Generator 101

AOG Meeting February 16, 2022

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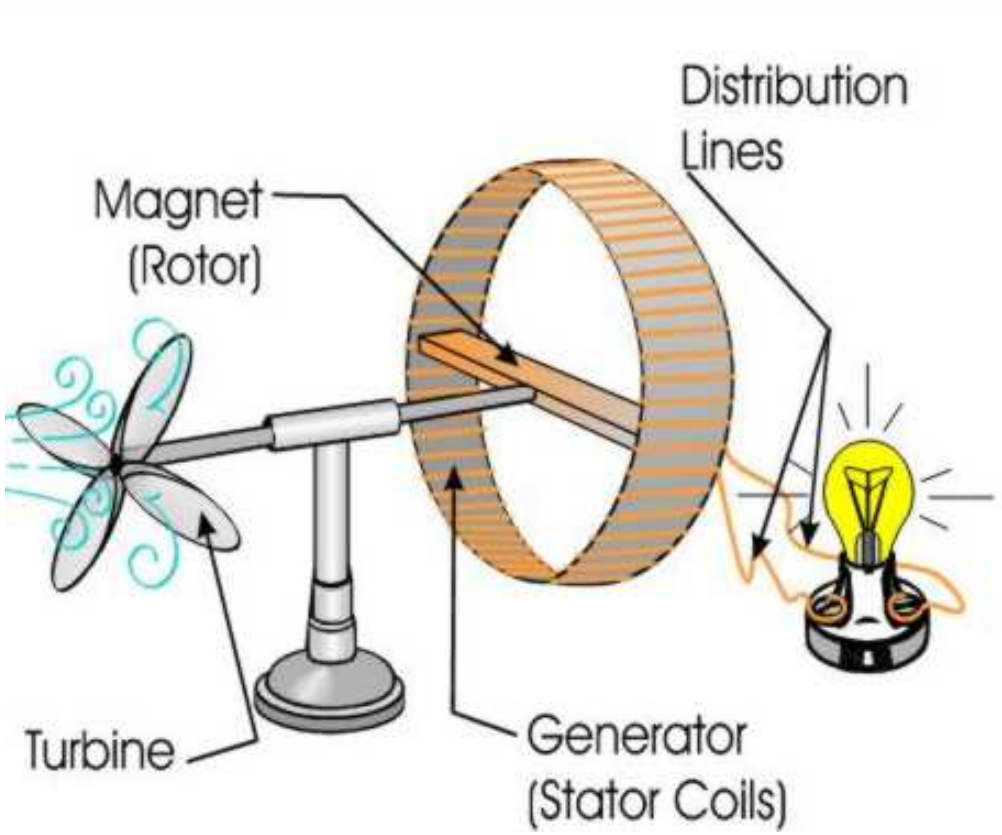
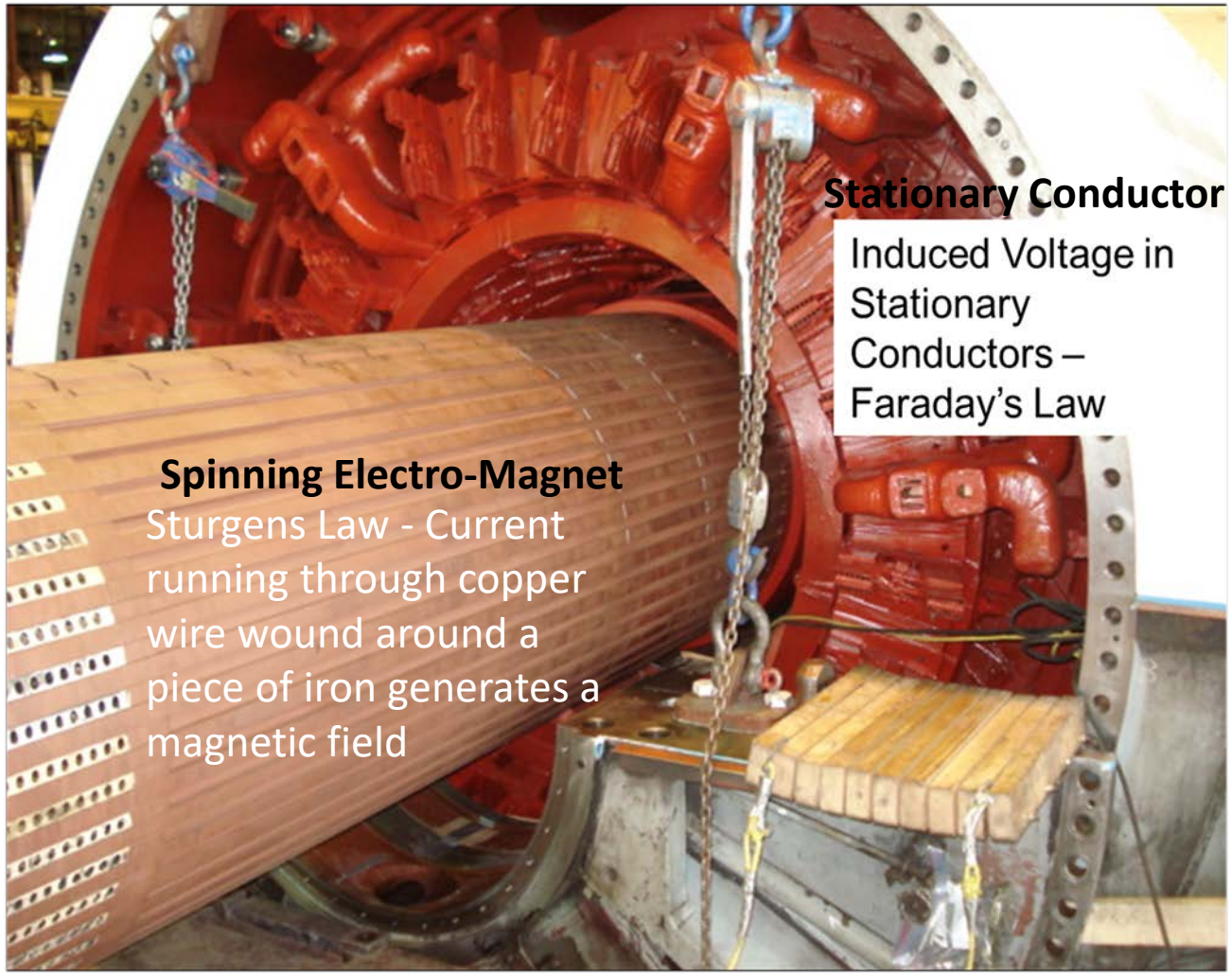
Electro-Magnets, Sturgeon & Faraday's Law

- Generator Rotor is an Electro-Magnet
- Invented in 1823 by William Sturgeon. Current running through copper wire wound around a piece of iron generates a magnetic field.
- Magnetic field is spinning at 3600 rpm from turbine.
- Faraday's Law (1831) says that a magnet moving across a copper conductor, will generate a voltage and current in that conductor
- Voltage and current is generated in the stator winding and taken out for distribution

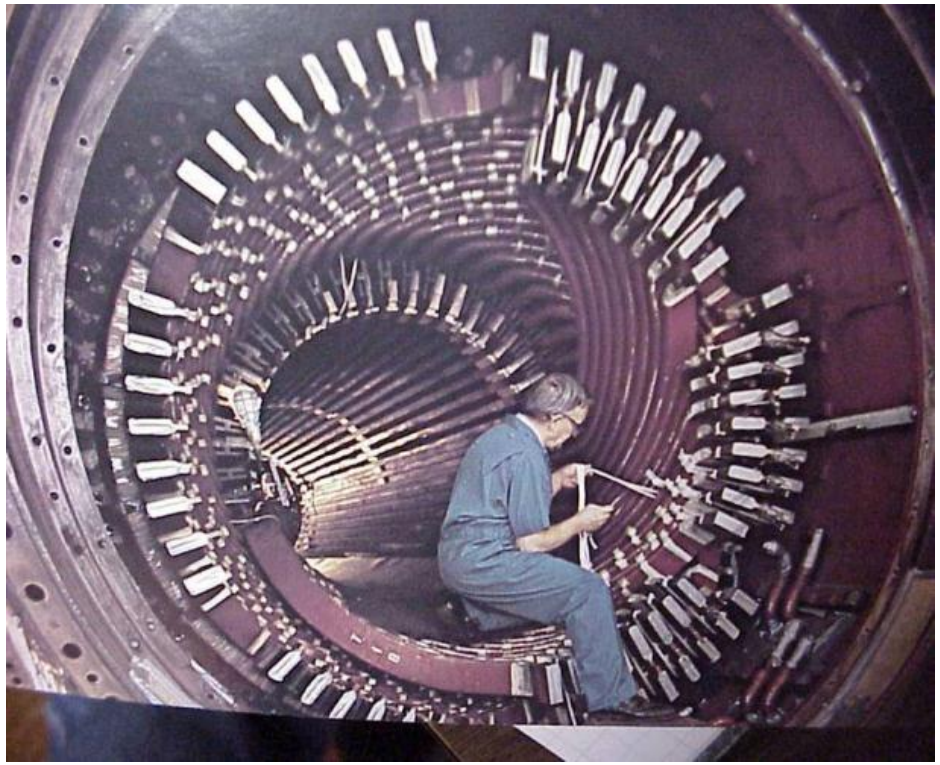


Generating Voltage and Current

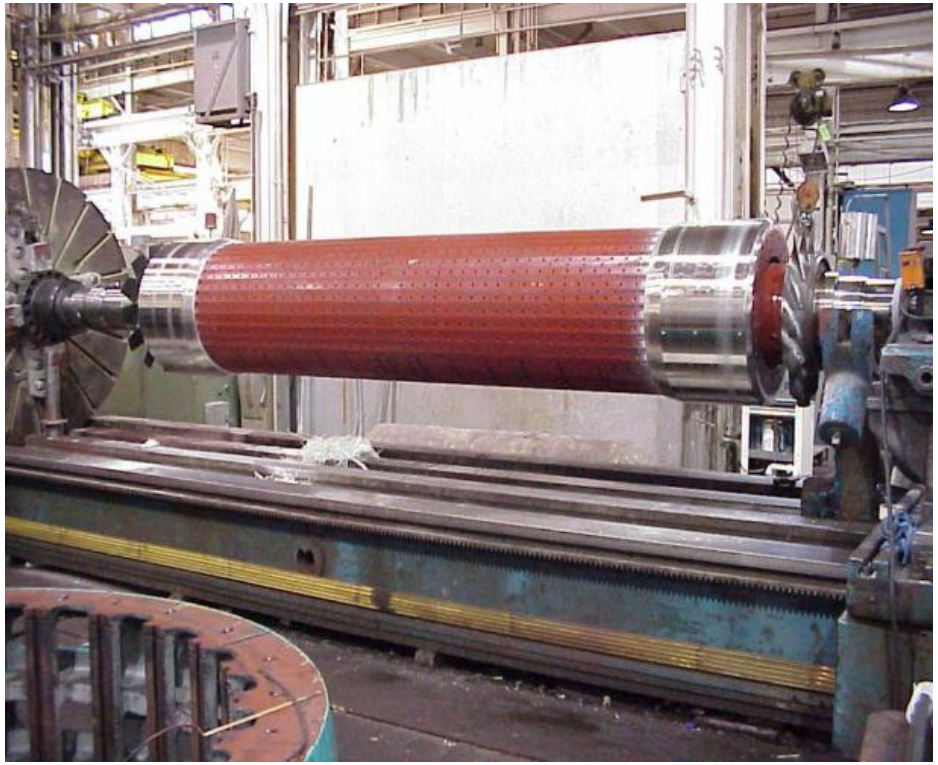
By Faraday's Law, an Electro Magnetic Flux (EMF) is generated. As the excited rotor spins, its flux cuts across the conductors, and voltage is induced. When conductors are connected to a load (the grid), a specific voltage and current are induced in the conductors.



Turbo Generator Stators & Rotors



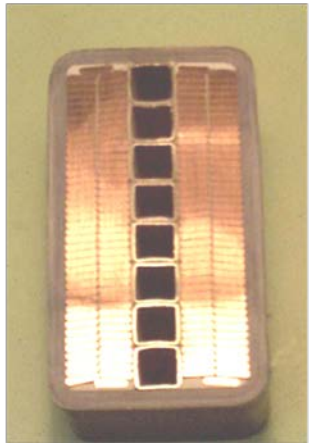
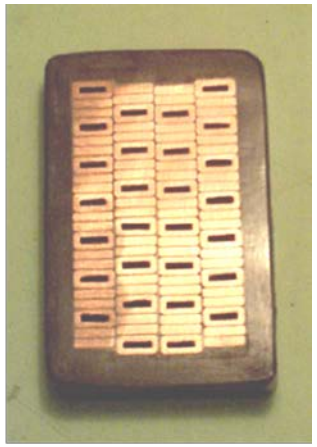
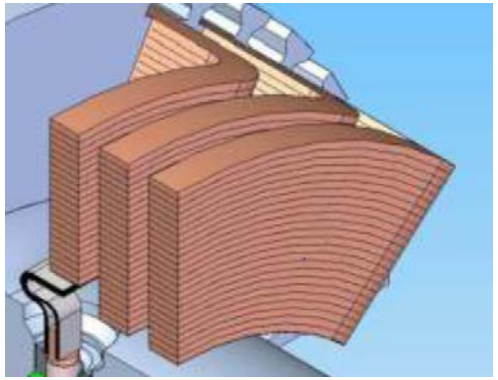
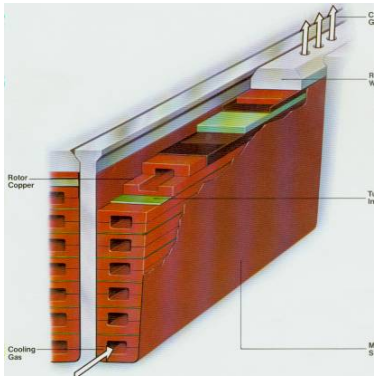
- Stator (Armature)
- High Voltage 13.8 to 27 kVac
- Stationary



- Rotor (Field)
- Low Voltage 125 to 500 vdc
- Turbo
  - 1500 – 3000 rpm – 50 Hz
  - 1800 – 3600 rpm – 60 Hz

Generator Cooling

- Importance of Cooling
  - Insulation Thermal Ratings
- Cooling Mediums
  - Gas
    - Air
    - Hydrogen
  - Liquid
    - Oil
    - Water
- Cooling Designs
  - Indirect
  - Direct

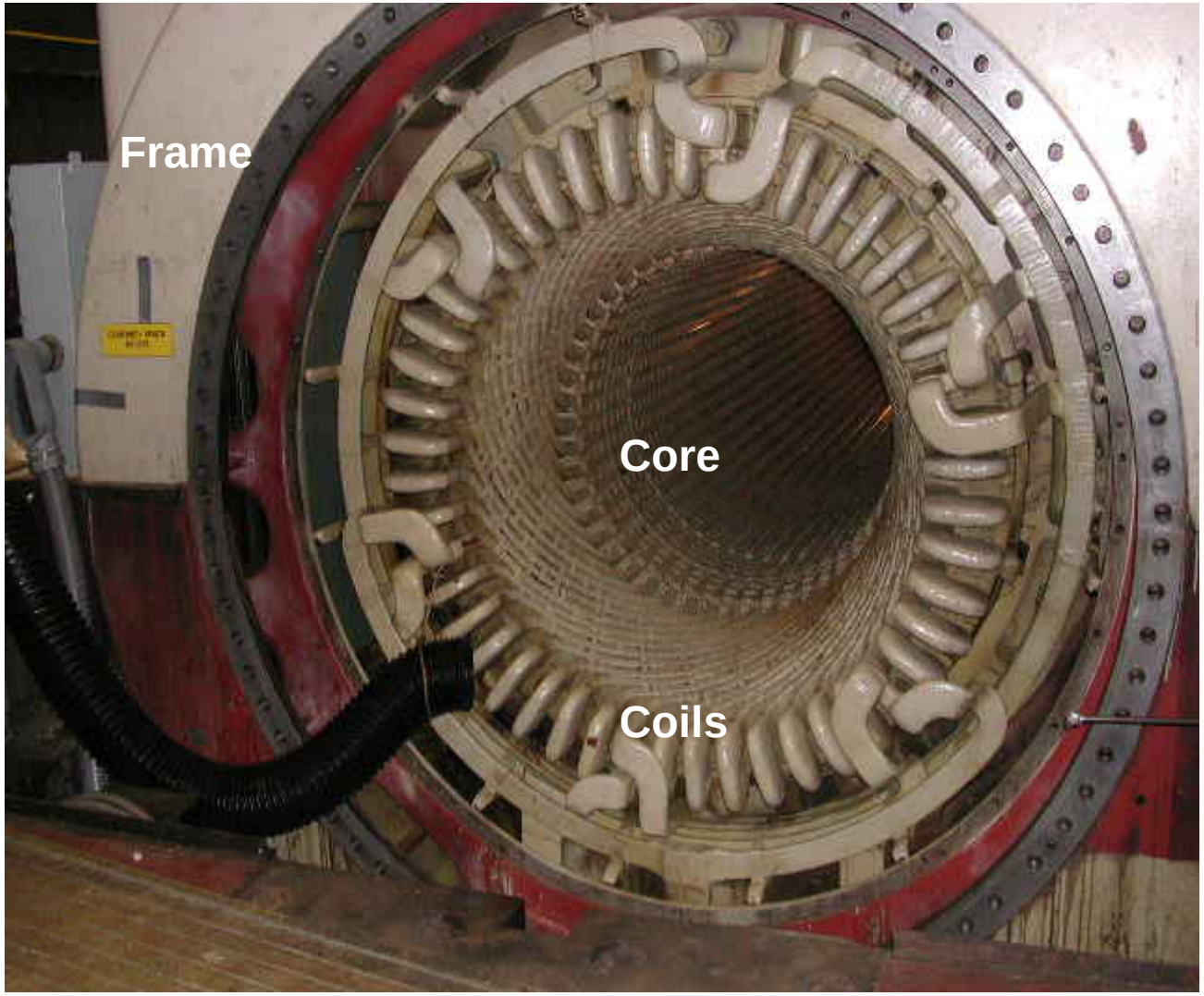
Generator Terminology **

* Source of definitions is the IEC's Electropedia at www.electropedia.org.

- **Stator** – the portion of a rotating machine that includes the stationary magnetic parts with their associated windings
- **Rotor or Field** – the rotating portion of a generator
- **Cylindrical Rotor Machine** – a machine having a cylindrically shaped rotor, the periphery of which may be provided with slots which accommodate the coil sides of a winding
- **Salient Pole Machine** – a machine in which the field poles project from the frame yoke or hub towards the air-gap
- **Alternating Current (AC) Generator** – a generator for the production of alternating current and voltage
- **Synchronous Machine** – an AC machine in which the frequency of the generated voltages and the speed of the machine are in a constant ratio
- **Excitation System** – the equipment providing the field current of a machine, including all regulating and control elements, as well as field discharge or suppression equipment and protective devices
- **Exciter** – the source that supplies all or part of the power to the field winding of an electrical. Exciters may be (1) direct current (DC) machines, (2) alternating current machines with rectifiers, or (3) static solid-state rectifiers. Exciters form part of the excitation system.
- **Direct Current (DC) Machine** – a machine incorporating an armature winding connected via a commutator to a direct current system and having magnetic poles that are excited from a source of direct or undulating current or which are permanent magnets

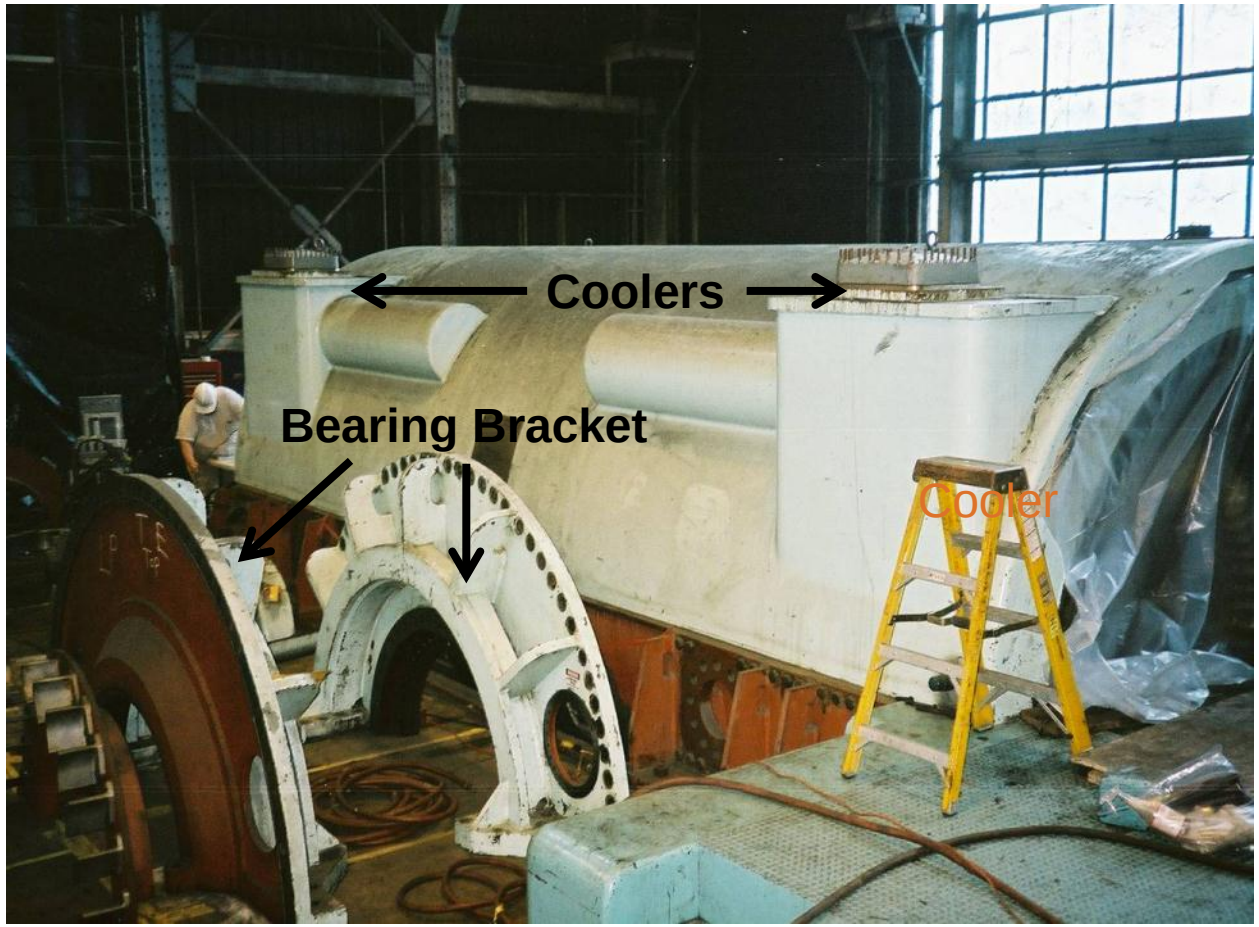
Generator Stators

- Stator consists of the frame, core iron and coils
- Frame holds everything together
- Core Iron provides a magnetic path for the flux
- Coils carry the current generated by the induced voltage



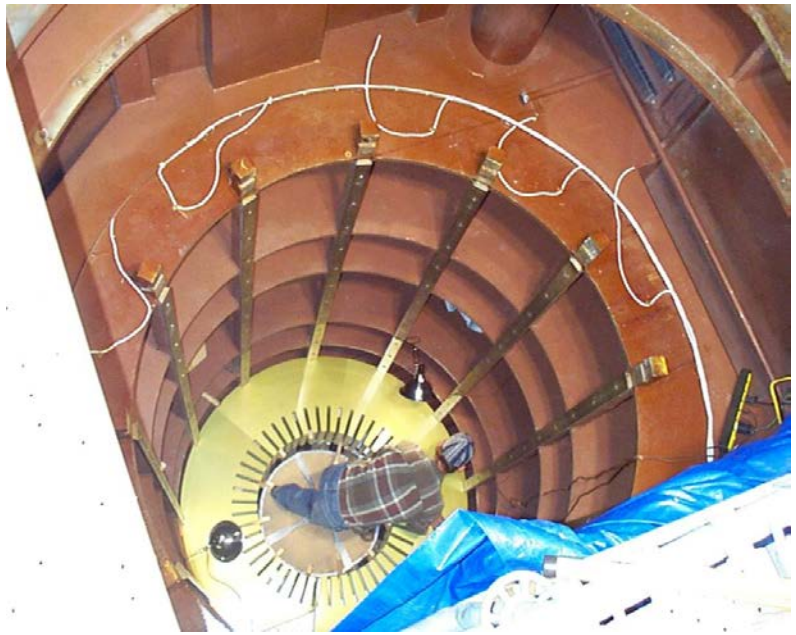
Generator Frame

- Frame holds hydrogen coolers
- Supports the bearing brackets that support the bearing, journals, and rotor
- Houses the “lead box” area where the main terminals exit



Looking Inside A Stator Frame

- Frame supports the core iron steel laminations
- Circular ribs add stiffness and rigidity
- Key bars or building bolts are welded to the circular ribs
- Core laminations are “located” by the key bars or building bolts

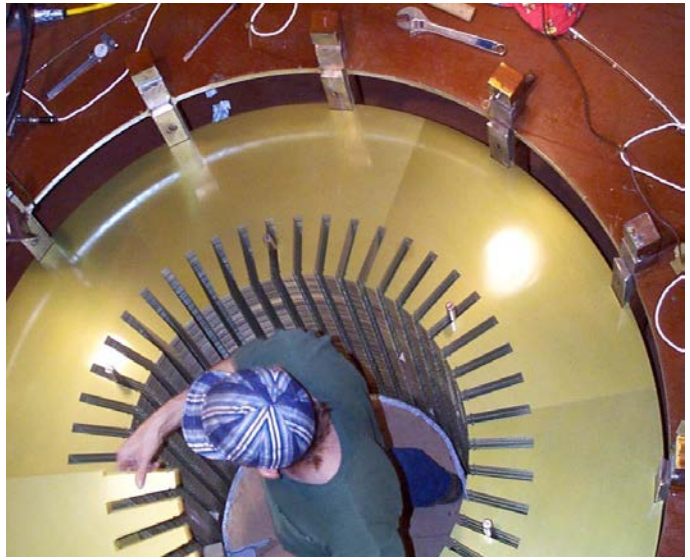


Core Lamination Coatings

- C-3 Organic coating
  - Lower temperature capability
  - Less die wear when punching laminations
  - More commonly used when punching lam’s
- C-5 – Ceramic coating
  - Higher temperature capability
  - High die wear if punched
  - Always used when laser cutting

Stator Core Iron

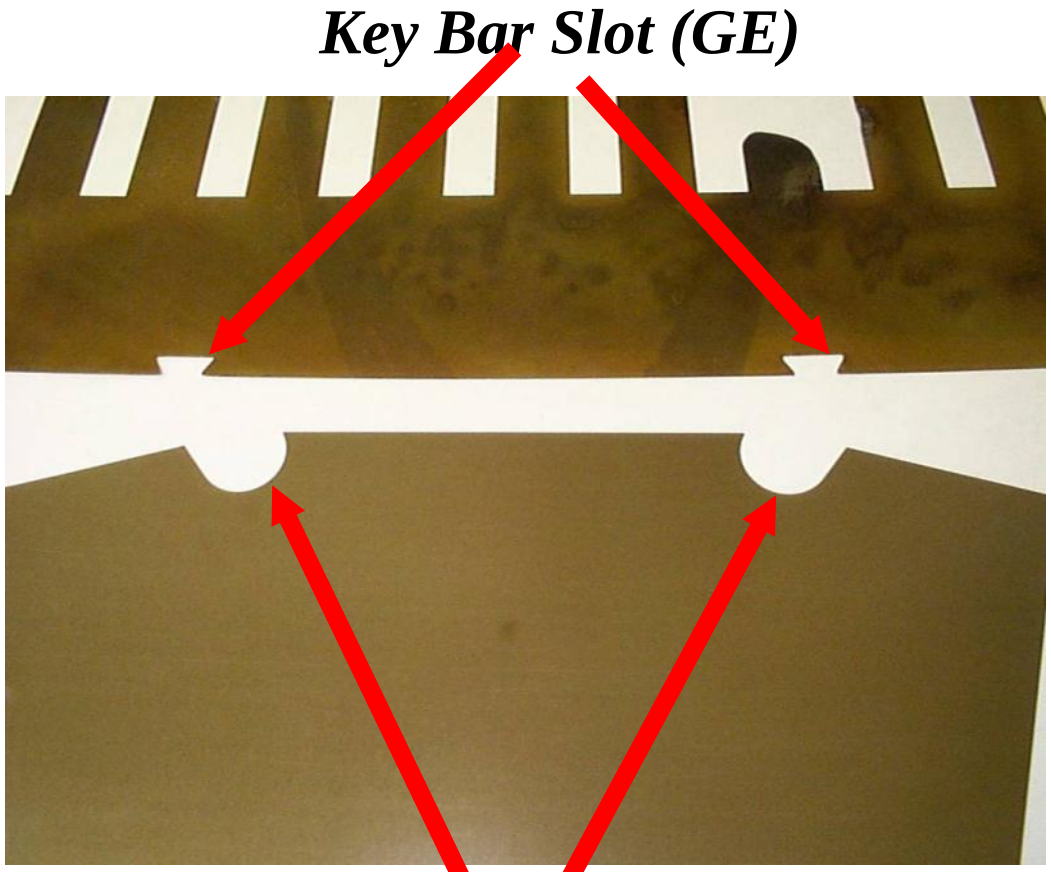
- Stator cores are usually stacked in vertical position
- Thousands of individually coated laminations form a solid iron structure
- Supports the coils
- Magnetic flux path



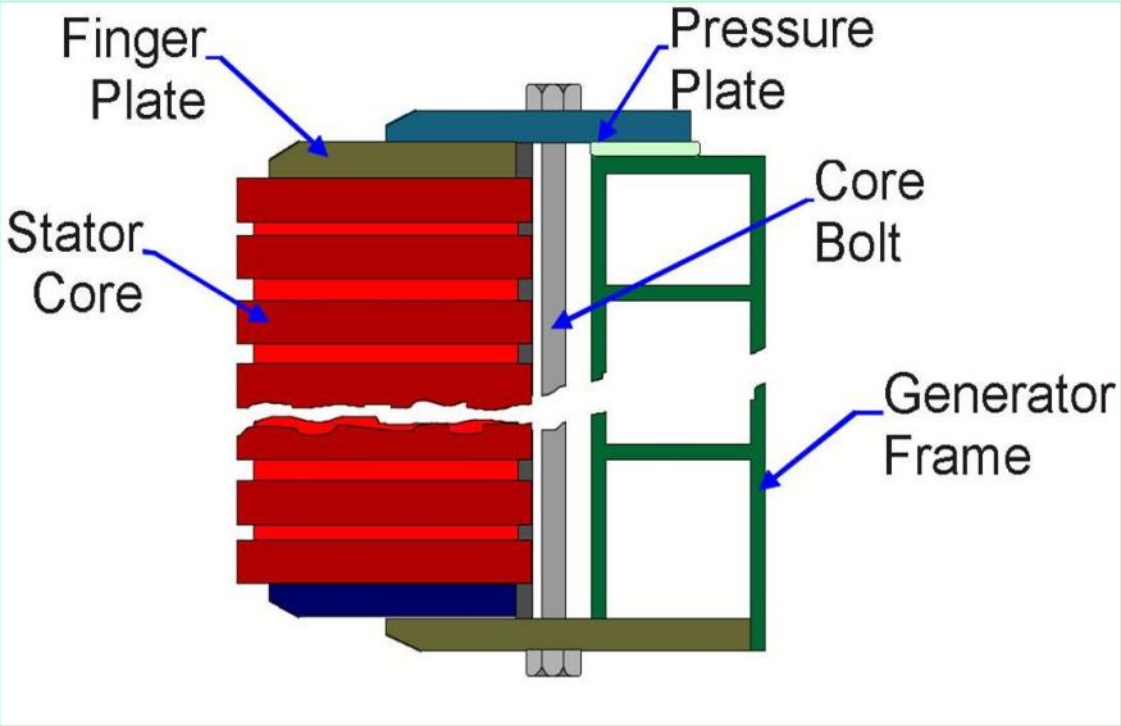
The “I” beams form spaces in the stator core for cooling gas to pass through and cool the core

Stator Core Lamination Styles

- Two main types of core lamination design: key bar and building bolt
- Core is made up of thousands of individual laminations
- Each one is coated with insulation
- M-19, 29 Gage (0.014 inches thick) is most common
- Low electrical loss steel

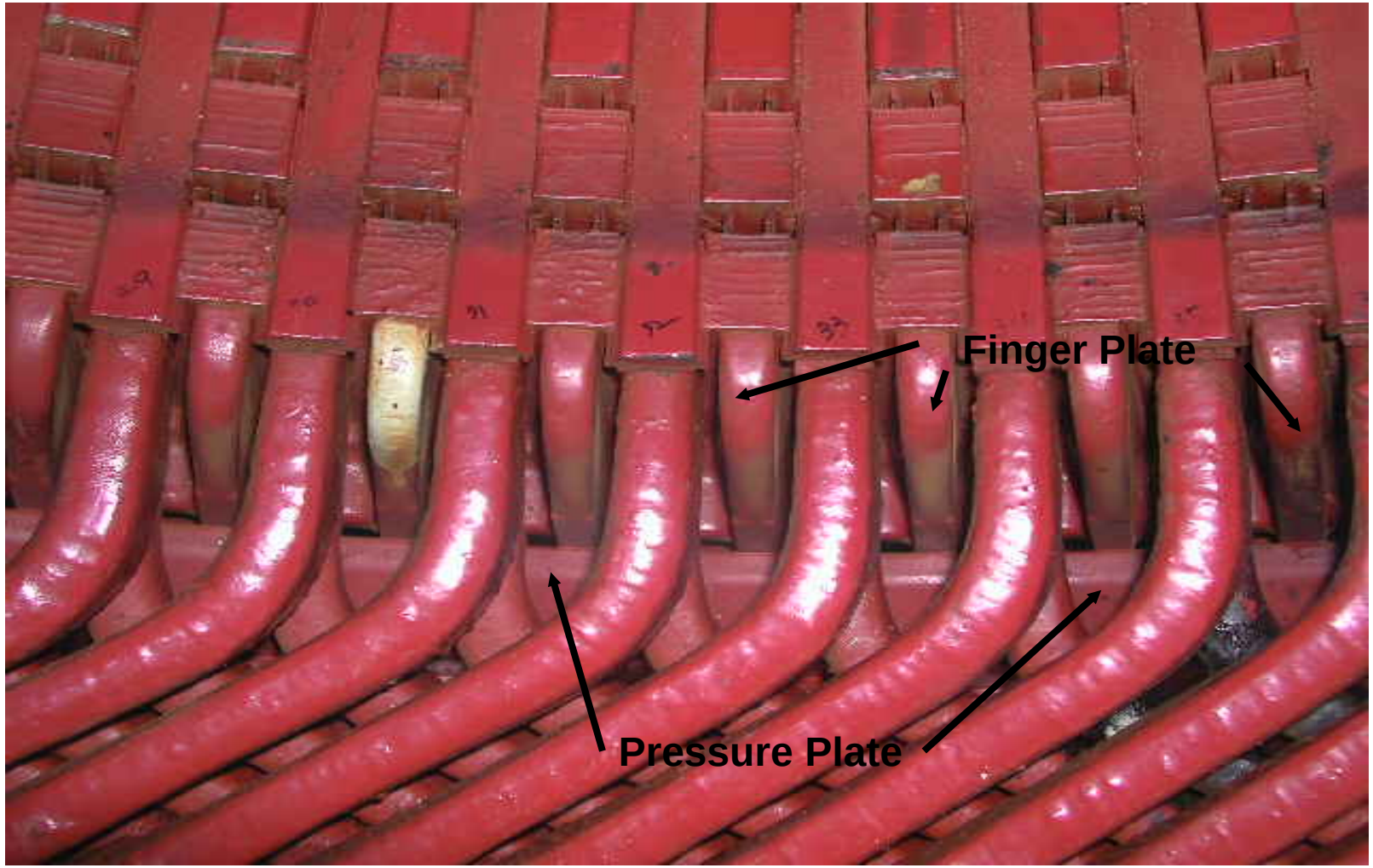


Stator Core Clamping

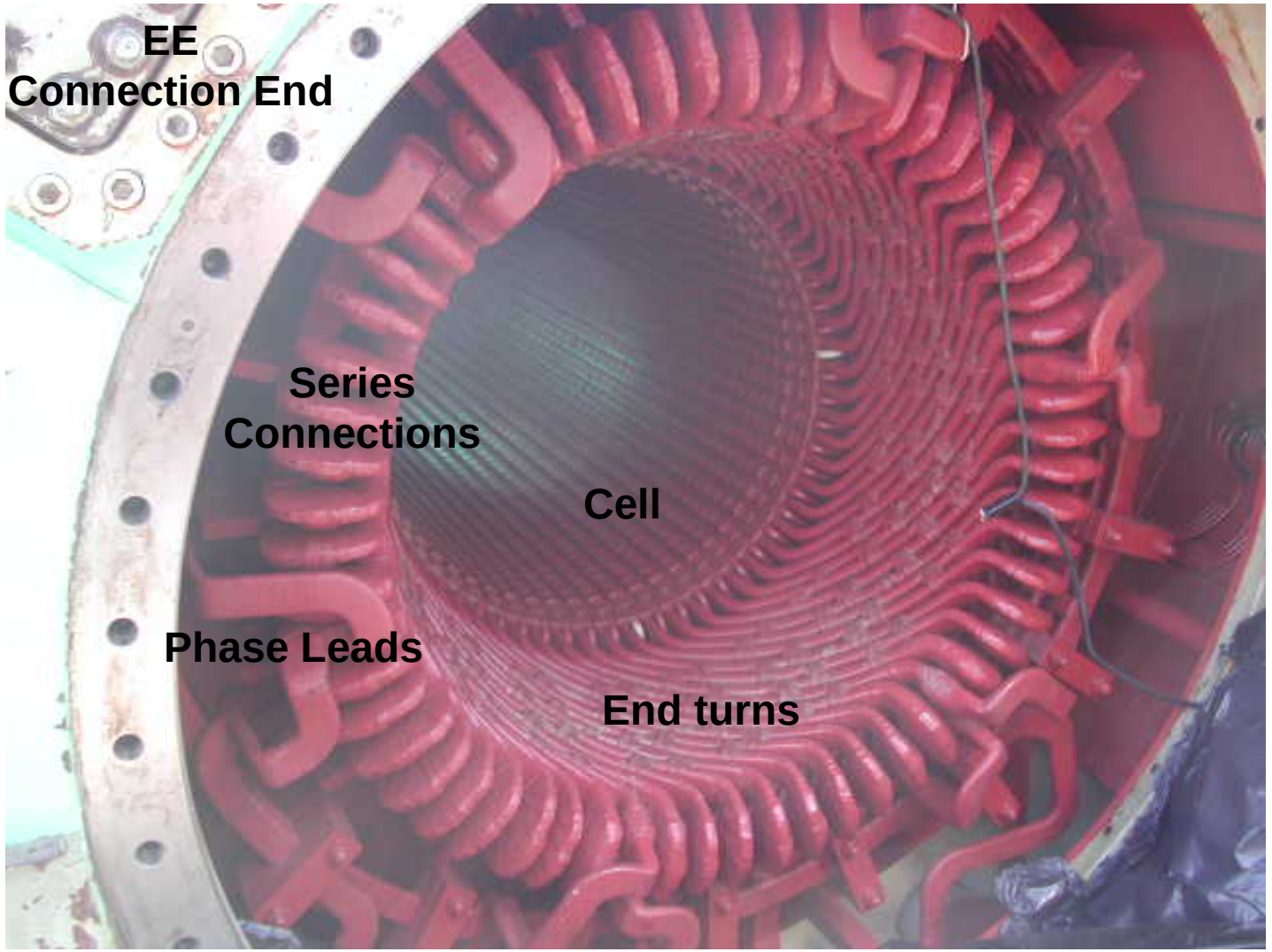


- Frame is also used as a bracing structure to clamp the core tight
- Core bolts are tightened, transmitting clamping force to pressure plate, finger plates, and then core
- Tension screws are sometimes used to stretch core bolt

Stator Core



Stator Winding



Generator Terminology **

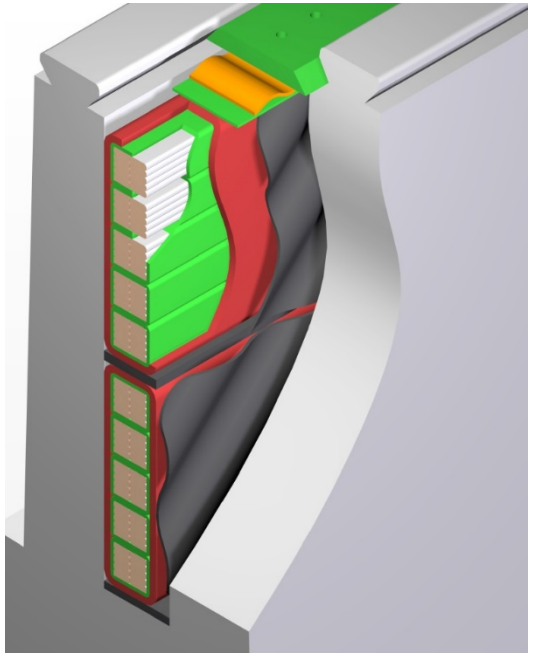
** Source of definitions is the IEC's Electropedia at www.electropedia.org.

- **Two-layer winding** – a distributed winding in which there are two coil sides in the depth of each slot. (Generators have two-layer windings.)
- **Coil** – a physical assembly of one or more electrical coil sections, generally surrounded by common insulation .
- **Coil or bar insulation** – the main insulation, to earth or between phases, surrounding a coil or a bar, additional to any conductor or turn insulation.
- **Multi-turn** (or diamond)coil – a complete coil. All coils making up the winding have the same shape and coil span.
- **Half-coil bar** – either of two parts, which when connected together, would form a complete coil. A bar consists of coil side and an appropriate end winding. (Other terms for 'coil side' are cell or slot portion of the coil.)
- **Roebel transposition** – a scheme of transposition in which strands occupy two height-wise tiers in a half coil, and at regular intervals through the core length one top strand and one bottom strand cross over to the other tier in such a way that each strand occupies every radial position in each tier.
- **Lamination** – a metal sheet, generally coated with an insulating material, used in the construction of parts of the magnetic circuit of the laminated stator or rotor of an electrical machine. (Laminations can be die- or laser-cut to shape.)

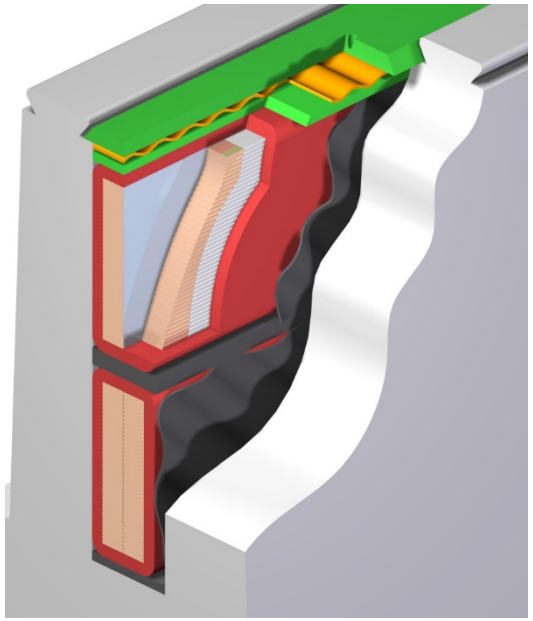
Stator Winding

- Stator winding is made of coils or bars
- Three main stator coil cooling types:
  - Conventional - air or hydrogen
  - Inner cooled - air or hydrogen
  - Liquid - water or oil cooled
- Cell portion fits in the core iron slots
- End turn portion hangs over the end, outside the core and is formed to an “involute” shape

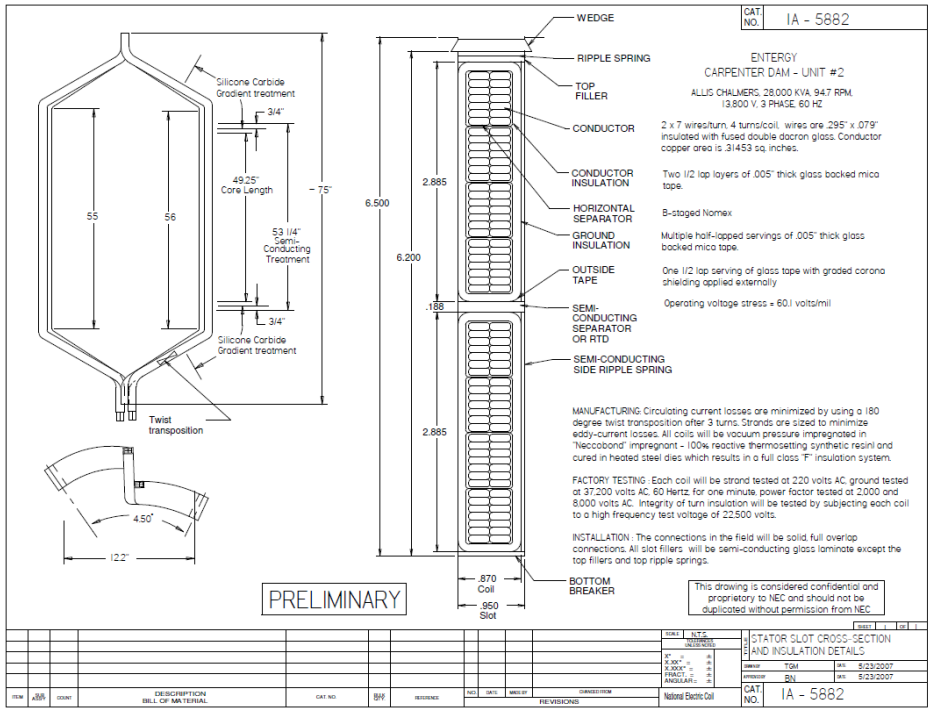
Multi-Turn Coil

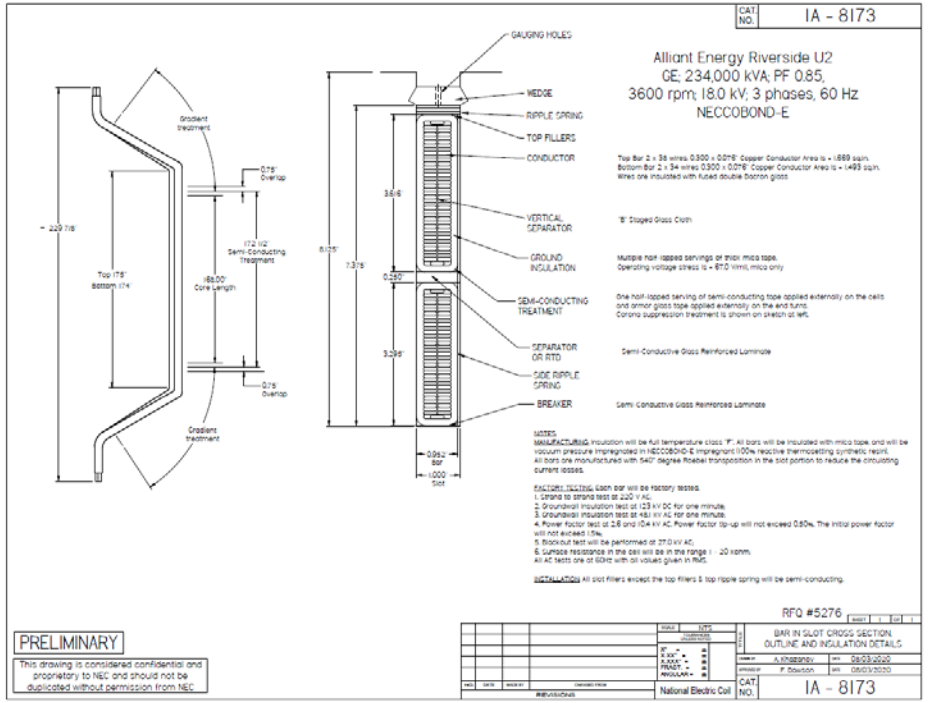


Roebel Bars



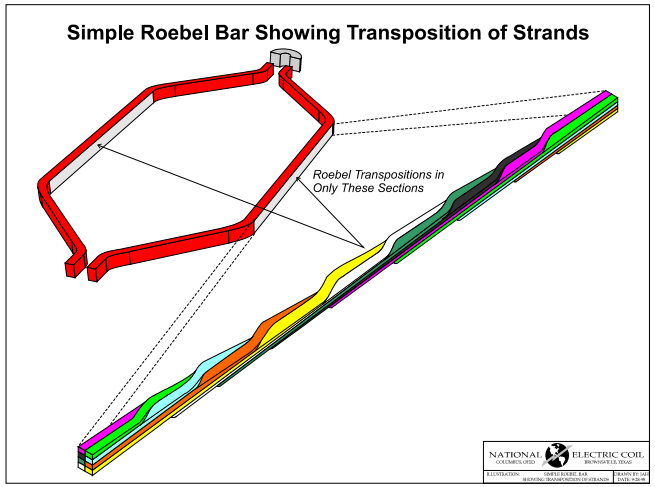
Bar -vs- Coil





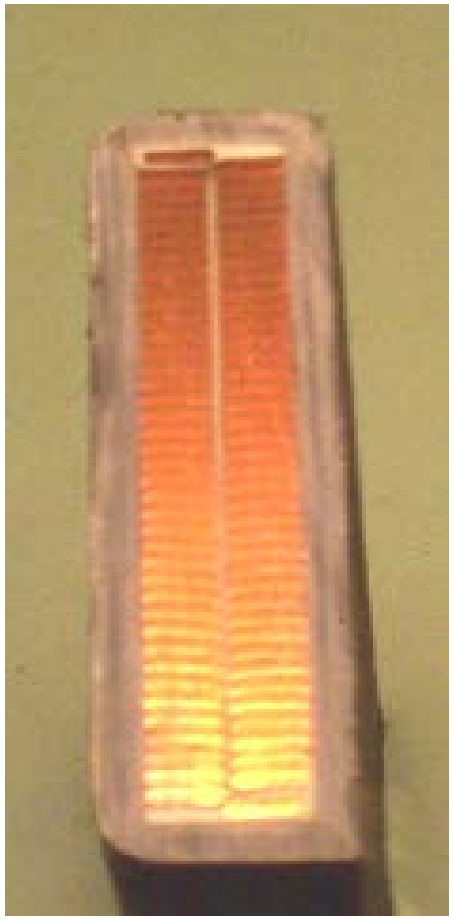
Multi-turn Coil
Twist Transposition

Losses?
Manufacturing Cost?
Winding Time?
Maintenance?



Optimize Coil Design – Lower Losses

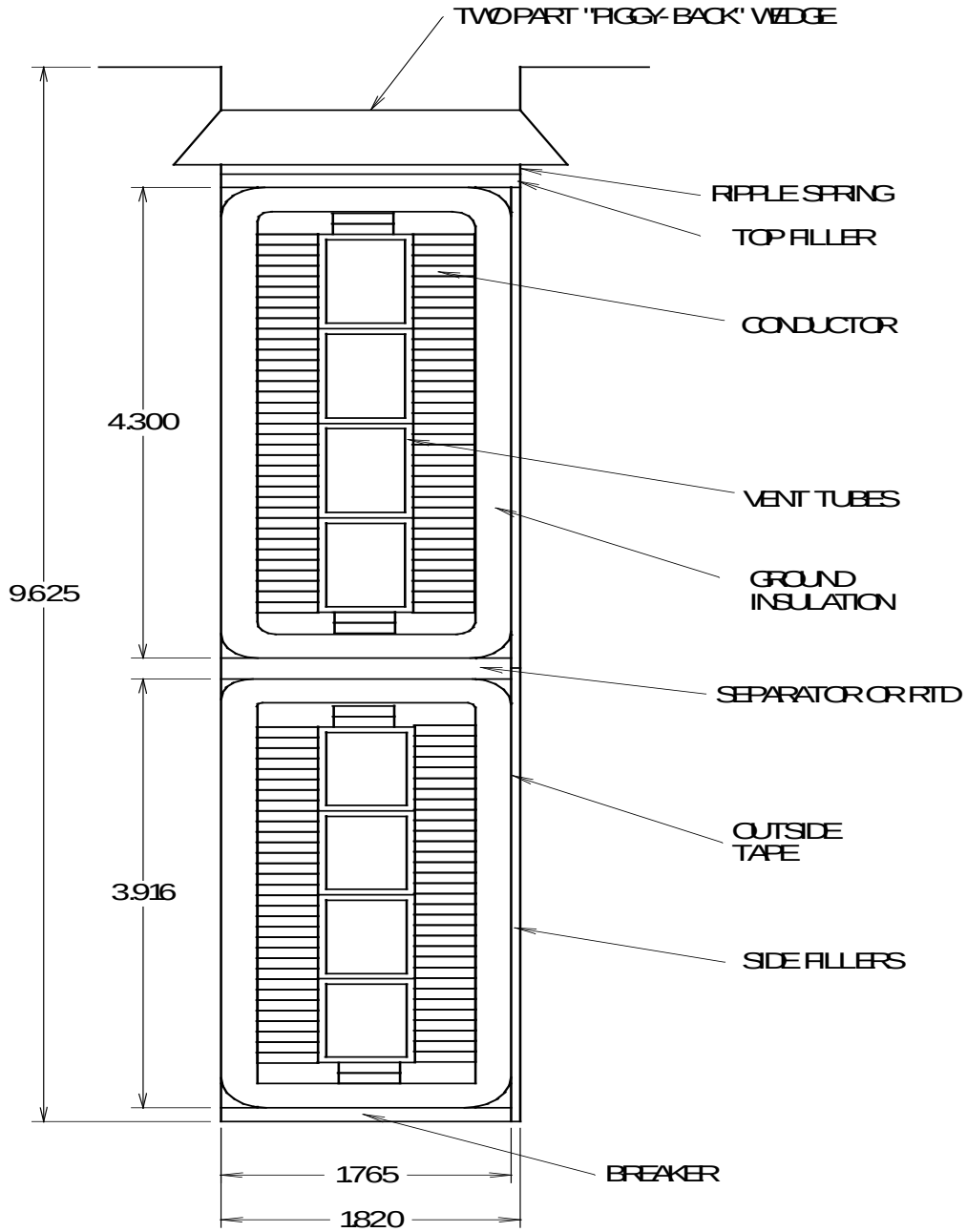
- I^2R Losses
  - inversely proportional to copper area – more total copper means lower I^2R losses – these losses are the highest percentage of total winding losses
- Strand/Eddy Current Losses
  - proportional to strand thickness – thicker strand means higher losses – slightly wider and thicker strand for Argentina – slightly higher Eddy Current losses but lower overall losses because of increase in copper cross sectional area
- Circulating Current Losses
  - voltage potential differences between strands
  - Roebel design eliminates



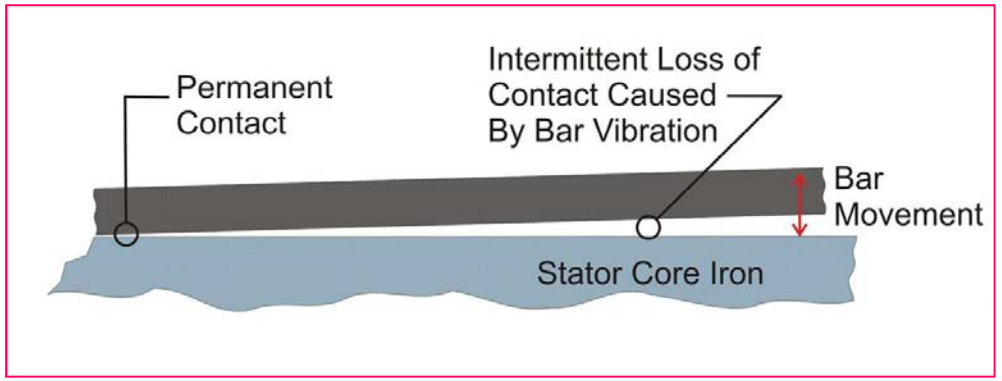
Conventional bar cross section

Slot Cross-Section

- Core lamination
- Top coil
- Bottom Coil
- Cooling tubes
- Copper Strands
- Ground insulation
- Top fillers
- Side fillers
- Bottom breaker
- Top wedge

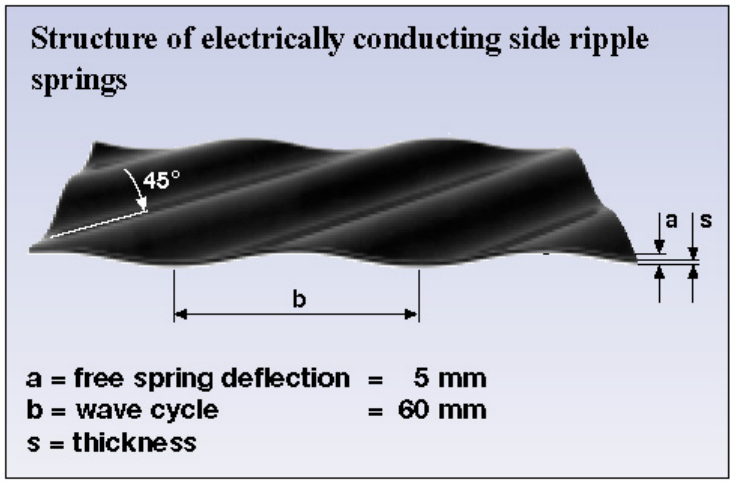


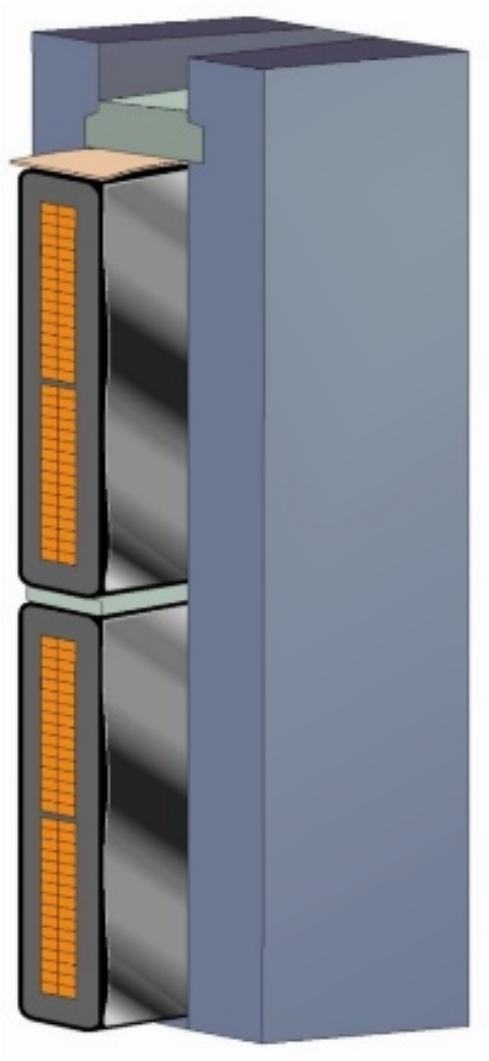
Result Of Inadequate Side Filler – Spark Erosion (SE)



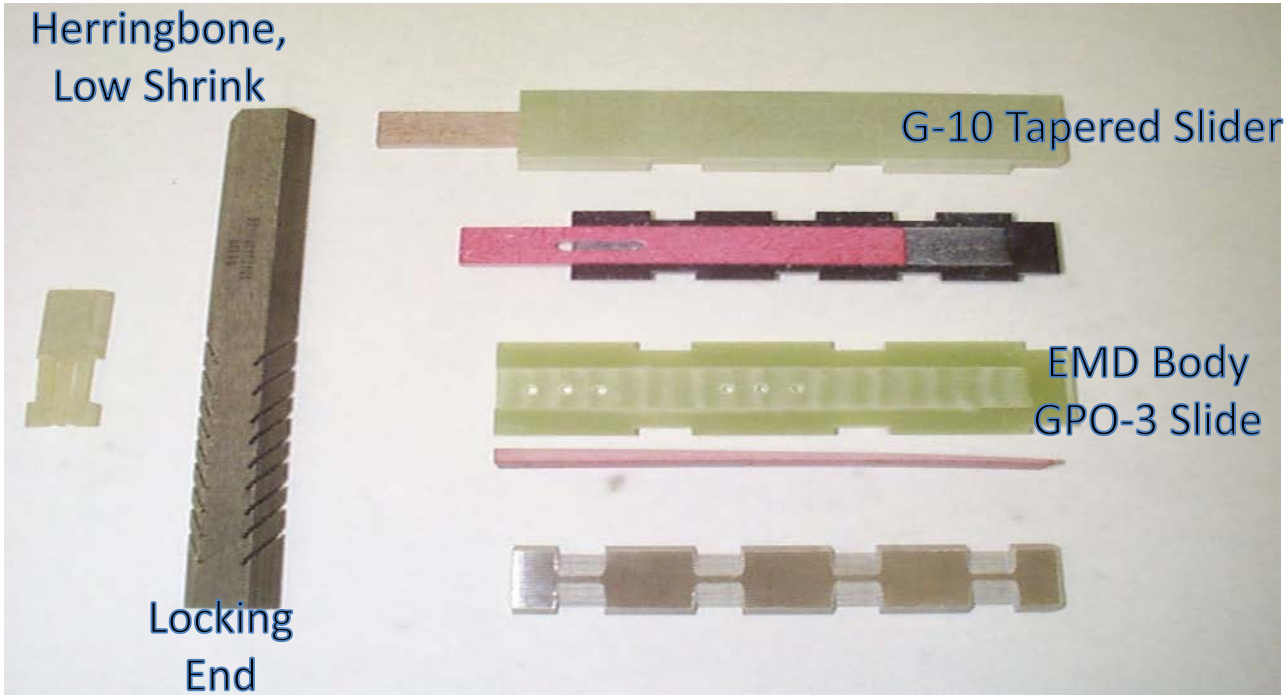
- High energy spark in the stator bar slot between the coil and the core.
- Intermittent contact of a loose bar in the slot repeatedly opens and closes the gap causing frequent sparking by the high energy in the core to the slot

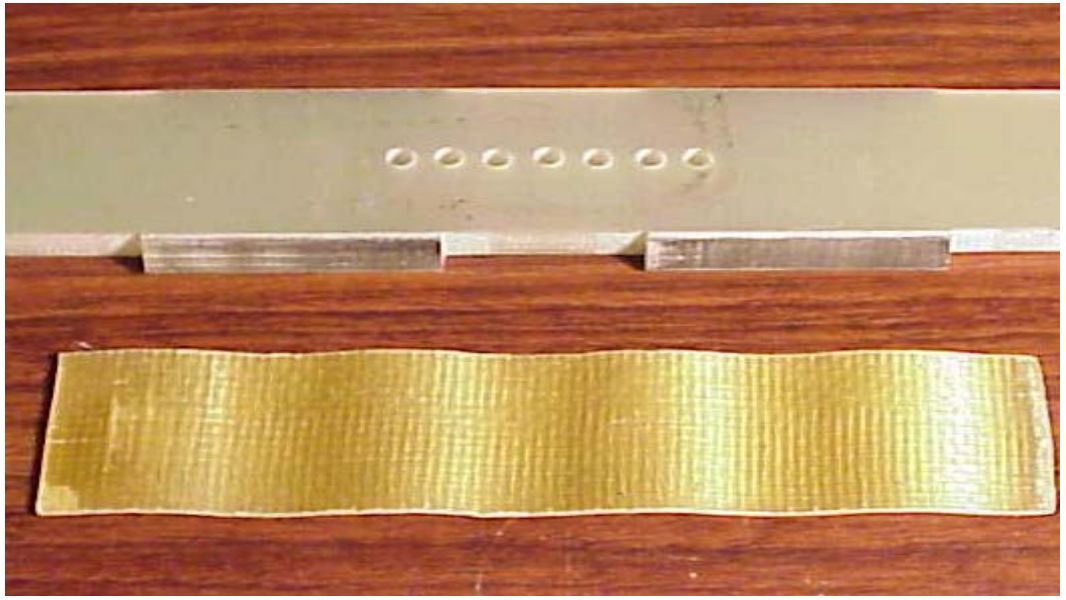
Primary Solution To Prevent Spark Erosion (SE)
Side Ripple Filler





Stator Slot Wedges

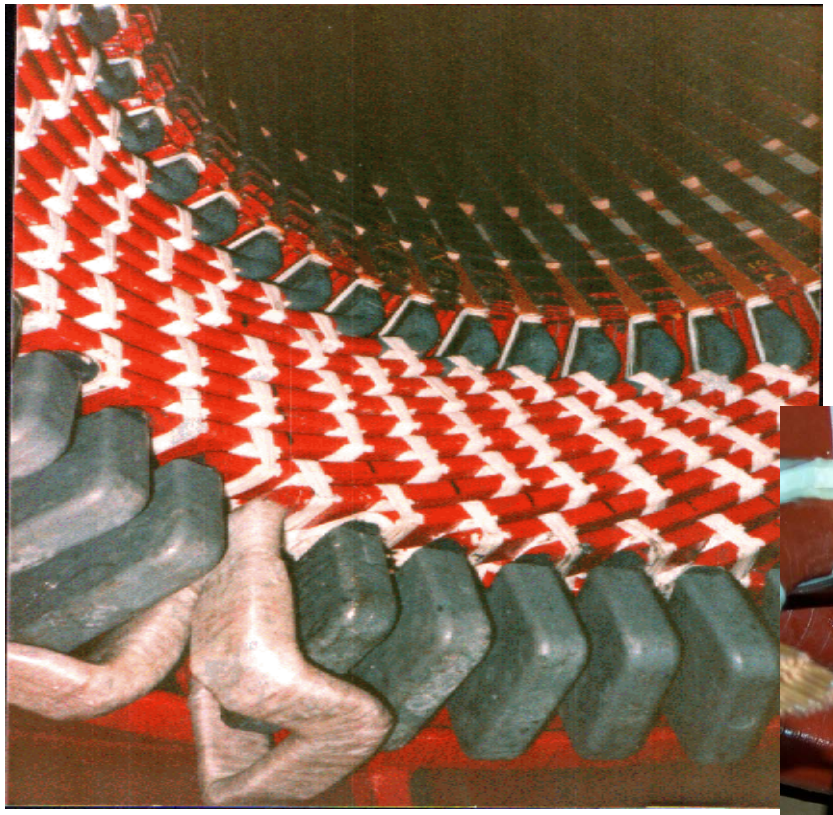




Slot wedges hold individual coils or bars in place in their slots in the core iron.

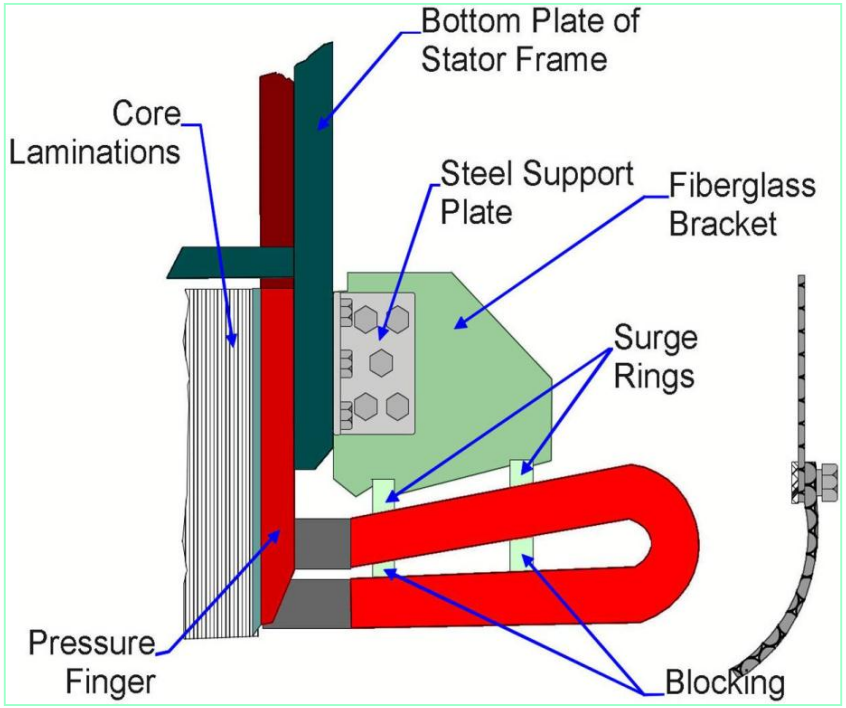
End Winding Blocking, Bracing, & Tying

- Blocking and tying between coils should be regular, even and consistent
- Coil end turns are consolidated into a homogenous, and arch-bound structure



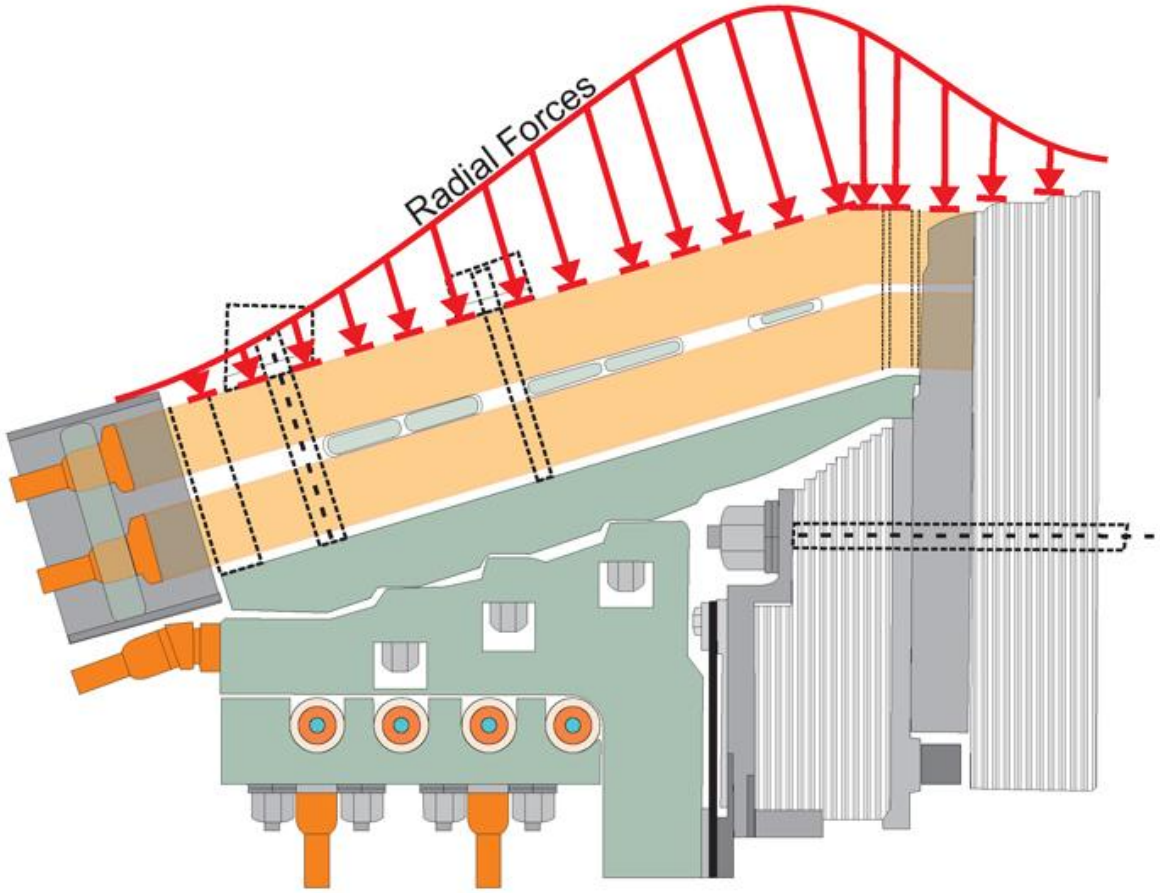
Stator Coil Bracing

- Diagram of simple bracing system with bracket and surge rings
- Decoupling system can be incorporated by allowing surge rings to slide on bracket surface



Fault Forces on End Turns

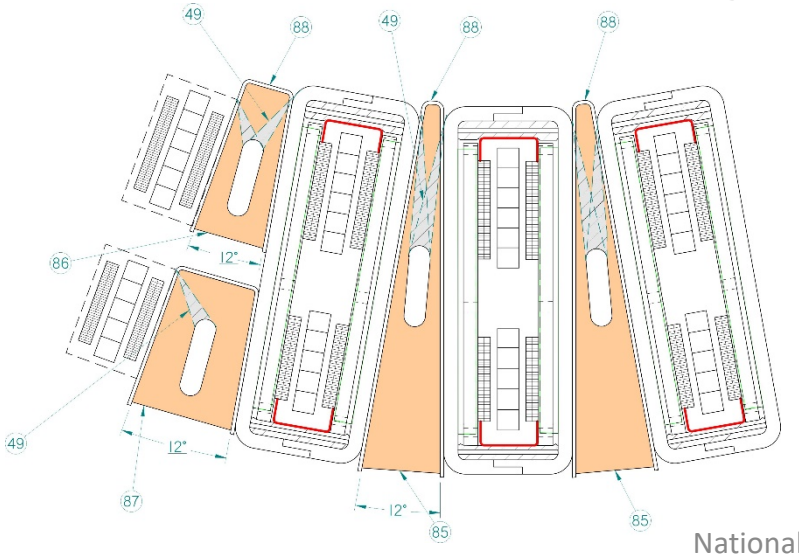
- Surge forces can occur during a fault, such as single-phase operation, or a lightning strike on the bus
- **The force is radial and distributed as shown**
- **Coil support brackets, or surge rings must handle**



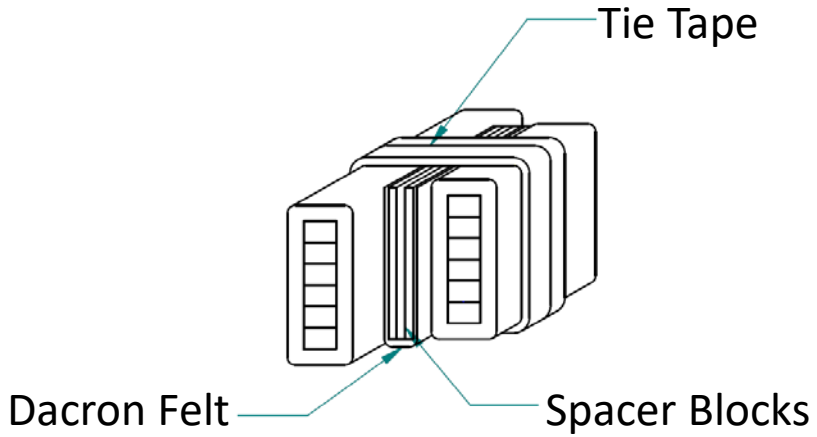
End Winding Stability

- Strength while allowing for thermal expansion and contraction
- Outside Limits of Resonance Exclusion Zone

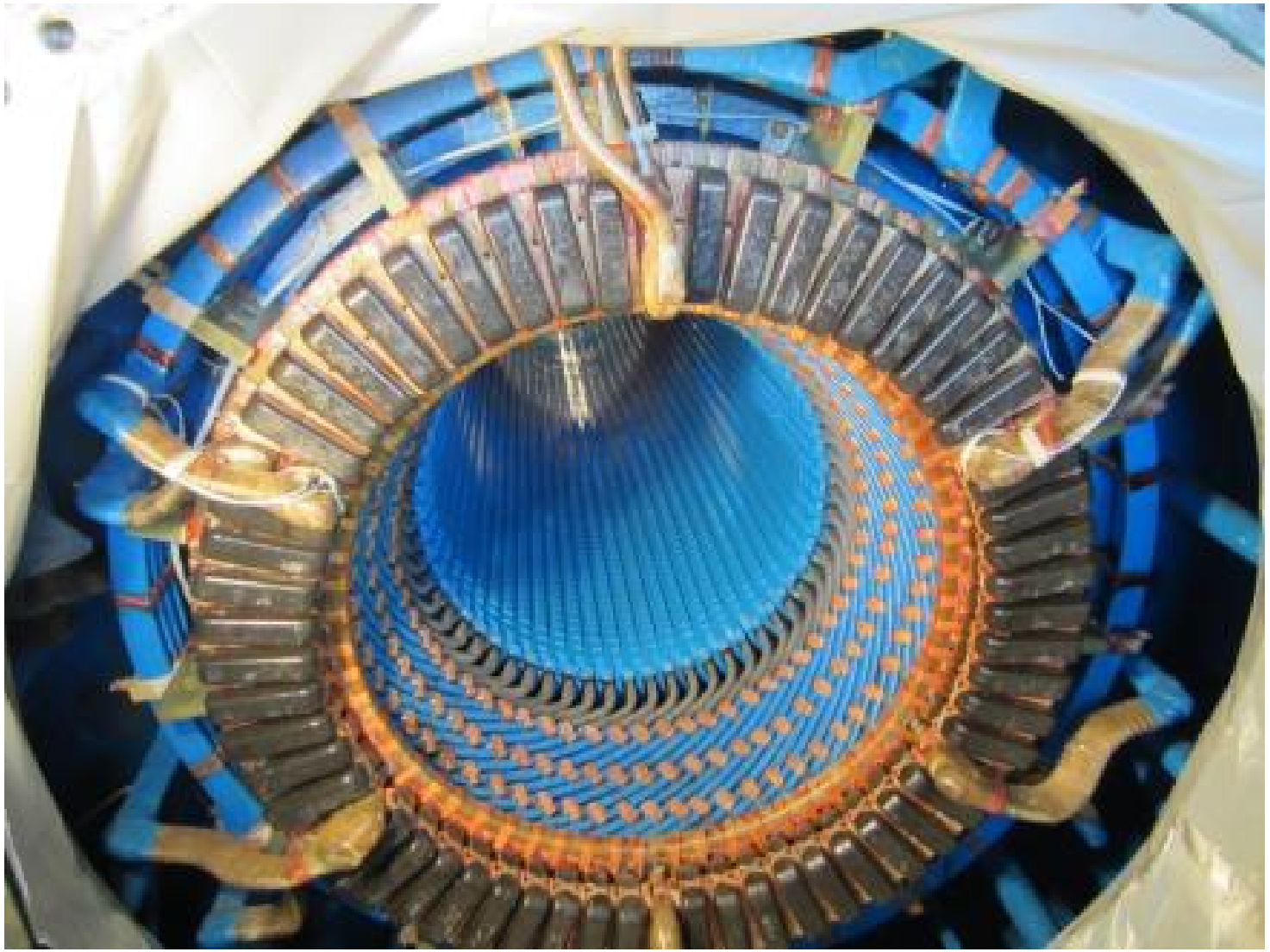
Series and Phase Blocking



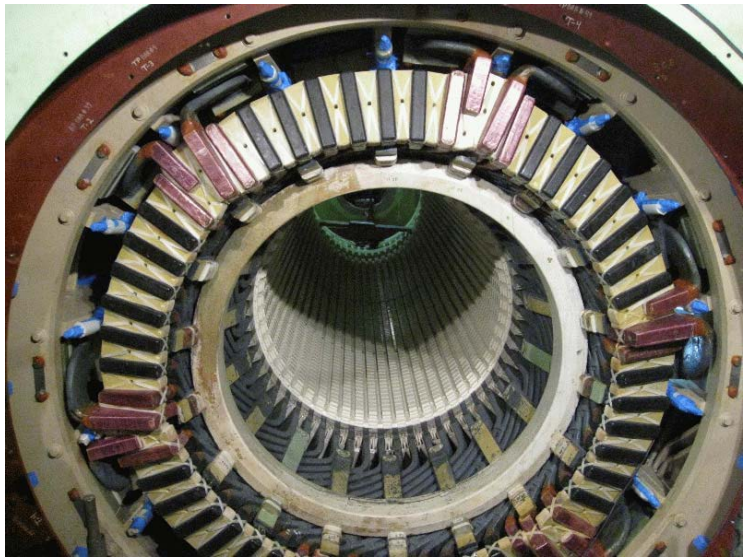
End Turn Spacer Blocking

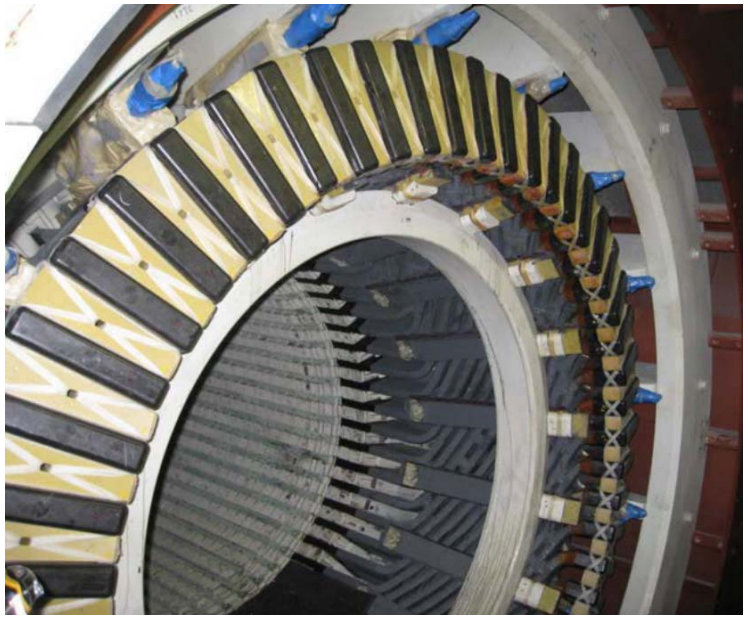


Coil Phase & Series Connections & Phase Rings



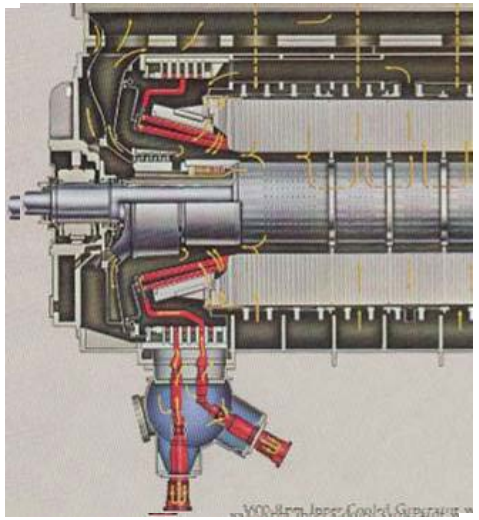
Alstom End Winding Support System





60WX232-109
Main lead
Resonance Failure

Stator Leads / Bushings



Generator Stator Questions?

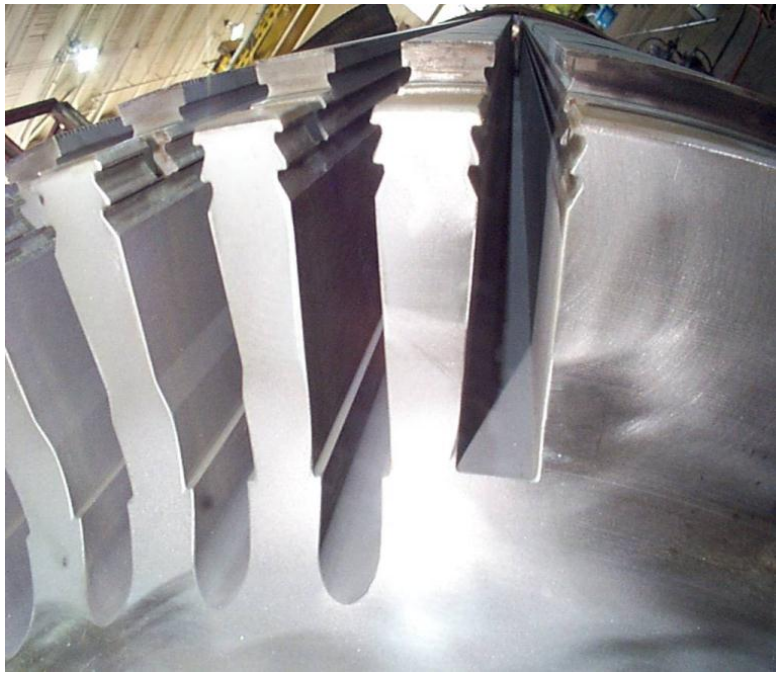
Rotors

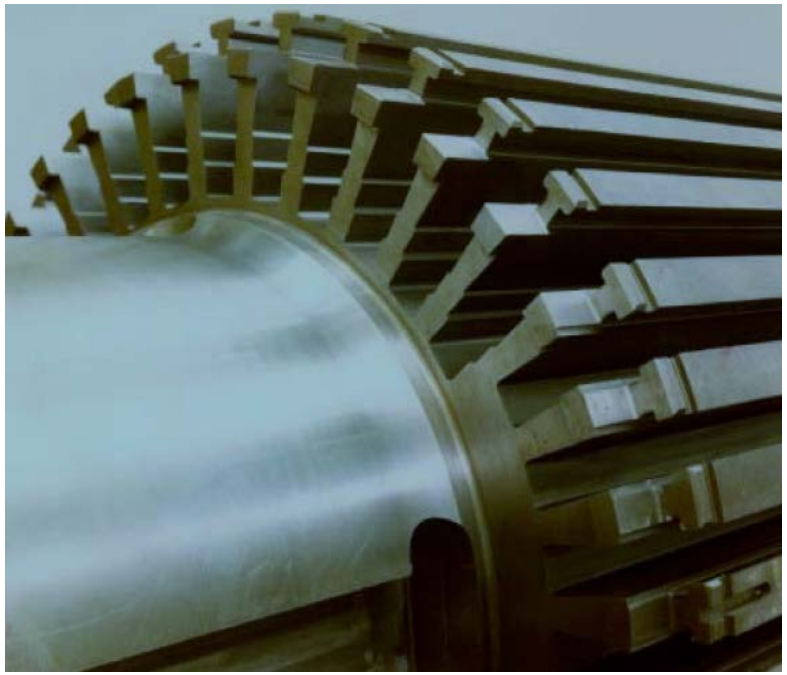
Rotor Forging

- Rotor forging machined from one piece of NiCrMoV steel
- Withstand torsional, lateral bending, vibratory and rotational stresses
- Torque from turbine is transmitted through coupling and shaft

Empty Rotor Slot

- Slots are machined in the rotor forging to hold the copper turns of the winding
- Wedge grooves “fir tree” or “T” shaped; allow wedges to hold copper turns in place during rotation

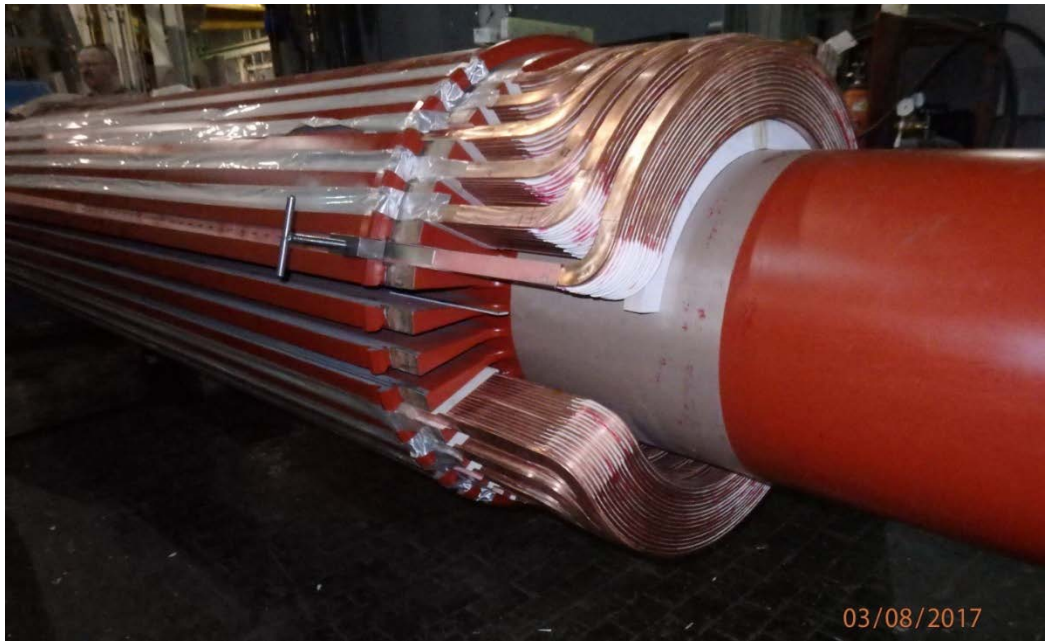




Rotor Slot Liners

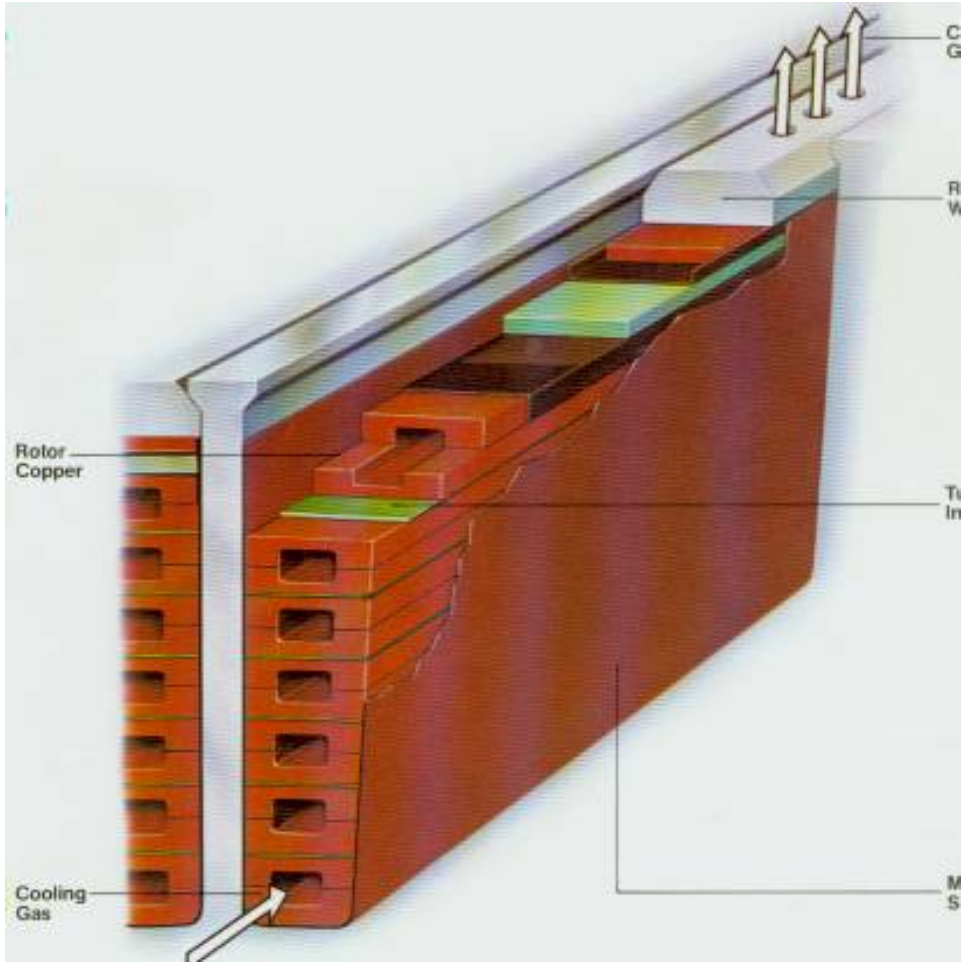
- Ground insulation for coils in the rotor forging slot region
- Manufactured from a variety of materials including Nomex, Mica, Glass, and various Films
- Typically, liner materials should not be mixed in a rotor to keep consistent thermal transfer properties

Rotor Windings



Inner Cooled Rotor Conductors

- Newer, larger hydrogen cooled units have inner cooling in the rotor conductors
- Cooling gas is in direct contact with the copper
- More efficient cooling

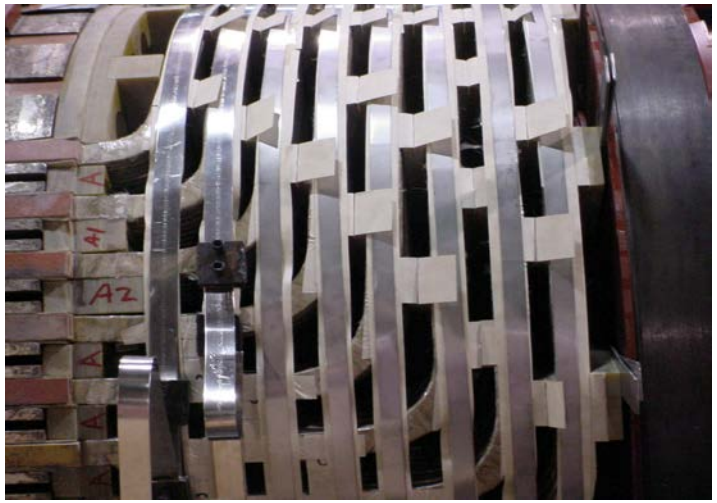


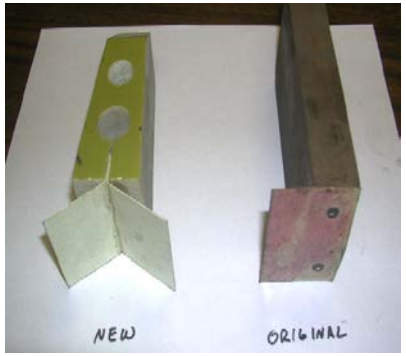
GE Diagonal Cooled Rotor Winding

- **On some large units, GE uses a diagonal cooled rotor winding cooling scheme**
- **Holes in copper are slightly offset with each turn**
- **Hydrogen gas travels up and out in a diagonal path**

End Winding Blocking

- End turn blocking:
  - supports the windings from distorting or shifting
- Coil to coil blocks
  - typically positioned in a diagonal pattern
  - generally fit snug between coils, with additional clearance between the last row of blocks and the centering ring
- Nomex tabs:
  - maintain the block position within the end turn winding arrangement
  - OEM Design –
    - Metal rivets have come out and can catch on the RR liner
  - Upgraded Design:
    - improved design with a double tab arrangement fixed in place with a slot and dowel pins



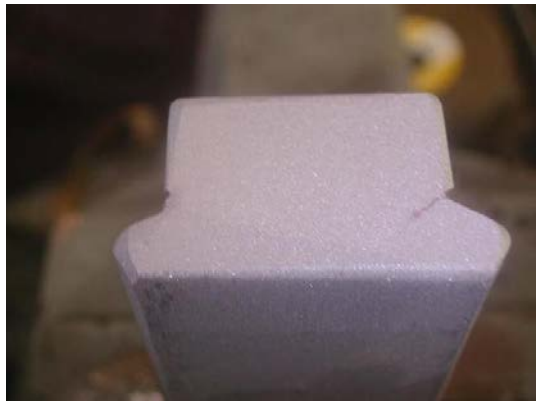


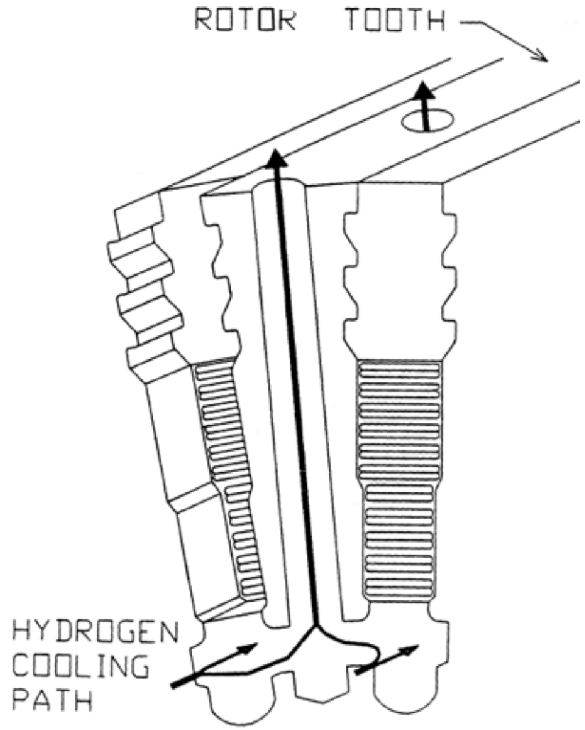
Rotor Slot Wedges

- Restrain the rotor coils in the slot against centrifugal forces
- Manufactured from magnetic steel, stainless steel, aluminum or titanium. Sometimes special brass/Beryllium copper is used for end wedges.

The wedges can have different geometries:

- Standard
- Pine tree type special
- Vented

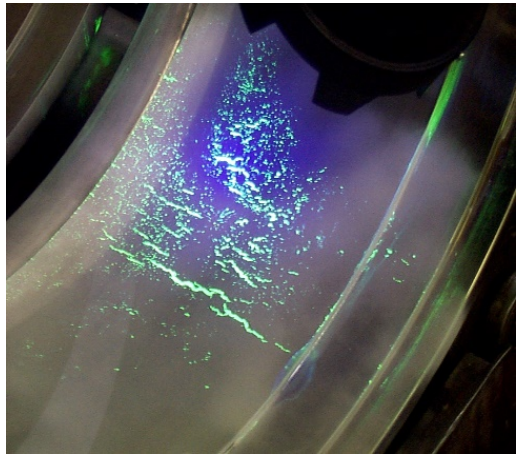




•Wedges subject to high centrifugal forces due to rotation at 3600 rpm

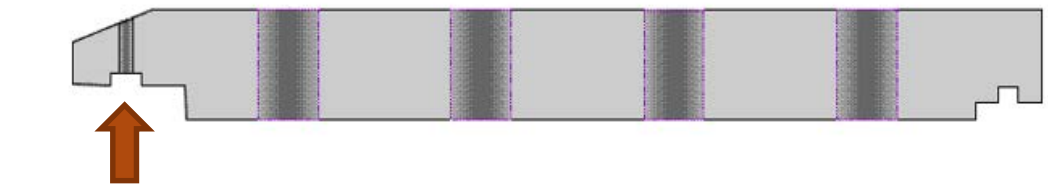
Retaining Rings

- Today made from alloy steel non-magnetic forging ASTM A-289 Class C (18Mn 18Cr)
- Older Alloy 18Mn 5Cr susceptible to SCC (picture on right below)



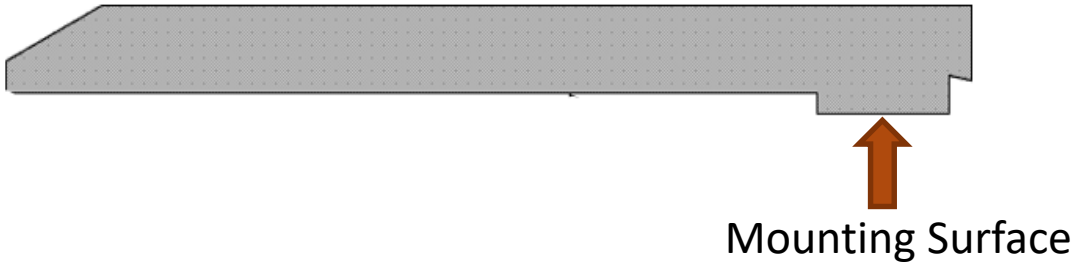
- Older and smaller units are more likely to have magnetic rings
- Holes are a good tell of magnetic rings especially on Westinghouse or Electric Machinery OEM's
- Some non Magnetic can have holes but typically indicative of a rotor upgrade.
- Holes in non magnetic rings require special machining / broaching.

Retaining Ring Mounting Types

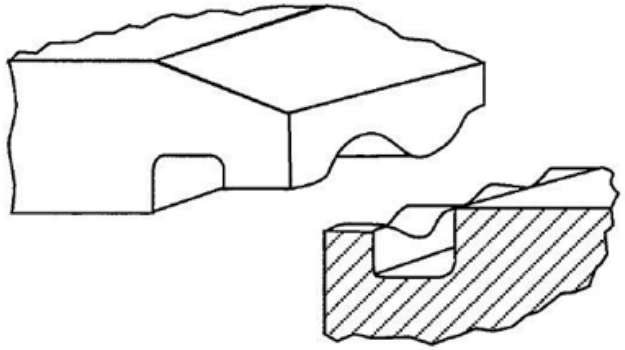


Body-Mounted Retaining Ring

- Magnetic rings often have holes – most non-magnetic don't
- Non Magnetic typically do not



Spindle-Mounted Retaining Ring



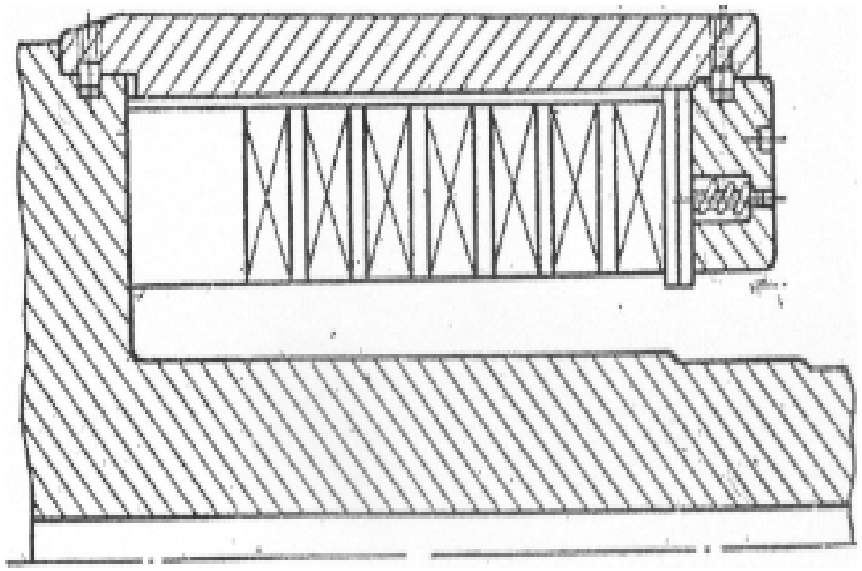
Bayonet Style Mounted Retaining Ring

- Shrink fit and a twist

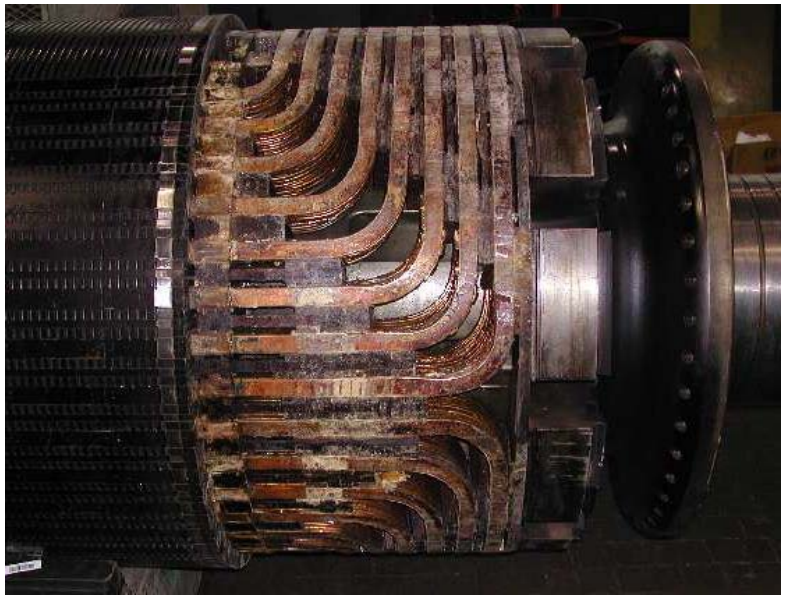
Retaining Ring Mounting

- **Most modern designs are body mounted to shaft with a snap ring at nose of ring**
- **Cantilevered off the back end of the ring**
- **No contact with shaft at back end**

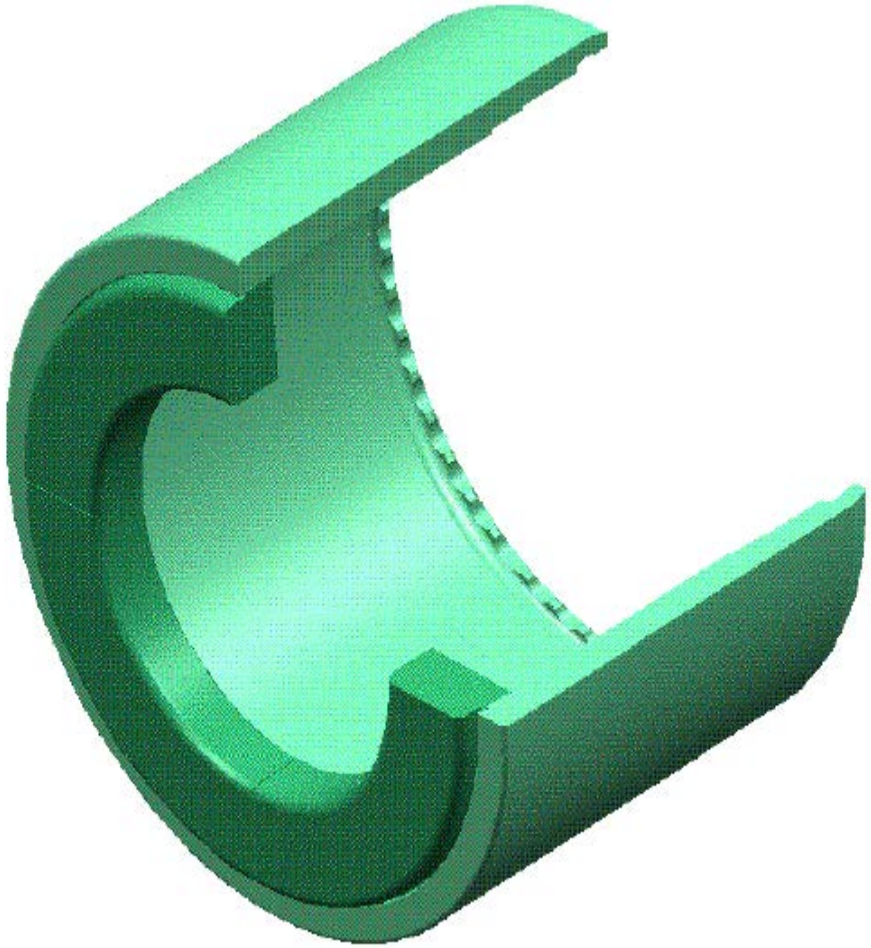
Body Mounted

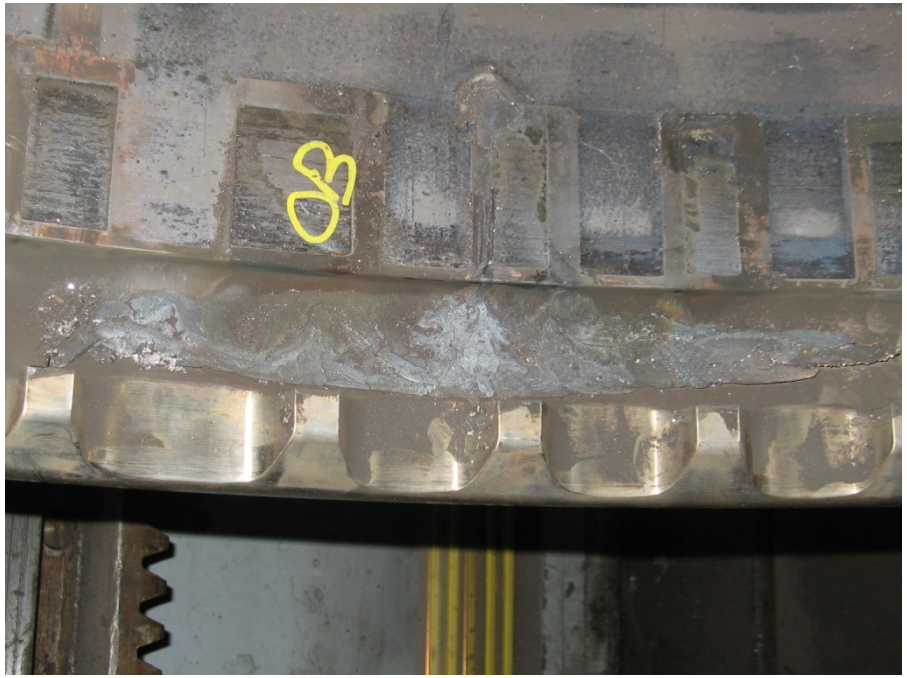


Spindle Mounted

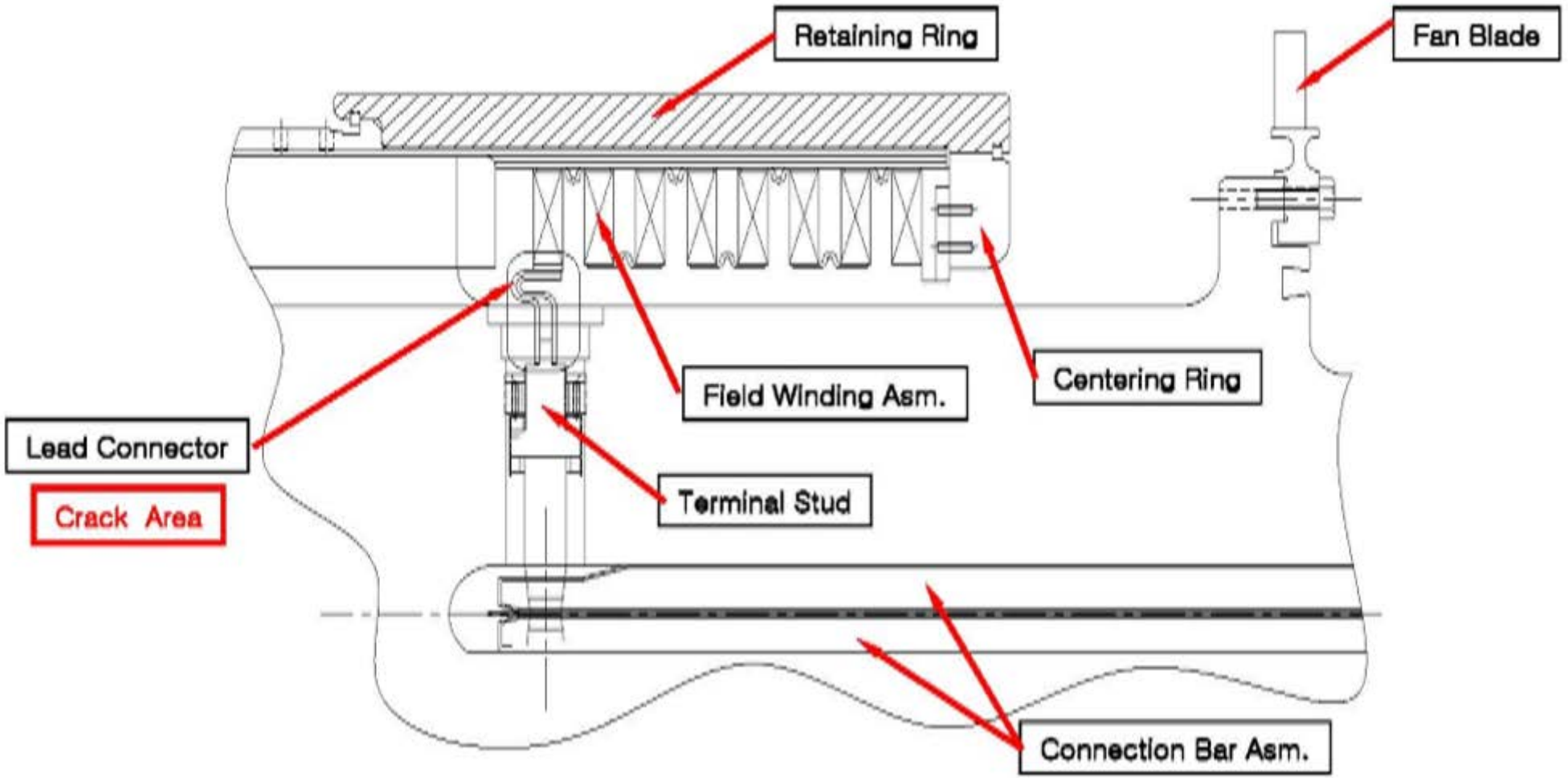


Bayonett Style Retaining Ring

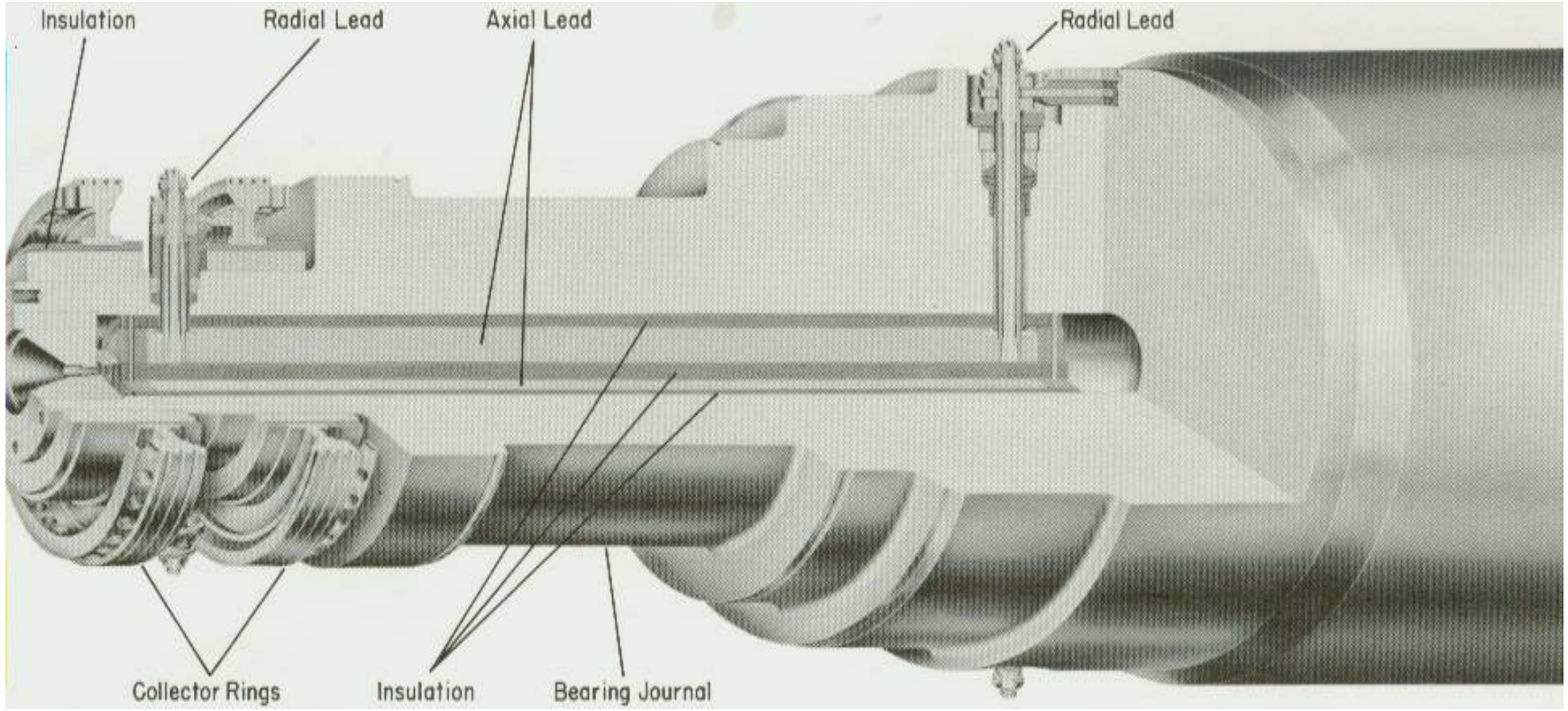




Rotor Ends

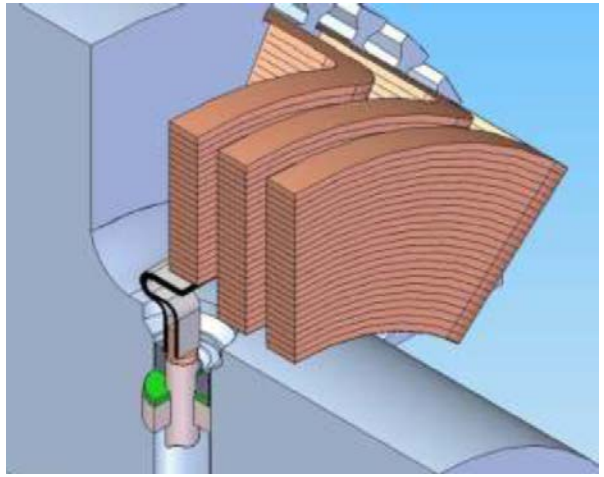


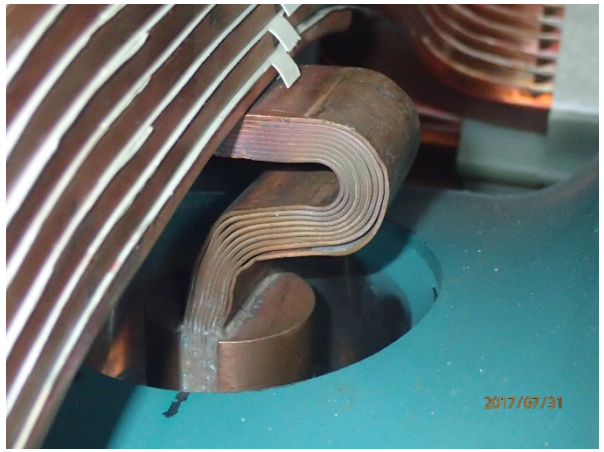
Slip Ring Connections

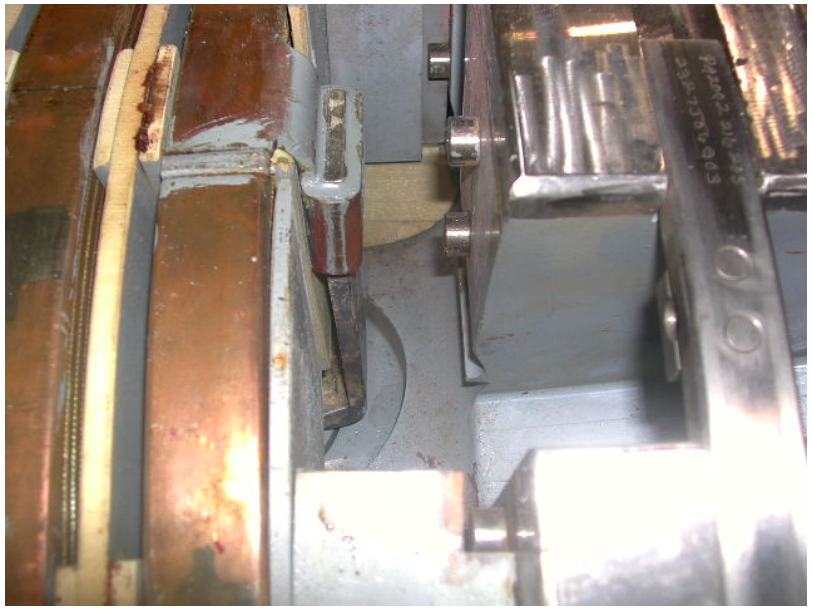


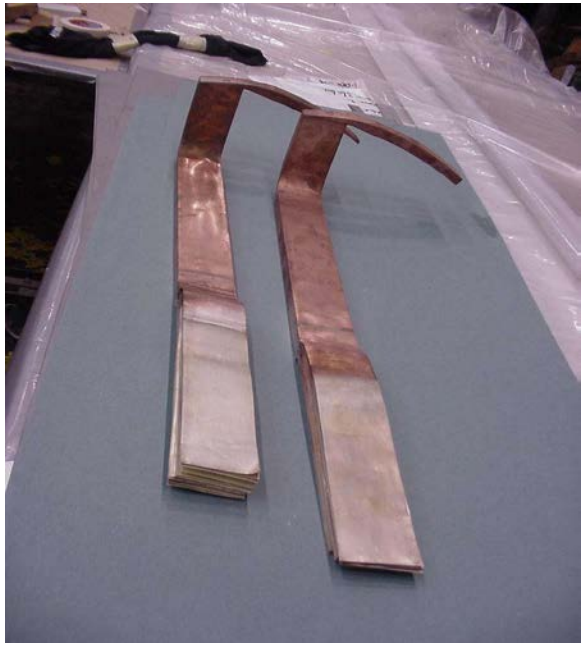
The connection leads from the slip ring to the rotor winding is a semi-rigid insulated connection running through the through hole and connected with insulated studs on either end.

Radial Stud and J –Strap Leads

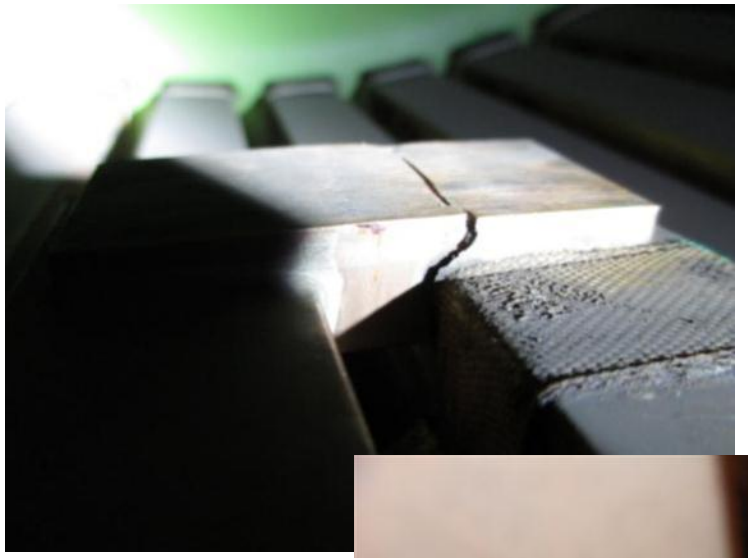




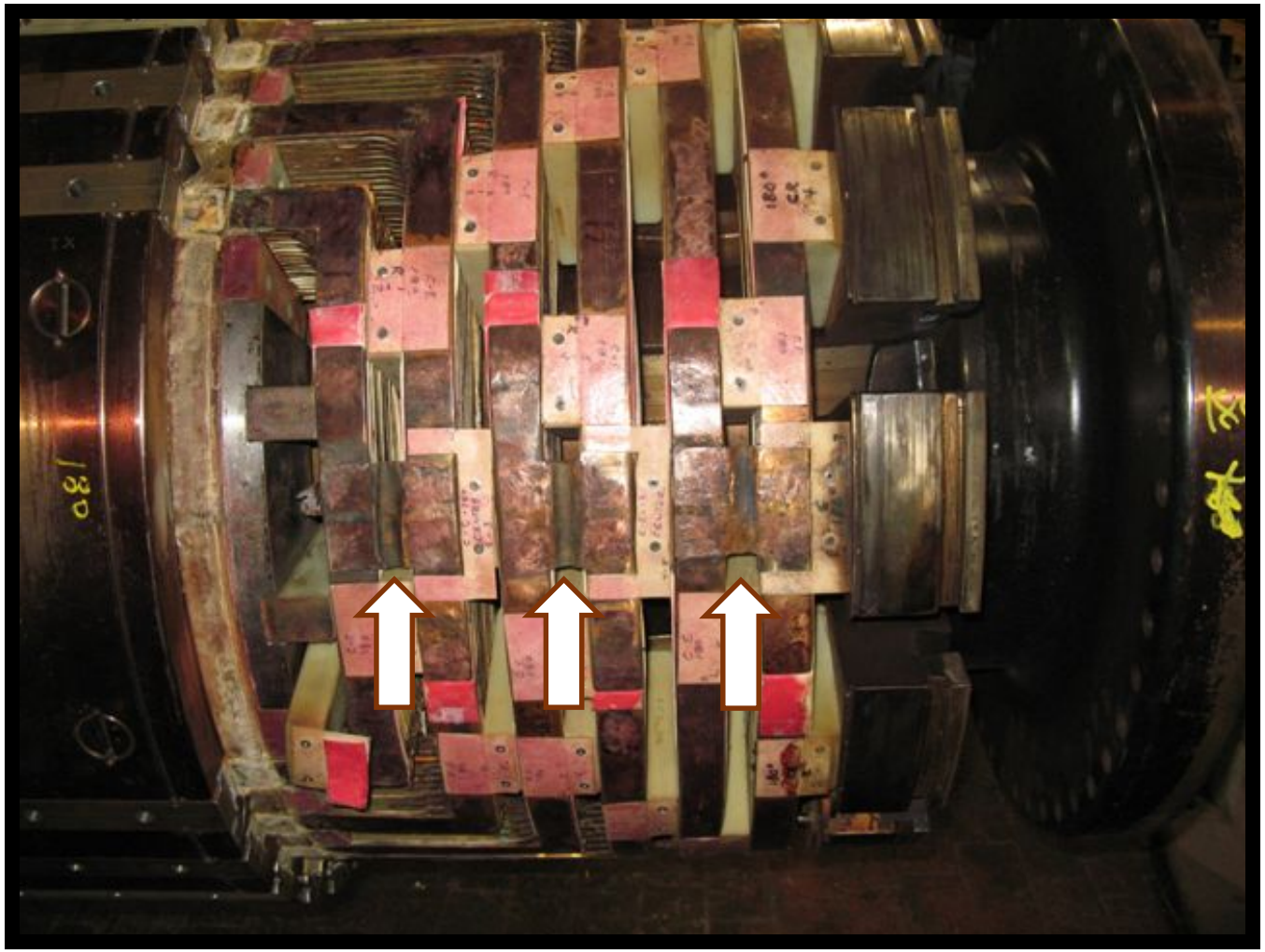




Alstom Pole to Pole Crossover Failure

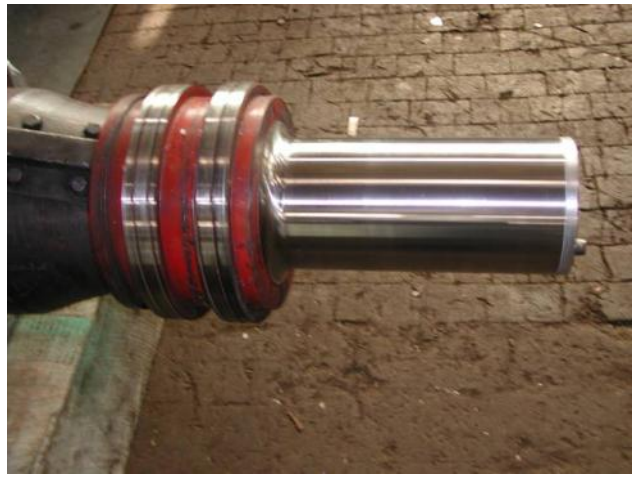


Coil to Coil Connectors



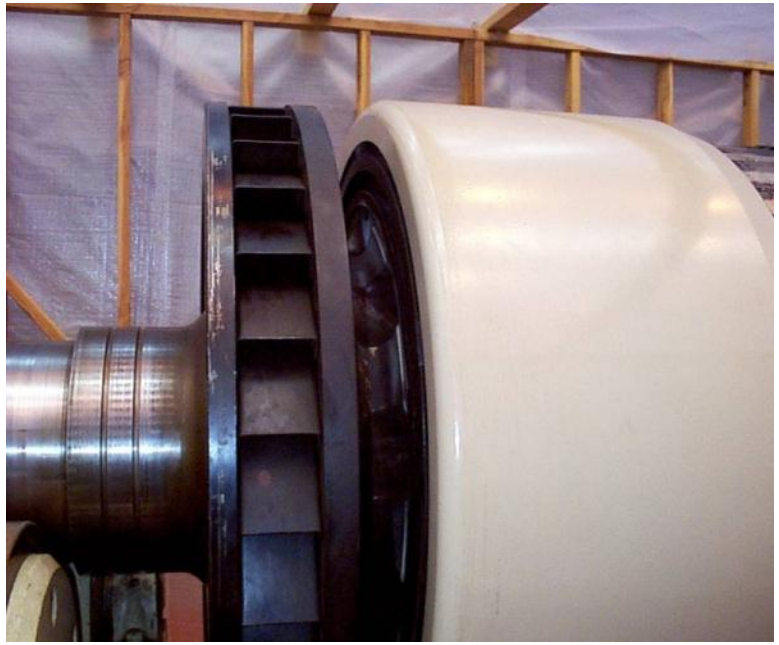
Collector Rings

- Size and number can vary depending upon he amount of current to be supplied to the rotor

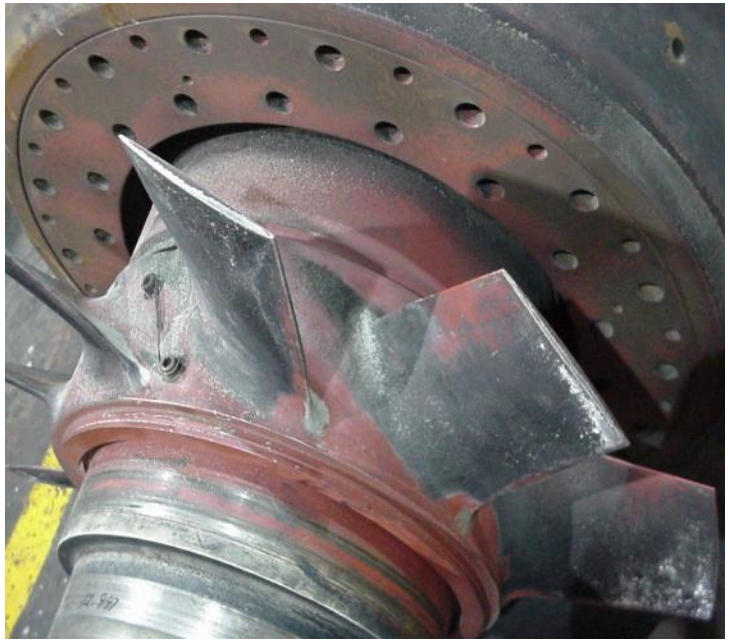


Rotor Fans / Blowers

Circulate cooling gas, so that the rotor and stator windings stay at normal operating temperatures.

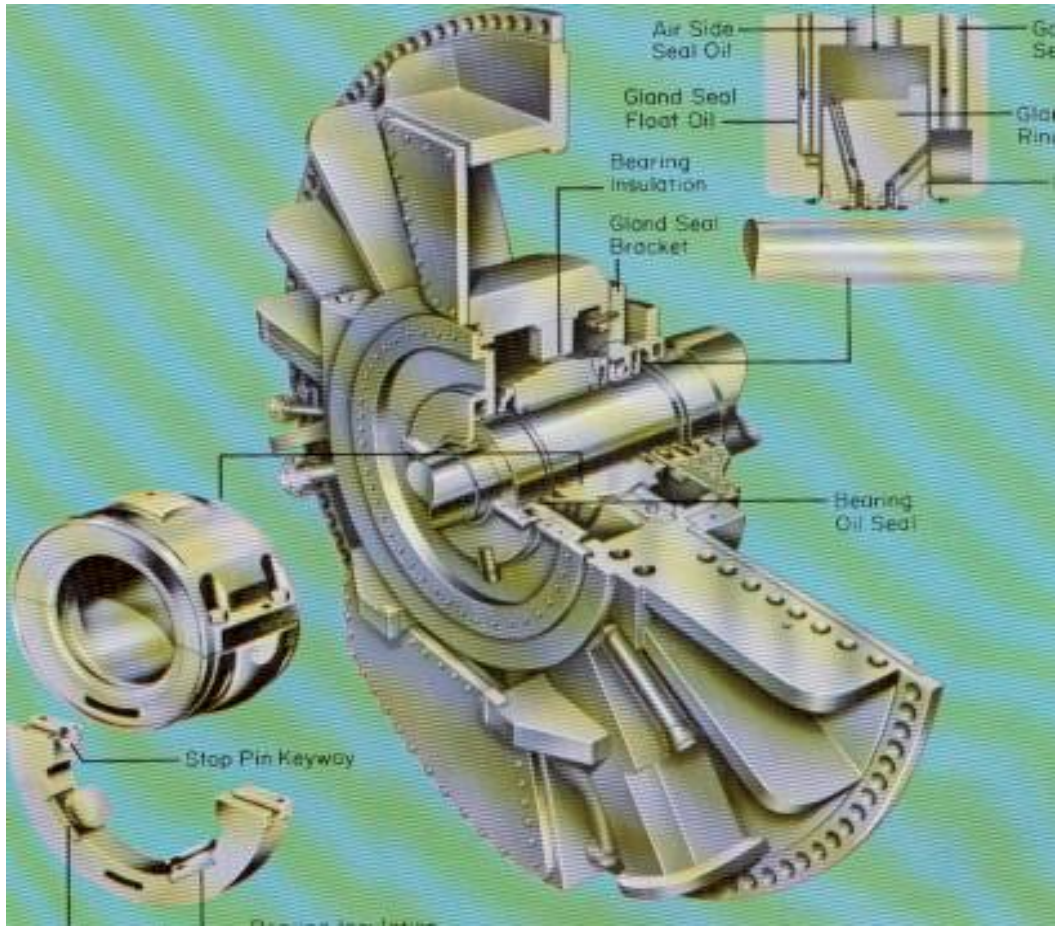


Squirrel Cage Fan



Axial Fan

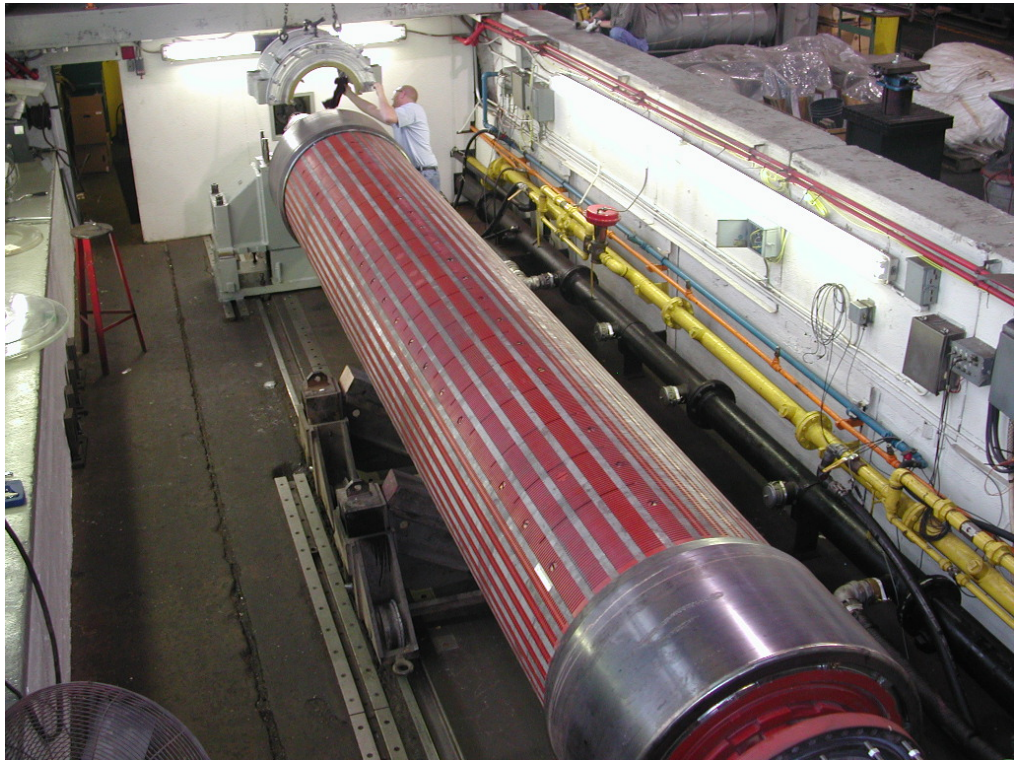
Rotor Journals & Bearings

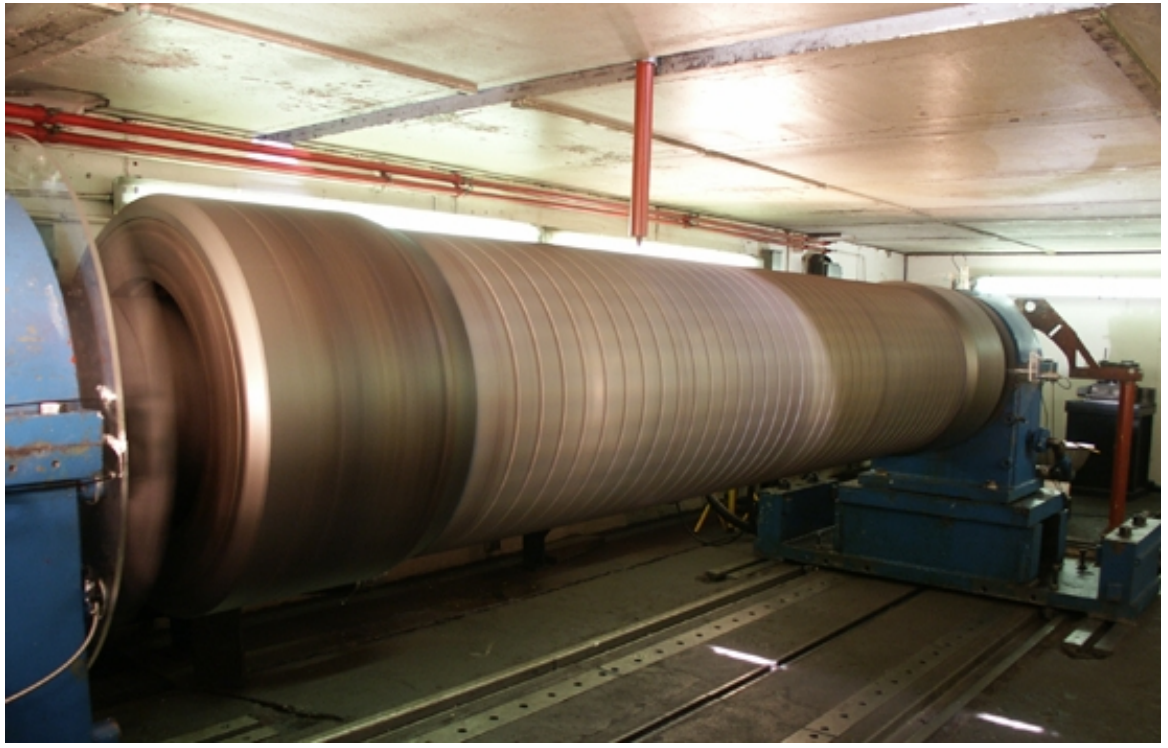


Polished surfaces for bearings to support the rotor

- Rotor Journal Damage can occur for several reasons
  - Often caused by lube oil contamination or starvation
  - Major damage can result in forging repairs
  - Minor damage may only require honing / polishing

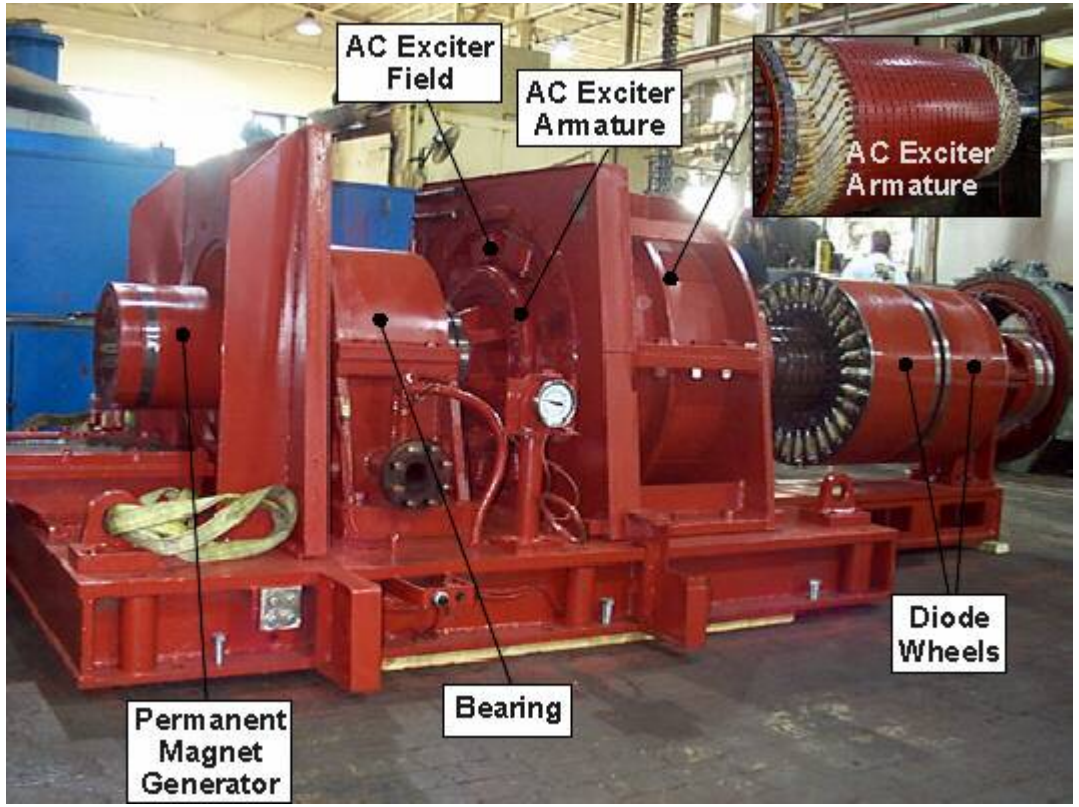
Rotor High Speed Balance





Flux Probe in Balance Pit

Brushless Excitation



Generator Resources

- Glossary of machine parts and electrical terminology
  - Section 411 – Rotating Machinery of the IEC's Electropedia (www.electropedia.org) contains those definitions most relevant to generators.
  - The glossary is multilingual. Most terms appear in at least French and English, but terms may also be shown in German, Spanish and many other languages.
- International Generator Technical Community
  - Online forum discussing a wide range of generator maintenance and related design issues.
  - Members-only, no-cost to join at www.generatortechnicalforum.org.

Stator &Rotor Questions & Discussion

W. Howard Moudy
Director of Operations
National Electric Coil
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(724) 787- 4967

Bonus Discussion - Generator Maintenance

- **Present Day Operational Challenges:**
  - Cycling
    - Speed
    - Load & VARS
  - Maintenance Program
    - Frequency
    - Decreased Cost
    - Disassembly

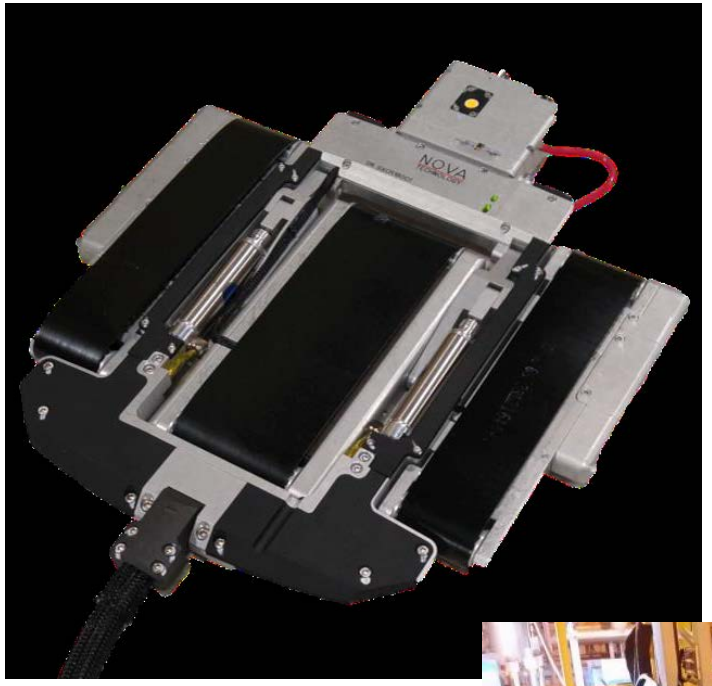
- **Purposes of Inspection & Testing**
  - Monitor
  - Identify
  - Evaluate
  - Qualify & Quantify
  - Trend

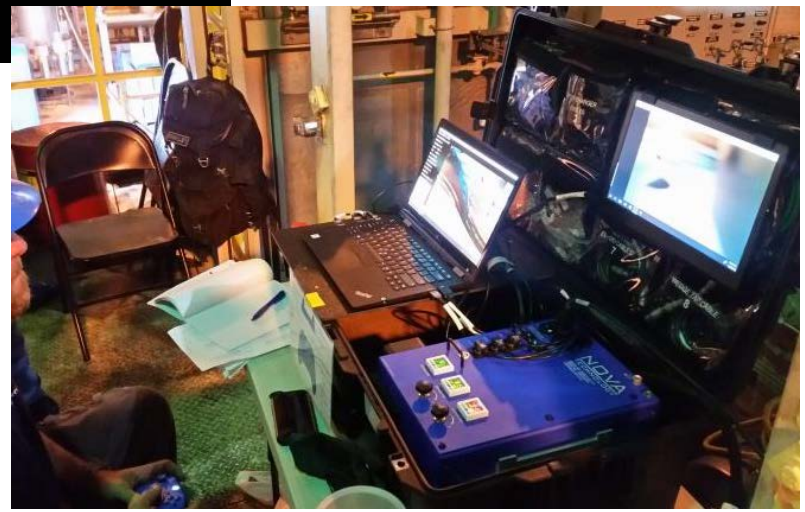
- **Become Aware of the Characteristics of Your Generator Model & Your Specific Machine**
  - Other Users
  - Industry Conferences & Events
  - On Line Forums
  - Vendors & OEM Bulletins

Visual Inspection – Robotic & Borescope

- Visual Inspection is the best overall maintenance value
- Robotic and Borescope Inspections are less intrusive & can be a price and schedule advantage
- Borescope & robotic technology continues to improve
  - getting smaller to gain greater access in tighter areas
  - Improved optics yielding improved clarity & insight
- Technology improvements have only increased the importance of:
  - experienced inspection and data gathering personnel
  - experienced generator design and engineering personnel for evaluation and recommendations.

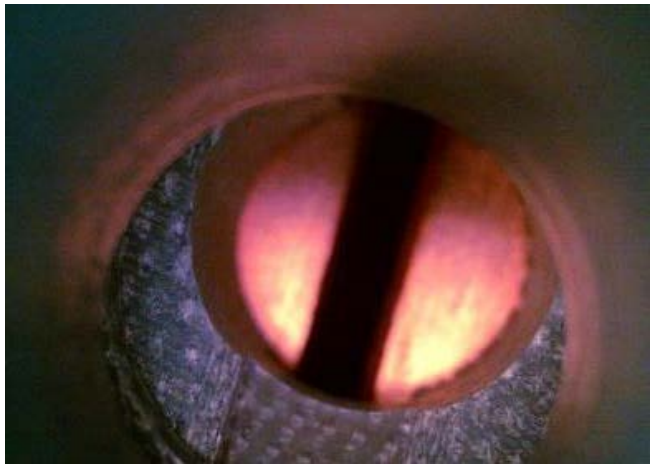
Generator Inspection Robot





- Crawler - 14.75”x 12.5” x 0.9” Weight – 6.5 lbs
- Visual Cameras - Video & 8x quality digital stills
- Enhanced LED lighting
- Wedge Tap - Compatible with Iris SWA
- El-Cid - Compatible with Iris Digital
- Speed: 1.66” / Second

Robotic Inspection Insight



Digital Stator Wedge Tap

[HGB]	Color
>= 600	
< 600 > 450	
< 450	

Numbers of wedges	33
Measurement points per wedge	2
Number of measurement points	66

Slot	Wedge 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	Amount lose [#]	Percent lose [%]	End Wedges lose	> 500 mm lose	Half of a third loose
1																																		24	36			
2																																		18	27	x		
3																																		25	38	x		
4																																		15	23	x		
5																																		16	24		very close	
6																																		20	30	x	very close	
7																																		19	29		very close	
8																																		20	30	x	very close	
9																																		7	11			
10																																		14	21	x		
11																																		16	24	x	very close	
12																																		20	30	x	very close	
13																																		7	11	x		
14																																		19	29	x		
15																																		8	12	x		
16																																		7	11	x		
17																																		25	38	x	very close	
18																																		17	26	x		
19																																		13	20	x		
20																																		12	18	x		
21																																		8	12	x		
22																																		15	23	x	very close	very close
23																																		13	20		very close	
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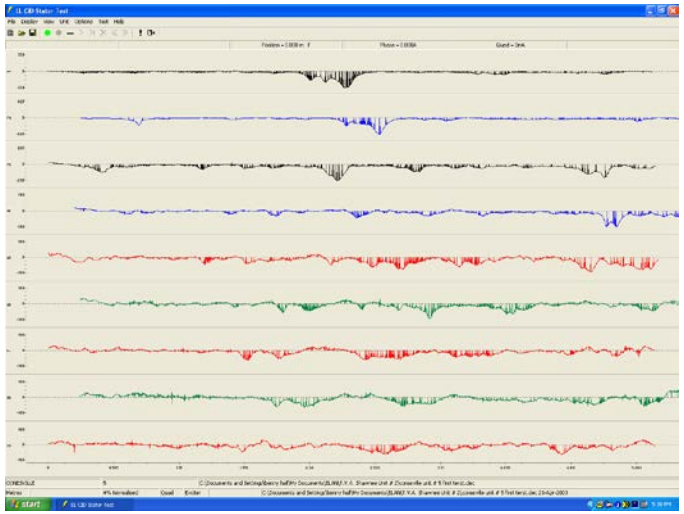
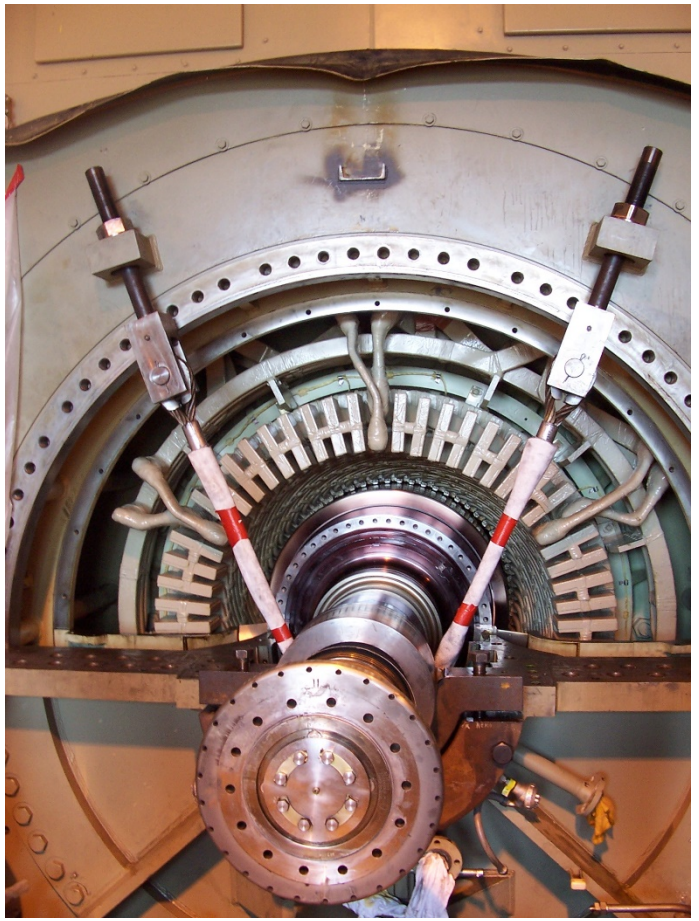
25																																		8	12			
26																																		12	18	x		
27																																		18	27		very close	
28																																		15	23	x	very close	
29																																		9	14			

Stator Core ELCID



Robotic Inspection
Required Generator Access

- Upper end bell removed on EE for Visual and Wedge Tap
- Upper end bell removed on EE and TE for ElCid
  - Excitation loop
- Challenge-
  - Air Gap clearance
  - Step iron and nose of retaining ring clearance



Generator Inspection & Testing

Standard Equipment Monitoring

Monitoring Activity	Purpose/Findings	Frequency
Temperature	Over-temperature operation	Continuous
Ground	Failure of ground insulation	Continuous
Lube Oil Analysis	Contamination, bearing babbit deterioration	Six Months
Vibration	Thermal sensitivity, loose component, imminent failure	Continuous

Inspection & Testing

Visual Inspection

Maintenance Activity	Purpose/Findings	Frequency
Stator Winding	Dusting, greasing, oily, broken ties, discoloration, wedge looseness, foreign object damage	Before every minor and major outage to help determine scope
Stator Core	Damaged iron, loose iron, discoloration, foreign objects	Major outages
Rotor	Discoloration from overheating, loose or shifted blocks, arcing	Before every minor and major outage to help determine scope

Inspection & Testing

Electrical Tests - Stator

Maintenance Activity	Purpose/Findings	Frequency
Insulation Resistance or “Megger” with PI	Determines presence of contamination	Minor and Major Outage
Winding Resistance	Integrity of brazed connections	Minor and Major Outage
Hipot	Proof test to “stress” insulation	Major Outage
D.C. Ramp	Determines insulation condition / strength	Major Outage

Inspection & Testing
Specialty Stator Tests

Maintenance Activity	Purpose/Findings	Frequency
ELCID – Electro-magnetic Core Imperfection Detection	Shorted laminations	Major outage
Core Loop	Shorted laminations	After rewinds or core repair
Wedge Tightness	Loose wedges	Major outage
Partial Discharge	Insulation deterioration, coil tightness in slot	Yearly
Bump test	Detects resonant frequencies	Major outage

Inspection & Testing

Electrical Tests - Rotor

Maintenance Activity	Purpose/Findings	Frequency
Insulation Resistance or “Megger” with PI	Presence of contamination &/or insulation deterioration	Minor and Major Outage
Winding Resistance	Integrity of brazed connections	Minor and Major Outage
Flux Probe	Rotor shorted turns (running)	Yearly
Pole Balance	Rotor shorted turns (stationary)	Major Outage

Inspection & Testing

Specialty Rotor Tests

Maintenance Activity	Purpose/Findings	Frequency
Boresonic Inspection	Forging Material Integrity	Rewind and based on past assessment
NDE – Retaining rings and other components	Detect cracks, corrosion and material deterioration	Major Outage and Rewinds
High Speed Balance	Qualify rotor mechanically & electrically and dynamic balance	After major rotor work and Rewinds

Testing Summary

BE SURE ALL CIRCUITS ARE DE-ENERGIZED)

MAINTENANCE ACTIVITY	SHOWS	FREQUENCY
Dielectric Absorption	Winding cleanliness	Major Outage
Polarization Index (PI)	Winding cleanliness/moisture	Major and Minor Outage Cycles
Power Factor	Insulation integrity	Major Outage Cycle
Partial Discharge (PD)	Coil tightness; insulation integrity	On-line or Outage Cycle
Megger	Integrity of Insulation	Major and Minor Outage Cycles
Blackout	Corona suppression integrity	Rewind
Resistance	Integrity of joints and connections	Major and Minor Outage Cycles
Flux Probe	Rotor winding shorts	On-line, Rewind
Rotor Impedance	Rotor winding shorts	Rewind
Ground Fault	Rotor Ground	Continuous
Split Voltage	Location of rotor grounds	As Needed
Voltage Drop	Presence of shorted turns	Major Outage Cycle
El Cid	Integrity of stator core	Major Outage Cycle
Core Loop	Integrity of stator core	Major Outage Cycle
Bolt Torque	Stator core looseness	Major Outage Cycle
Ultrasonic	Cracks, defects in forgings	Major Outage Cycle
Temperature Monitoring	Normal/abnormal operation	On-line and Continuous
Dye Penetrant	Cracks, defects in forgings	Major Outage Cycle
Eddy Current	Cracks, defects in forgings	Major Outage Cycle
Magnetic Particle	Cracks, defects in forgings	Major Outage Cycle
Wedge Mapping	Stator winding tightness	Major Outage Cycle
Hi-Pot	Insulation integrity	Major Outage Cycle
Vibration	Rotor imbalance	Monthly and On-line
Visual Inspection	Normal/Abnormal Performance	As Available
Oil Chemistry and Count	Bearing oil contamination	Twice Yearly

Generator Maintenance Final Remarks
The Importance Of Trending

- Documentation should be a conscious intent as part of planning that carries through execution of the outage, rather than just gathering up the information after the outage is over.
- Documented information provides valuable insight about where we have been and where we are.
- Trended information provides invaluable insight about where we are going. (Not a crystal ball but the next best thing!)

- Outage Reports
  - Should be kept together, organized by date, so they can be easily referenced
  - Electronic and paper files
  - Track recommendations, their completion and the details of completion (process, date)
  - Test Results – File by date
    - Normalize temperature and humidity
    - Trend

Generator Questions & Discussion

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