knowledge of the design complexity as well as manufacturing limitations. For example, a simple connection ring designed for a 2 pole, 2 circuit stator winding contains 5 to 8 braze joints, including the lead connector or terminal. This type of ring is shown in Figure 11. The ring segment is constructed from one large arc section (main ring section) and two backset sections. In addition, the lead connector or terminal connection adds two or more brazes to the complete assembly.

Because each backset has multiple precision bends, they are formed separately and then brazed to the pre-formed ring segments to ensure the final form of the whole ring assembly. Attempting to manufacture the ring segments and backsets from one piece is impractical while considering the complicated bends, the precision required, and the overall bulk of one large piece of copper.

A typical ring assembly as shown in Figure 11 or Figure 12 weighs approximately 100 – 600 pounds (each) with a diameter of approximately 8 – 12 feet. The physical dimensions of the assembly, the weight of the assembly, as well as the material composition (hollow copper), and of course the electrical insulation all contribute to the challenges associated with manufacturing and handling a complete ring. GE has specific handling practices for both manufacturing and installation to ensure no deformation occurs to the ring assembly.

A more complex ring, designed for a 3 circuit generator winding is shown in Figure 12. This ring is comprised of two main ring sections which span at least ½ of the circumference, 3 backset sections which attach to the 3 circuits, and finally the terminal which attaches to a high voltage bushing.

The complexity and quantity and weight of the rings and jumpers increases substantially with 4 pole generators and higher output 2 pole generators.

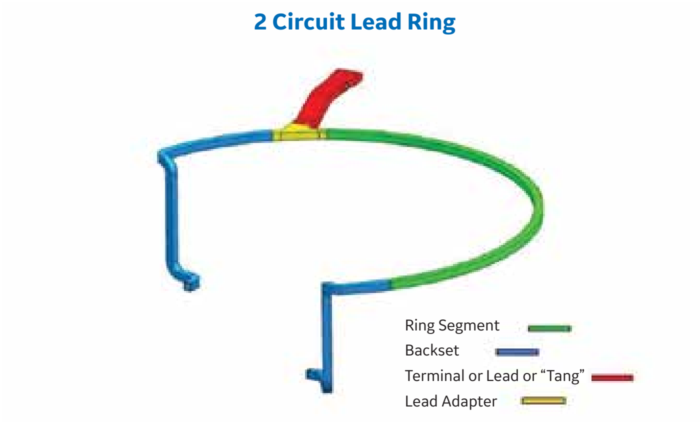


Figure 11. 2 CIrcuit Lead Ring

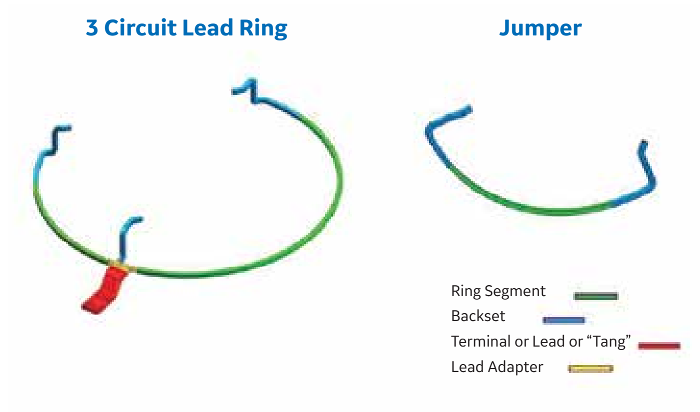


Figure 12. 3 CIrcuit Lead Ring and Jumper

B. End Winding Basket Design

In addition to the complexity of the connection rings and jumper arrangement, the end-winding basket system which supports and retains the connection rings is a complex non-metallic structure. The majority of the fleet was built with GE's Tetra-loc® end-winding system which is still used today (with small improvements over the decades). This time proven design allows for axial expansion of the end-winding system during operation with the utilization of bearing pads (Chemloy pads) and will also support extreme transient forces. Chemloy is a trade name for graphite impregnated teflon. The bearing pads are located between the axial supports (gunstocks) and the support bracket which is attached to the core compression flange as shown in Figure 13.

This enables the basket structure to move axially with the rings and stator winding during thermal expansion and contraction. The axial supports are connected to the core compression flange and multiple circumferential glass rings connect each axial support to form a basket.

A replacement basket is shown in Figure 14 and Figure 15. This rigid structure is composed of non-metallic materials; glass rings and blocks, glass roving and epoxy. The entire assembly is subjected to wear, fatigue and gradual loosening over time due to temperature and mechanical forces both steady state and transient.

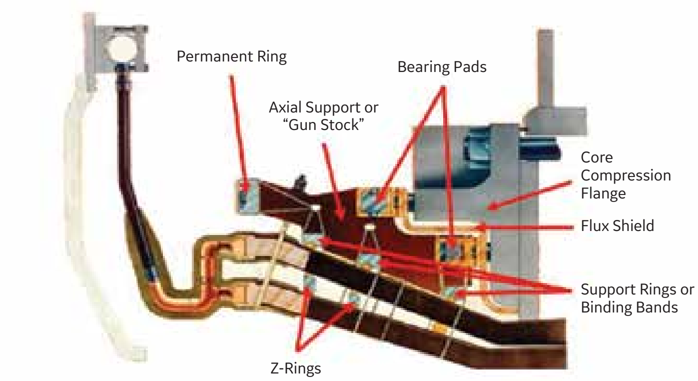
Note Figure 16, it shows a cut away view of the axial supports and support rings and a partial flux shield.

Historically, the end-winding basket has been replaced on a condition based approach. In most cases customers have elected to re-apply glass roving and replace the bearing pads where necessary and keep the original end winding basket during a rewind. This repair approach has been acceptable but has been evolving recently and more customers are replacing them now due to condition.

Summary

To summarize, GE recommends to replace both the connection rings and the Tetra-Loc end winding basket (LCCR system) during a full Liquid Cooled Stator Rewind for long term reliability and since it is an optimum time to do so.

Tetraloc End Winding Support System
Cross Sectional View



Glass Roving and Epoxy ties are shown as white bands connecting the bars, axial supports and rings.

Figure 13. Tetraloc End Winding Support System, Cross Sectional View

Partially Assembled Tetraloc End Winding Basket

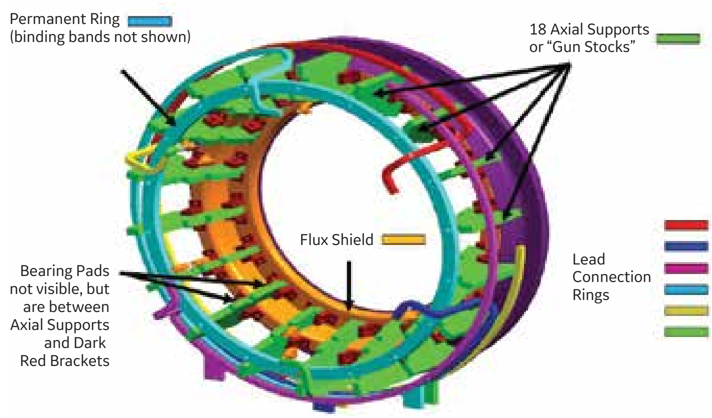
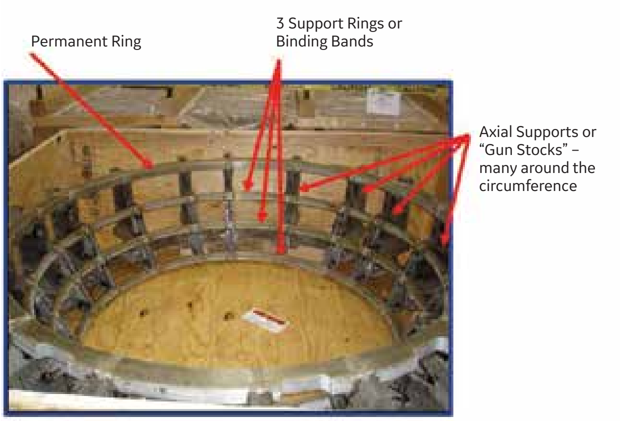


Figure 15. Partially Assembled Tetraloc End Winding Basket

Replacement Tetraloc End Winding Basket



Flux Shield not shown.

Figure 14. Replacement Tetraloc End Winding Basket

Terminology of Connection Rings

The stator bars and rings are removed to better show the axial supports and support rings.

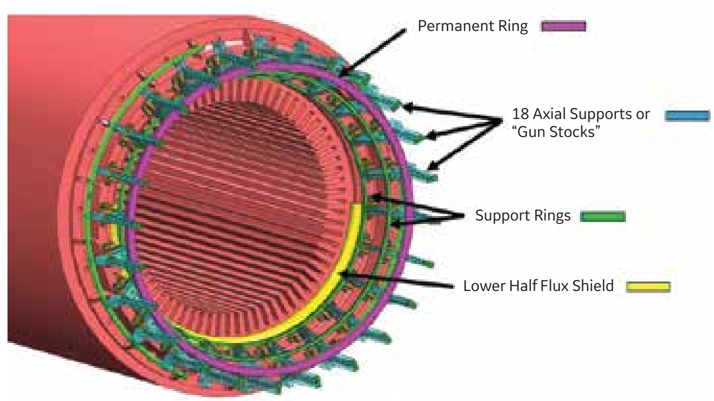


Figure 16. Tetraloc End WInding Basket Structure

4. Recent new development of Phos-Free Braze Technology in Liquid-Cooled Stator Connection Rings.

A. Root cause of crevice corrosion

Manufacturers have joined copper components for large steam turbine-generator stator winding connection rings with various filler metals, but primarily with copper, silver, and phosphorus-containing braze alloys. This family of alloys has been user-friendly for brazing copper components in factory environments, without a flux or without particular positioning to contain the alloy and prevent run-out. These braze alloys continue to be widely used in the industry. When used to join copper components that come in contact with cooling water in directly water-cooled stator windings, phosphorus-containing braze alloys are prone to accelerated corrosion mechanisms that can lead to eventual water leakage. Connection ring water leaks can degrade high-voltage insulation on the connection rings, result in stator winding hydraulic leakage (HIT SKID) test failures during test and inspection outages or after full stator rewinds, and extend test, inspection, and refurbishment outages to repair the leaks. The root cause of the corrosion has been identified as the presence of phosphorus in the braze alloy. Reference Figure 17.

Figure 17. Connection ring braze joint water leak identified during on-site test and inspection

The mechanism by which brazed joints in connection rings develop leaks in service is referred to as crevice corrosion. This is the same mechanism that led to leaks in clip-to-strand brazes prior to development of GE's phosphorus-free brazing technology. This section briefly discusses crevice corrosion and illustrates the ways in which phosphorus-free technology eliminates it as a risk.

The braze alloys used in both legacy clip-to-strand and connection ring joints contain a significant amount of phosphorus. It acts as a self-fluxing agent during the brazing process, and enables robust brazes to be made by relatively simple methods.

When this solidified braze alloy containing phosphorus is exposed to water, some of the phosphorus atoms from the alloy are released into the water, where they react to form phosphoric acid. In a large volume of water, or if the water is flowing and continually replenished, the small amount of phosphoric acid produced is too dilute to be a factor. But in a tiny volume of stagnant water, such as can be present at the root of a crevice, the phosphoric acid concentration can become significant, eventually reaching levels high enough to attack copper. When this happens at a crevice in a copper-to-copper braze joint, attack of the copper exposes more braze alloy, which releases more phosphorus, and so on. The process continues until the joint develops a leak.

During the GE Stator Bar Clip-to-Strand Phos-Free Braze development program starting in the early 2000's, liquid cooled water clips were exposed to water chemistry, flow rates and temperatures consistent with generator operating conditions.

Individual clip sample were brazed with the Phos-Free alloy, with the original stator bar clip to strand braze alloy, and with the original connection ring braze alloy. After exposure times ranging between a few months and six years, clips were removed from testing and evaluated metallographically.

Several hundred braze interfaces were examined per clip at high magnification. Crevice corrosion sites were observed for both the original stator bar clip to strand braze alloy and the original connection ring braze alloy clips, and typical corrosion rates for each braze alloy were estimated based on these observations. The highest rate of crevice corrosion attack was seen in the stator bar clip to strand braze alloy. Crevice corrosion in the connection ring braze alloy clips occurred at an order of magnitude slower than for stator bar clip to strand braze alloy. The difference in rate is due to the different braze alloy chemistries. It is very important to note that no crevice corrosion of any sort was found in the 30 Phos-Free clips exposed up to 6 years.

The higher stator bar clip to strand braze alloy corrosion rate determined in this laboratory testing was consistent with observations on clips returned from actual generators. At the time this work was performed, GE did not have field parts available to validate the connection ring braze corrosion rates.

Recently, however, GE performed microscopic evaluations on metallographic sections from connection ring braze joints from a set of fossil 2-pole (Figures 18 and 19) and nuclear 4-pole (Figures 20 and 21) water cooled connection rings. These connection rings were replaced during a Liquid Cooled Stator Rewind and braze joint samples made available to GE for section testing.

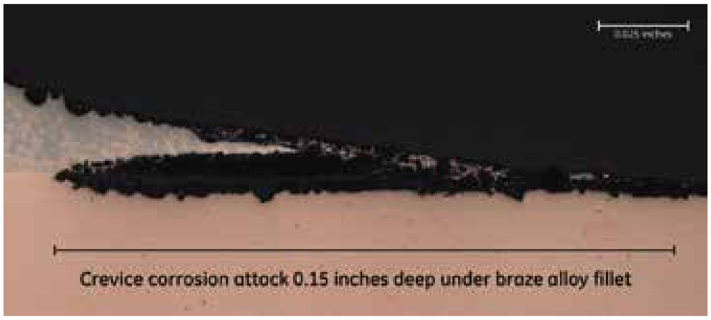
The connection ring braze joints contain the same material combination as the clips tested in Phos-Free program discussed above, and presented an opportunity to validate the connection ring braze corrosion rates calculated during the Phos-Free laboratory testing program. The crevice corrosion rates estimated from the in-service field units were found to be consistent with those from the laboratory corrosion work discussed above.

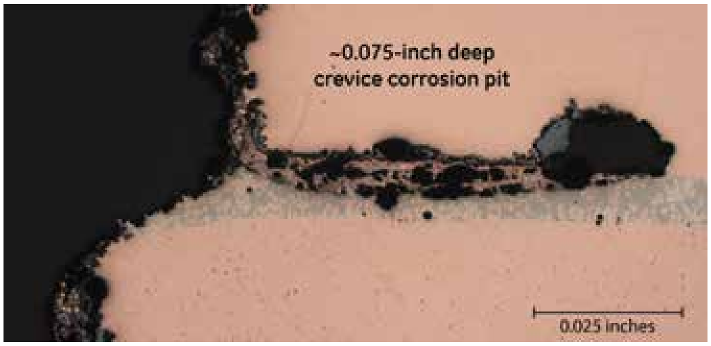
When considering corrosion rate, connection ring joint lengths, and typical porosity, the calculated time to leak is consistent with

GE's fleet experience. This work validates both the risk of crevice corrosion, and the typical time-to-leak for connection rings. GE expects to see connection ring leaks in the future throughout the fleet as it ages.

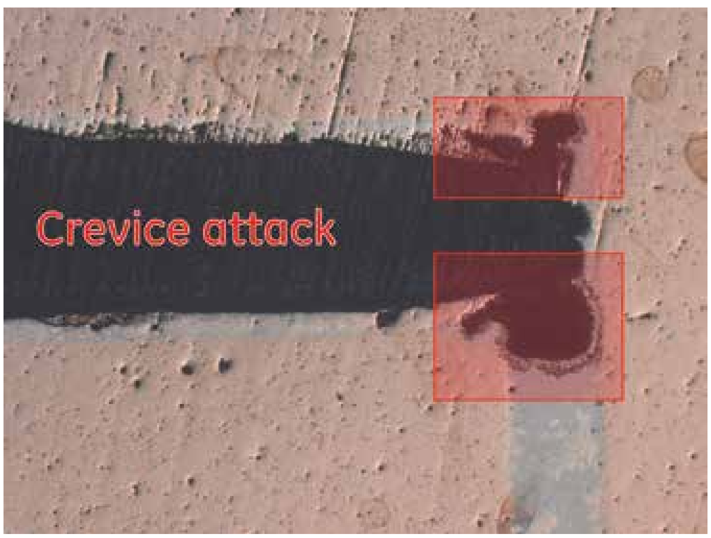
As the name implies, GE's phosphorus-free braze technology employs alloys that do not contain phosphorus—or any other element with the potential to form an acid in crevices. From a metallurgical standpoint, removing phosphorus from the picture is highly desirable, because it completely shuts off the possibility of a crevice attack mechanism.

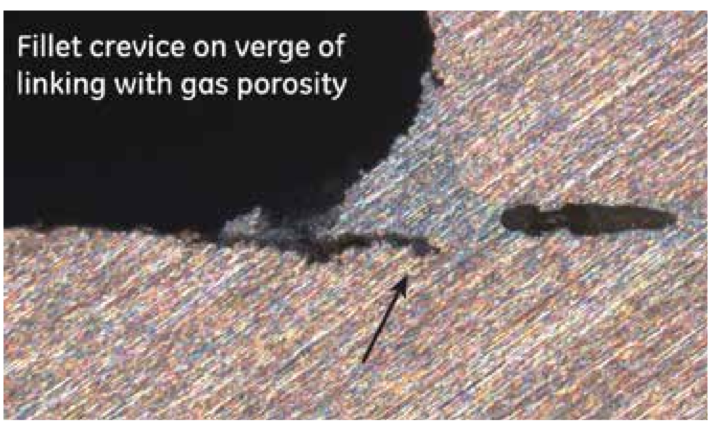
Our track record for successful phosphorus free brazing technology is demonstrated by over 15000 leak free liquid cooled stator bars put in service in the last 10 years.





Figures 18 and 19. Connection Ring Braze Joint Corrosion Sites from Fossil, 2-pole Water-Cooled Connection Ring Samples





Figures 20 and 21. Connection Ring Braze Joint Corrosion Sites from Nuclear, 4-pole Water-Cooled Connection Ring Samples

B. Development of phos-free brazing technology for stator bars

Once the corrosion mechanism of phosphorus-containing braze joints in the presence of water was well-understood, GE initiated a technology program in 2000 to develop and implement a copper brazing technology that would eliminate the root cause of the braze joint corrosion that was resulting in braze joint water leaks in stator bar clip-to-strand braze joints. These braze joints were particularly prone to corrosion due to the high phosphorus content in the braze alloy in the presence of water and the numerous opportunities for corrosion paths to develop in these complex braze joints. Beginning in 2001, GE developed phos-free braze joint technology, manufacturing infrastructure and factory-hardened brazing methods to produce stator bar clip-to-strand braze joints consistently and with zero defects. Over 500 braze joints were made and tested to perfect the technology. GE confirmed the absence of crevice corrosion in phos-free braze joints using continuous water flow loops over a six-year period in a test configuration. The fleet leader stator winding with this technology has been in service since 2005, over 30,000 clip-to-strand braze joints have been produced and put into service, and there have been no reports of clip-to-strand braze joint leaks in any of these braze joints. Reference Figure 22 for a clip to strand braze joint.

Figure 22. Cutaway of stator bar clip-to-strand braze joint

C. Application of proven technology to connection ring braze joints

Following successful design and service validation of the phos-free braze joint technology on stator bar clip-to-strand braze joints, in 2011 GE initiated a technology program to introduce phosphorus-free braze joints on water-cooled stator winding connections rings. This program leveraged much of what GE has done since 2001 on clip to strand braze improvements. Stator winding connection ring braze joints are quite different from stator bar clip-to-strand braze joints, reference Figure 23 for a typical connection ring view. The GE liquid-cooled generator fleet has many connection ring designs due to design evolution over a 60-year period, braze joint configurations are varied within a connection ring, and individual braze joints can vary greatly in geometry and mass. Application of phos-free braze joint technology required the development of creative and innovative manufacturing methods, technologies and a commitment to an accelerated test and learn development methodology. Many new design, manufacturing, and test technologies have been developed to enable efficient and consistent manufacturing of phos-free, leak-free stator winding connection rings.

D. Enabling technologies development and implementation

GE has implemented several enabling technologies to produce life-time leak-free water-cooled connection rings. Component copper specifications and braze alloys have been selected to enable long term corrosion resistance. Braze joint components have been redesigned and standardized to enable consistent brazing with phosphorus-free alloys and ensure consistent joint integrity. Manufacturing methods enable flux-less brazing with phosphorus-free alloys in a high-throughput manufacturing line with the use of flexible fixturing and ambient-enabling workstations. Reference Figure 24. GE has retooled connection ring manufacturing facilities with modern, state of the art brazing manufacturing technologies and process control equipment. Brazing processes are programmed and repeatable. Hydraulic testing of connection rings is equivalent to the stringent testing performed on stator bars and they include the use of extremely sensitive helium tracer gas testing. A multi-million dollar investment in connection ring design, manufacturing, and testing technologies leverages the service validation of the stator bar phosphorus-free clip-to-strand braze joint technology.

Figure 24. Connection ring brazing workstations

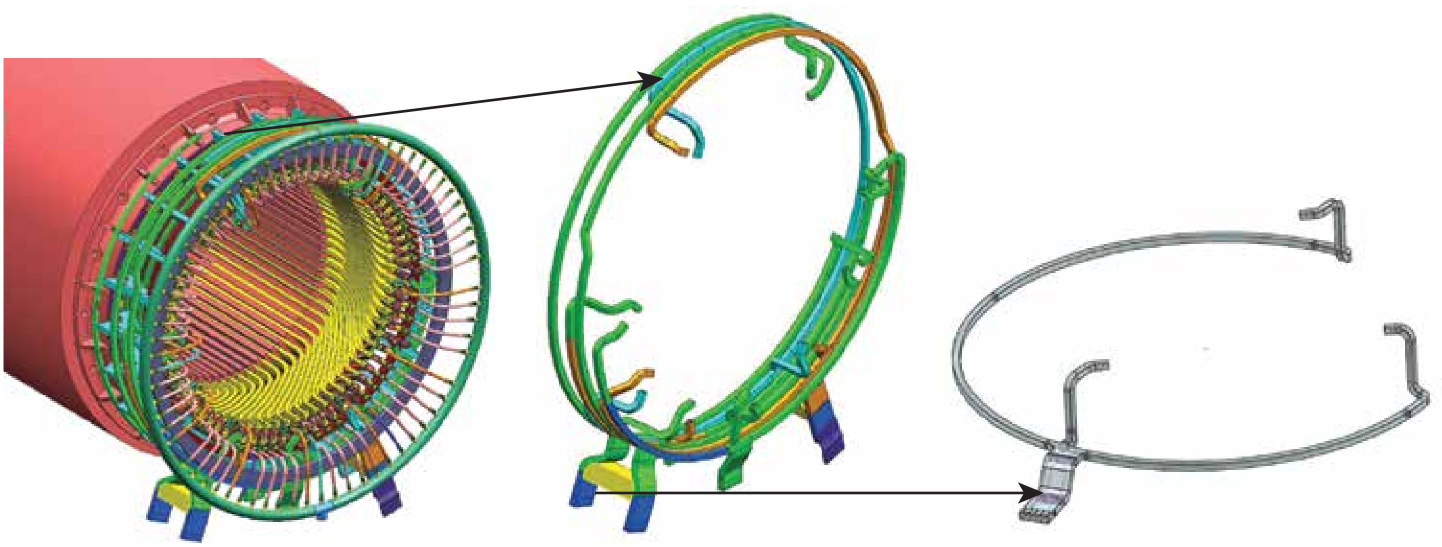


Figure 23. Generator liquid-cooled stator connection rings

E. Braze joint quality verification strategies

Brazing quality control strategies rely on brazing process methods qualifications, technician continuous training and qualification;

- first piece qualifications,
- automation of the brazing process,
- electronic process record keeping,
- adherence to frozen manufacturing methods and brazing process protocols,
- stringent one-over-one visual inspection requirements,
- and highly sensitive hydraulic leak tests.

Following completion of fabrication and brazing, the final shape of each connection ring is confirmed on a full-scale template and each ring is flushed with a cleaning agent to eliminate contaminants and ensure hydraulic continuity.

F. First shipment of Phos-Free brazed Connection Rings

GE completed the first shipment of phosphorus-free brazed connection rings (Reference Figure 25) in 2014 and the connection rings were installed during a full stator rewind and placed into service in 2015.

Figure 25. Phos-free liquid-cooled connection rings

5. Conclusion

This document has provided recent experience showing operational reliability information for the Liquid Cooled Connection Ring System.

GE has provided current leak data fleet data and now evidence of crevice corrosion.

Inspection and monitoring recommendations have been described to assist customers in risk assessment.

Based upon material condition, repairs or replacement may be prudent and GE is providing repair, replacement and upgrade options with commensurate pros and cons to help the decision making process.

6. Frequently Asked Questions

1. *Q. My generator does not have leaks in the Connection Rings. Do I need to replace them?*

A. Replacing the Connection Ring System is based on condition and should take into account several variables such as assessing the condition of the electrical insulation due to decades of thermal ageing using electrical tests, visual inspection for tightness or looseness of the end winding basket support system (this may cause insulation fretting and wear) and leaks. In addition to potential condition issues, it is recommended to replace them at the time of a Liquid Cooled Stator Rewind as this is a logical time to do it from a logistics point of view.

2. *Q. We have a planned stator rewind with Phos-Free Stator Bar Clip to Strand Brazes coming up but have not included new Connection Rings, what are my options to limit our risk?*

A. It would be prudent to review previous test reports to see if there were leaks or signs of mechanical and electrical insulation wear. If no previous test information is available it would be prudent to develop a contingency plan (reference Section Two repair options) and inspect the connection rings at the very start of the outage.

3. *Q. We have had a previous LCSR with Non-Phos-Free Stator Bar Clip to Strand Brazes. What should we do with our LCCR system?*

A. The Connection Rings can develop leaks and can have degraded insulation due to temperature cycling and mechanical wear. They should be continued to be inspected and monitored. This applies to a non Phos-Free Stator Winding as well. They may all need to be replaced eventually based on material condition.

4. *Q. How much cycle time does Connection Ring replacement add to the cycle time of a Liquid Cooled Stator Rewind?*

A. It varies on a case by case basis. If it is planned up front prior to the outage, it may be possible to be done within the existing outage window, in some cases it may take several extra shifts. New Connection Rings generally provide for a shorter outage than refurbished Connection Rings.

5. *Q. Are new end winding support baskets required with the installation of new connection rings?*

A. It is recommended to do so as the basket has a finite life and now is the time to replace it. If it is done after the rewind basically another rewind needs to be done to remove and replace the basket.

6. *Q. What if we only want to replace the connection rings and we choose not to do a full stator rewind – what do we do about the Tetra-loc end winding basket?*

A. Replacement of the connection rings while keeping the existing stator winding will need review on a case by case basis. The end winding basket is not feasible to remove and replace without removing the stator bars. So the basket would need to remain.

7. *Q. Does LCSR's still contain phosphorous brazes? If so, why?*

A. GE Liquid Cooled Generators have experienced crevice corrosion clip to strand leaks some years ago as documented in TIL 1098 for example. There had been 1000's of individual strand leaks and GE prioritized repairs in this area some time ago – such as developing the Phos-Free stator clip braze upgrade.

In a later time frame and to a much smaller degree, GE Liquid Cooled Generators have experienced crevice corrosion leaks in the Connection Ring System as explained in this document. GE has dedicated resources more recently to provide upgrades in this Connection Ring System area such as the Phos-Free braze option for rewinds.

There is still phosphorus containing braze in the series loops. There have been extremely few leaks in series loops and repair is quite feasible. Experience shows it is not practical to perform induction brazing (required for Phos-Free braze) due to the complex and inaccessible space in these areas of the generator. This is why torch brazing using phosphorus containing braze material is currently still performed.

8. *Q. What are the differences in materials and processes between GE's design-validated stator bar clip-to-strand braze joint technology and the new liquid-cooled connection ring braze joint technology?*

A. None.

9. *Q. Can Phos-Free braze joint technology be implemented in the field during inspection outages to repair connection ring leaks?*

A. No.

10. *Q. Why does GE use Helium for a tracer gas and not other gases such as SF6?*

A. SF6 is heavier than air and therefore can be a safety hazard. SF6 is a potent greenhouse gas. And SF6 has a much larger molar mass so it is not as useful as a tracer gas in small leaks.

11. *Q. Is GE aware of any stator grounds due to crevice corrosion water leaks in connection rings?*

A. Not to the best of our knowledge at the time of this document.

12. *Q. Is GE aware of any oil cooled connection ring leaks?*

A. Not to the best of our knowledge at the time of this document.

7. Acknowledgements

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8. List of Figures

9. References

GER 3751-A Understanding, Diagnosing, and Repairing Leaks in Water-Cooled Generator Stator Windings

TIL 1447-2 Water-Cooled Stator Winding Update

TIL 1311-2 Inspection, Testing, Monitoring, Maintenance for Generators with Liquid Cooled Stator

TIL 1098-3R3 Inspection of Generator with Water Cooled Stator Windings

Notes

Imagination at work

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