# Welcome to the Steam Generator Management Technology Workshop

Brent Capell
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Steam Generator Management and Technology Workshop
Shanghai, China
July 7-9, 2025

# Welcome to the Steam Generator Management Technology Workshop

Steam Generator Management Technology workshop provides a forum for sharing and an opportunity for members to learn from EPRI experts on topics related to nuclear power plant steam generators. The workshop will be held in China in 2025 and will focus on promoting a variety of shared interests regarding steam generator asset management to inform decisions on the safe, reliable, and economic operation of steam generators. The workshop is to review the most recent research activities including issues with anti-vibration bars, moisture carry-over, foreign objects, managing wear in SG tubes, leak detection, and aging management.

# Introductions

- Please give:
  - Your Name
  - Your Organization

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# Maintenance of SG Tubes Following NEI 97-06

NUCLEAR


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# NEI 97-06

- Available on the US NRC website, ML111310708
- An initiative adopted by 100% of the US utilities
- Provides a framework for structuring and strengthening existing Steam Generator Programs
- The detailed development of the programmatic attributes are in the EPRI SGMP Guideline documents

# Other Resources Available on the NRC Website

- 10 CFR Part 50, Appendix A, General Design Criteria for Nuclear Power Plants
- 10 CFR 50.65, Maintenance Rule
- 10 CFR 100, Reactor Site Criteria

# SGMP Guidelines

- PWR SG Examination Guidelines
- PWR Primary-to-Secondary Leak Guidelines
- PWR Secondary Water Chemistry Guidelines
- PWR Primary Water Chemistry Guidelines
- SG Integrity Assessment Guidelines
- SG In Situ Pressure Test Guidelines

# Performance Criteria

- Identifies the standards against which performance is measured
- Based on structural and leakage integrity
- Meeting the performance criteria provides reasonable assurance that the steam generator tubing remains capable of fulfilling its specific safety functions

# Structural Performance Criteria

- All in-service steam generator tubes shall retain structural integrity over the full range of normal operating conditions (including startup, operation in the power range, hot standby, cool down and all anticipated transients included in the design specification) and design basis accidents.
- This includes retaining a safety factor of 3.0 against burst under normal steady state full power operation primary-to-secondary pressure differential and a safety factor of 1.4 against burst applied to the design basis accident primary-to-secondary pressure differentials.
- Question:  What is the pressure differential?
  - Response:  It is the difference between the primary and secondary pressure.  Actual or design pressures can be used.
- Apart from the above requirements, additional loading conditions associated with the design basis accidents, or combination of accidents in accordance with the design and licensing basis, shall also be evaluated to determine if the associated loads contribute significantly to burst or collapse. In the assessment of tube integrity, those loads that do significantly affect burst or collapse shall be determined and assessed in combination with the loads due to pressure with a safety factor of 1.2 on the combined primary loads and 1.0 on axial secondary loads.

# Accident-Induced Leakage Performance Criterion

- The primary to secondary-accident induced leakage rate for any design basis accident, other than a steam generator tube rupture, shall not exceed the leakage rate assumed in the accident analysis in terms of total leakage rate for all steam generators and leakage rate for an individual steam generator.
- Leakage is not to exceed 1 gallons per minute (227 l/hr) per steam generator, except for specific types of degradation at specific locations when implementing alternate repair criteria as documented in the Steam Generator Program technical specifications.

# Operational Leakage Performance Criterion

- The RCS operational primary-to-secondary leakage through any one steam generator shall be limited to 150 gallons per day (23.6 l/hr).

# Questions on Slides 7 and 8

- What are the sources for leakage limits? How did the US industry reach those numbers?
  - Response: The 1 gallon per minute is a requirement by the US NRC. However, the accident-induced leakage limit is also equal to the amount of leakage assumed in the plant's accident analyses. For some plants in the US there are accident analyses that assume there will be only 0.5 gpd through a SG. Therefore, that plant's limit would be 0.5 gpd unless they change the accident analyses
  - Response: For the operational leakage, the limit was set to provide margin to burst at steam line break pressure differential for normal operating conditions.
    - Plants in the US have a lower limit in their administrative procedures and many shut down soon after leakage is known to be increasing.

# Questions on Slides 7 and 8

- If there is a leak, what approaches can be used to identify the location of the leak?
  - Response: In the US, utilities have successfully used secondary hydro test to identify the leaking tube followed by eddy current testing
- What are the methods for leak detection
  - Response: Detection of radio-isotopes through monitors in the plant.
- What is an alternate repair criteria (ARC)
  - Response: This is a technical specification change submitted to the NRC to allow crack-like indications to remain in service when they meet certain criteria. There are currently two in use in the US:
    - NRC Generic Letter 95-05 describes a methodology for leaving cracks within the confine of drilled hole support plates in service based on eddy current voltage
    - The Alloy 600TT fleet have a methodology for allowing crack-like indications deep within the tubesheet in service based on the fact that they are precluded from burst. (H*). These plants have a small amount of leakage to account for in their operational assessment

# Ensuring SG Tubing Meets Performance Criteria

- Degradation Assessment
- Primary Side Inspections
- Integrity Assessments
- Plugging and Repairs
- Foreign Material Exclusion
- Secondary Side Visual Inspections
- Primary-to-Secondary Leak Monitoring

# Question on Slide 11

- For operational assessment results which exceed the criteria, what is the action
  - Response:  In the US, the utility must report to the NRC.  This typically results in a cited violation.  A root cause investigation is completed to determine that cause of the failure.  Many times, the cause is nonconservative assumptions in the operational assessment.  Tubes are plugged and future inspection intervals may be changed (more frequent inspections).
- If members in China encounter such a failed tube, what is the best way to discuss this with the report to a local regulator?
  - Response:  Results of a root cause and preventive actions will assist the plant's ability to convince themselves and the regulator they can startup and operate safely.

# Other Questions

- For OA evaluations, how is the growth rate for flaws estimated?
  - Response:  For wear mechanisms, where there are wear flaws left in service each outage, the growth rate can be calculated by subtracting the current eddy current depth from the past eddy current depth.  If there is not enough data to establish a growth rate, growth rates from steam generators with similar design and operating conditions can be used.
- For an in-situ pressure test, how is it performed in the US; how are the tubes tested
  - Response:  The US eddy current vendors have tooling that can be inserted into the tube, tube flaw is isolated and pressure is applied up to accident and 3 x normal differential pressure.  If the flaw doesn’t leak it passes condition monitoring.

# Other Questions

- When conducting the tube integrity assessment, does the US use the probability assessment safety analysis?
- Response:  We assume the question is regarding a probabilistic assessment versus a deterministic assessment.  A deterministic assessment is based on a single tube projection that will yield a conservative answer for the full bundle.  These assessments require each input to be taken at the 95$^{th}$ percentile worst case values.  Probabilistic assessments consider the entire flaw population for a given degradation mechanism.  Monte Carlo simulation methods are used to predict the distribution of end of cycle structural integrity parameters so that the lower 95th percentile of the worst case burst pressure values may be obtained. By accounting for all of the at-risk tubes in the bundle and modeling all flaws (both detected and non-detected), the probabilistic method, with appropriate statistical distributions for each important input variable, produces the different sets of possible outcomes to establish the probability of burst.
- When SGs have many flaws or significant growth rates, the probabilistic methodology is the best way to assess the bundle.  The deterministic methodology will be very conservative.

# Other Questions

- What is the frequency of visual inspections for secondary side components?
  - Response: This is based on risk. If a plant has a history of issues with foreign material in the SG bundle, they may inspect every outage. If not, the secondary side inspections are performed at the same frequency as primary side inspections.
- What is the range of visual inspections?
  - Response: See SGMP Technical Report 302029282 with details.
- Sometimes tubes can be damaged by foreign objects. How does the US inspect and assess the tubes?
  - Response: Eddy current and visual inspections are performed in the US. Foreign object wear is assessed like other wear mechanisms. In the US, the wear is plugged at 40% through wall. However, with foreign object wear, the part must be removed so that further damage will not be possible. If the part is not removed, plugging and stabilizing may be necessary. Also, tubes surrounding the part will be plugged and stabilized in case the part migrates.

# Other Questions

- What about the case where impact of foreign object could cause any erosion and a wear scar?
  - Response:  Each case should be analyzed individually.  See answer to question above.
- In China, there are SGs with Alloy 690TT tubing.  Any different approach?
  - Response:  The methodologies for inspection, repair, and assessments are the same.  The only mechanism experienced to date is wear, so assessments are typically easier than assessing cracking.  SGs with Alloy 690TT are able to inspect less frequently if the operational assessment supports.

# Other Important Elements of a SG Program

- Maintaining and monitoring primary and secondary water chemistry to mitigate corrosion
- Overseeing vendors
- Self-Assessments
- Reporting

# Degradation Assessment

- Purpose is to ensure the appropriate inspections are performed during the upcoming inspection
- Important features:
  - Identifying existing and potential degradation mechanisms
  - Choosing techniques to test for identified degradation
  - Establishing the number of tubes to be inspected
  - Establishing the tube integrity limits for tube integrity assessments

# Primary Side Inspections

- Plan and conduct inspections
- Important features:
  - Sampling to support the upcoming inspection interval and to satisfy Technical Specifications
  - Obtaining the information necessary to develop integrity assessments
  - Qualifying the inspection program by determining the accuracy and defining the elements for enhancing NDE system performance, including technique and analysis

# Integrity Assessments

- Assessments determine if the tube bundle meets performance criteria or will meet performance criteria at the next inspection
- Important features:
  - Condition Monitoring – A backward-looking assessment which confirms that adequate steam generator tube integrity has been maintained during the previous inspection interval
  - Operational Assessment – A forward-looking assessment which demonstrates that the tube integrity performance criteria will be met throughout the next inspection interval

# Tube Plugging and Repairs

- Tube plugging and repairs ensure that tube flaws that exceed plugging limit and flaws that could grow to a size that would not meet performance criteria at the next inspection are removed from service
- Important features:
  - Qualify plugging and repair methods
    - Considers the specific steam generator conditions and mockup testing.
  - Clearly identify engineering prerequisites and plant conditions prior to performing the plugging or repair.
  - Implement process controls to ensure proper performance of the plugging and repair including the consideration of post maintenance testing.

# Foreign Material Exclusion

- Preclude the introduction of foreign objects whenever the SG is open
- Important procedure features:
  - Detailed accountability for all tools and equipment used during any activity when the primary or secondary side is open
  - Appropriate controls and accountability for foreign objects such as eyeglasses and personal dosimetry
  - Cleanliness requirements
  - Accountability for components and parts removed from the internals of major components (e.g., reassembly of cut and removed components)

# Secondary Side Visuals

- The program defines when secondary-side visual inspections are to be performed, the scope of inspection, and the inspection procedures and methodology to be used.

# Primary-to-Secondary Leak Monitoring

- Primary-to-secondary leak monitoring is an important defense-in-depth measure that assists plant staff in monitoring overall tube integrity during operation.
- Monitoring gives operators information needed to safely respond to situations in which tube integrity becomes impaired and significant leakage or tube failure occurs.
- Additionally, operational leakage is an important tool for assessing the effectiveness of a Steam Generator Program.
  - Plants assess any observed operational leakage to determine if adjustments to the inspection program or integrity assessments are warranted

# Water Chemistry Control

- Procedures for monitoring and controlling secondary-side water chemistry to inhibit secondary-side corrosion-induced degradation
- Procedures for monitoring and controlling primary-side water chemistry to inhibit primary-side corrosion-induced degradation

# Overseeing Vendors

- When the licensee contracts portions of the SG work scope, the responsibility for program implementation and compliance with requirements always remains with the licensee.
- It is the licensee's responsibility to plan, direct, and evaluate all steam generator activities.
- Critical aspects of this oversight include but are not limited to the following:
  - Review and approve the scope of work to be performed by a contractor
  - Review and approve the Degradation Assessment
  - Review and approve the contractor's examination procedures
  - Monitor the contractor's examination work progress
  - Review and approve the contractor's deliverables
  - Review and approve the tube integrity assessment (CM/OA) and associated support documents

# Self-Assessments

- Perform self-assessments of the Steam Generator Program.
- This review is performed by knowledgeable utility personnel or a contractor with independent experts selected by the licensee on a periodic basis.
- The self-assessment identifies areas for program improvement, along with program strengths.
- The assessment includes all the major program elements described in NEI 97-06

# Reporting

- Reports to Regulator as applicable
- In the US, it is expected that SGMP be notified on the following items:
  - Any confirmed tube degradation of a type or in a location that has not been previously experienced
  - In situ tests that result in leakage or burst
  - NDE and metallurgical data on any pulled steam generator tubes
  - Any significant steam generator operating experience that has generic implications for the industry
  - Steam generator inspection results (submitted to the EPRI SGMP through timely updating of the Steam Generator Degradation Database)

# Summary

- With a strong steam generator program, utilities will have a reasonable assurance that the steam generator tubing will remain capable of fulfilling its specific safety functions

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# CGN Using US Technical Specifications as Framework

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# NRC Website Has Examples of Applications for Revising SG Technical Specification

- One example:  ML21222A227, a US plant with Alloy 690TT tubing
- All applications for revising SG Technical Specifications are open to the public on the NRC's website
- This plant used TSTF-577
  - NRC's Safety Evaluation is on the NRC Website, ML21098A188
- The Alloy 690TT technical basis is operating experience
- The NRC's safety evaluation will provide information

# Sections to Include

- Description of what is being requested
  - US plants' latest applications have been to change the SG Technical Specification
- A safety evaluation must be completed
  - For TSTF-577, US plants could reference the NRC's safety evaluation and describe any variations
  - CGN could use the NRC's safety evaluation
- No significant hazards consideration analysis
  - The change should not create the possibility of:
    - A significant increase in the probability or consequence of an accident previously evaluated
    - A new or different kind of accident from any previously evaluated
    - A reduction in margin of safety
- Environmental consideration
  - Does the changes have an environmental impact?
  -

# Create or Change the Steam Generator Program Section in Technical Specifications

- Describe the provisions for maintaining SG tube integrity
  - Provisions for condition monitoring – evaluation of the as-found condition of the tubing with respect to the performance criteria
- Describe the performance criteria that will be used to ensure tube integrity is maintained
- Describe the plugging limit
  - In the US the limit has been set at 40%

# Create or Change the Steam Generator Program Section in Technical Specifications

- Describe the commitment made for inspections of the SG tubing
  - In the US for Alloy 690TT tubing:
    - Inspect 100% of the tubes in each SG during the first refueling outage following SG installation
    - At the first refueling outage following SG installation, inspect 100% of the tubes in each SG at least every 96 effective full power months, which defines the inspection period
    - If crack indications are found in any SG tube, the next inspection for each affected and potentially affected SG for the degradation mechanism that caused the crack indication shall be at the next refueling outage.
      - If definitive information, such as from examination of a pulled tube, diagnostic nondestructive testing, or engineering evaluation indicates that a crack-like indication is not associated with a crack, then the indication need not be treated as a crack.
- Describe provisions for primary-to-secondary leakage

# Create or Change the Steam Generator Tube Inspection Report

- In the US because we have performance-based inspection, the reporting is detailed
  - Report submitted to the report to the NRC 180 days after entry into Mode 4
  - Report the scope of inspections performed on each SG
  - For each mechanism found report the following:
    - The NDE technique used
    - The location, orientation, size, and voltage for each indication.
    - Description of condition monitoring assessment and results, including the margin to the performance criteria and comparison with the margin predicted from the last inspection
    - Number of tubes plugged
    - Summary of the tube integrity conditions predicted at the next inspection relative to the performance criteria
    - Number and percentage of tubes plugged to date in each SG
    - Results of any SG secondary side inspections

# Questions Regarding How CGN Would Use NEI 97-06

- Provide an example of how a plant would use NEI 97-06 to develop their technical specification
- Response:  We are not able to discuss details of SG Technical Specifications; however, ML21222A227 is an example of a plant that revised their technical specifications using NEI 97-06.
- The US technical specifications have evolved over time.  TSTF-449 was the first to use NEI 97-06 and EPRI SGMP guidelines for technical bases to move toward a more performance based inspection requirements.  TSTF-510 provided longer inspection intervals and TSTF-577 provided even longer.

# Questions on Day 3 Regarding Technical Specifications, NEI 97-06 and AP1000

- AP1000 units have severe wear issues.  Is it a unique or deviation case of NEI 97-06?
  - Response:  The basics of NEI 97-06 should still be applicable to a unit with severe wear issues.  There are units in the US that have large numbers of wear but they still maintain tube integrity by inspecting according to the operational assessment results.
- Why does AP-1000 unit have the high number of wear flaws?
  - Response:  This is a design issue that EPRI cannot provide answers to because the information is proprietary to design or manufacturing vendors

# Questions on Day 3 Regarding Technical Specifications, NEI 97-06 and AP1000

- Question: What are the number of plants adopted TSTF-577 in US
  - Response: 52 units have approval or are waiting approval to implement TSTF-577. The remaining 12 units did not adopt TSTF-577 due to excessive wear or cracking that would not make the Technical Specification worth the effort.
- Question: Is the basic direction of inspection requirement relaxed from TSTF-449 to TSTF-577
  - Response: Yes, our technical bases is strengthened with more inspection data from the SGs with improved material. It can be demonstrated that some SGs can operate longer between inspections based on the OE.

# Questions on Day 3 Regarding Technical Specifications, NEI 97-06 and AP1000

- Question: Can EPRI show data provide to the NRC for TSTF 577 approval?
  - Response: The EPRI team is not sure if this question is referring to TSTF-577 or TSTF-449. This may be a good topic for future workshop.

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# Comparison of Codes Used for SG Maintenance

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- Summary of Publicly Available Information on SG Tubing Fitness for Service Rules
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  - France
  - Republic of Korea
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- Limited Information for Other Countries
  - Czech Republic
  - Germany
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  - Slovenia
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  - Switzerland
- Summary of Minimum Inspection Requirements

# Regulations for SG Operators in the US

- Federal Regulations
  - General Design Criteria in Appendix A to Part 50 of Title 10 (10 CFR Part 50, Appendix A)
    - Establish the fundamental regulatory requirements for reactor coolant pressure boundary components
  - 10 CFR Part 50, Appendix B
    - Establish quality assurance requirements for the design, construction, and operation of nuclear power plants
      - Several paragraphs are relevant to SGs
        - Control of Special Processes
        - Test Control
        - Correction Action

# Regulations for SG Operators in the US

- Federal Regulations (continued)
  - 10 CFR Part 50.55a, Codes and Standards have design and inspection requirements
  - 10 CFR Part 50.65, Maintenance Rule states that licensees shall monitor the performance or condition of SGs to provide reasonable assurance that they are capable of fulfilling their intended safety function.

# Regulations for SG Operators in the US

- Technical Specifications
  - Required to obtain an operating license
  - Include commitments to ensure reactor coolant boundary integrity is maintained
  - For the SG, these have evolved over the years

# Inspection Requirements

- Current Technical Specification for Alloy 690TT tubing requires that 100% of the SG tubing be inspected with probes that can identify any mechanism that may be present along the length of the tubing every 96 effective full power months
  - Specific commitments for meeting the performance criteria sometimes limits the operating time
- All tubing shall be inspected during the first refueling outage

# Technical Analysis Methods

- Tube integrity must be confirmed during each SG in-service inspection through the Condition Monitoring process
  - Refers to EPRI SGMP Guideline Documents for methods
- All tubes with measure flaw sizes that exceed the tube repair criteria shall be plugged
- Operational leakage shall not exceed approximately 150 gallons per day (23.6 l/hr)

# Acceptance Criteria

- Structural Performance Criteria
  - All in-service SG tubes shall retain structural integrity over the full range of normal operating conditions and design basis accidents
    - Induces retaining a safety factor of 3.0 against burst and 1.4 against design basis accident
- Accident-Induced Leakage Performance Criteria
  - Leakage is not to exceed what is assumed in the accident analyses and not to exceed 1 gallon per minute (227 l/hr) per SG
- Operational Leakage Performance Criteria
  - Leakage through any one SG shall be limited to 150 gallons per day (23.6 l/hr)

# Legislation for SG Operators in France

- Section 14 of Book V, Chapter VII of the French Environment Code
- The 1999 Operation Order
- ESPN Order (2015), amended in 2018
- Order of 20 November 2017

# Inspection Requirements from Legislation

- A preservice inspection, equivalent to a complete in-service inspection, must be performed before the SGs enter service.
- The first complete requalification inspection is to be performed no later than 30 calendar months after the first fuel load.
- The interval between complete inspections (e.g., 100% of the tube bundle for SGs) must not exceed 10 years unless a deferment (expected to be no more than 1 year) is granted by the French Nuclear Safety Authority, the Autorité de sûreté nucléaire (ASN).
- Partial inspections must be carried out during every refueling outage between the complete inspections, with the interval between either a full and partial inspection or two partial inspections not to exceed 24 calendar months for the MPS.
- A hydraulic test using pressures at least equal to 1.2 times the design pressure must be performed on all 100% of the in-service SG tube population during each complete inspection in the presence of a representative appointed by the ASN.

# RSE-M Code

- Rules for In-service Inspection of Nuclear Power Plant Components
- EDF drafted the first edition of RSE-M Code in 1990 and worked with Framatome to revise it in 1997, published by AFCEN
  - Changes have been made to the Code, but no inspection requirements or acceptance criteria have changed

# RSE-M Code Inspection Requirements

- Required to use inspection methods that are qualified by an entity accredited by French Accreditation Committee (or equivalent)
  - Axial and rotating probe types to be determined by the plant operator based on degradation
- Confirm leak tightness of the bundle using a tracer gas and hydraulic proof tests on the entire vessel at pressure to a least 1.2 times the design pressure
- SG In Service Inspection program is defined by EDF in procedures
  - Reviewed and accepted by the ASN

# EDF Guidelines Inspection Requirements

- For Alloy 690TT tubing, inspections are performed such that 100% of tubing is inspected every 8 years
- Question: What is EPRI's interpretation on that requirement?
- Response: The licensees are able to develop their own specific inspection plans as long as they meet the stated goal of 100% every 8 years.
- During 10-year periodic inspection, 100% of the tubing must be inspected
- Bobbin coil probes are used as the base inspection, additional inspections are sometimes performed with other probes such as rotating coil probs

# Technical Analysis Methods

- EDF procedures allow degradation-specific repair criteria
  - Operator can determine the maximum acceptable flaw size for cracking depending upon the reliability of the plant's leakage detection
  - For wear, EDF procedures are consistent with the ASME Code and plug wear defects at 40% through wall
- Question: It is stated that the operator can determine the maximum acceptable flaw size for cracking. How does the licensee discuss with a regulator?
- Response: EPRI does not have the specifics of how EdF interacts with the regulator. But, a technical bases with test results are likely required to leave crack-like indications in service.

# Acceptance Criteria

- Minimize risk of SG tube ruptures
  - Defects can be reliably detected by leakage before a rupture can occur both during normal operations and accident conditions
  - Monitoring methods can reliably detect and characterize degradation
  - Maximum allowable leak rate prior to shutdown is 3 liters per hour for Alloy 690TT tubes

# Legislation for SGs in Korea

- Korea Institute for Nuclear Safety (KINS) acts as a technical support body and performs activities such as safety reviews, regulatory inspections, and R&D
  - Supports the preparation of technical standards for nuclear safety regulations
- In 2011, the Republic of Korea established the Nuclear Safety and Security Commission (NSSC)
  - Independent of any ministry and reports to the President
  - Primary safety regulatory authority
  - Responsible for establishment of safety regulations

# Inspection Requirements

- Regulation requires plants to have Technical Specifications to describe inspections conducted to ensure safe operation, including frequency
  - Frequency is based on operational experience or probabilistic safety analysis
- Eddy current is the expected method for inspection
  - Performance must be demonstrated and supplemented with plant-specific design characteristics
- The most recent Technical Specification includes the contents of SGMP and refers to NEI 97-06
  - Includes frequency of inspections, scope, and acceptance criteria

# Regulation for SGs in South Africa

- Regulated by the National Nuclear Regulator (NNR)
- Safety Standards and Regulatory Practice document presents the safety requirements
  - Nuclear plants must be maintained and inspected to ensure the reliability of the systems and components important for safety
  - Operational safety assessments must be performed and submitted to NNR

# Inspection Requirements

- In-service Inspection of SGs follow EDF SG procedures
- For the replacement steam generators with Alloy 690TT tubing
  - All tubes must be inspected by bobbin coil probes prior to service
  - During the first outage after replacement, 100% of the tubing must be inspected with bobbin coil probes
  - Subsequent inspections of a random sample of all SGs are to be performed during alternating refueling outages (at least every 36 months for a unit)
  - Visual inspections and sludge lancing are to be performed
    - No details of frequency or scope in public documents
- Acceptance criteria follows EDF procedures
- Question: The French Code says they inspect at least every 39 months so is it different by country?
- Response: Yes, it can be different by country.

# Regulation for SGs in Canada

- Regulated by the Canadian Nuclear Safety Commission
  - Licensees in Canada are required to comply with the Canadian Standards Association (CSA)
    - Describes periodic inspections of components

# Inspection Requirements

- Employ methods that are appropriate to the components being inspected for each damage mechanism
  - Eddy current and UT are utilized
- Scope and frequency
  - Preservice inspection of 25% random sample in each SG after installation
  - Periodic inspection intervals
    - 25% sample of the SGs in a specific unit
    - At least one periodic inspection of all SGs by the end of the fourth interval
    - For the sample, examine a minimum of 25 tubes for each mechanism that is postulated and plausible

# Inspection Intervals

| Inspection interval* | Years since first net power date |
|---|---|
| Baseline | Pre-service |
| 1 | 4–6 |
| 2 | 10–12 |
| 3 | 16–18 |
| 4 | 22–24 |
| 5 | 28–30 |
| 6 | 34–36 |
| 7 | 40–42 |
| 8 | 46–48 |
| 9 | 52–54 |
| 10 | 58–60 |

*For example, interval 1 runs from the first day after 3 years of operation to the last day of the sixth year of operation, providing a 3-year window to perform the required inspections.

# Acceptance Criteria

- Tube pulls are required for high-risk degradation
- Condition monitoring and Operational Assessment required
- Acceptance criteria prohibiting leakage
  - Determine the maximum allowable flaw size
  - Safety factors on assessments of 3.0 for normal operation, 1.5 for accident loads
- Acceptance criteria permitting leakage
  - Apply maximum tolerable flaw size that would cause leakage but leak before break can be demonstrated
    - Used for flaws with limited leakage expected
- Maintains the same ASME-based 40% plugging limit

# Public Information on SG Inspections in Czech Republic

- All tubes were to be inspected prior to service.
- Subsequent inspections were typically to be performed within “4 to 6 years / fuel cycles”
- The ECT practices (i.e., testing methods, probes used, inspection intervals, inspection scopes, etc.) based on recommended ASME procedures (understood to include the ASME Boiler and Pressure Vessel Code).
- Repairs based on the defect depth, amplitude of the ECT signal, and OE.

# Public Information on SG Inspections in Germany

- SG tubes must be inspected using procedures and techniques capable of detecting flaws / local wall thinning on the inside and outside of the tube.
- ECT shall be in accordance with standards
- Flaws resulting in >20% reduction in wall thickness (including dents) shall be recorded.
- ECT shall be performed on 20% of the full length of the tubes in each SG, with consideration given to the locations of higher susceptibility.
- Inspection of all SGs must be performed in intervals of 4−5 years (understood to mean that 20% of the tubes in each SG must be inspected within this time period), with half of the SGs covered mid-way through the applicable inspection interval.
- Repair of an individual flaw is to be performed if the flaw is estimated to have resulted in a 30% reduction in wall thickness.
- Question: How are these tubes repaired
- Response: Some type of plugging is the common method for repairing flawed SG tubes. We are not directly involved with the German fleet so we do not know exactly how they repair tubes.
- Primary-to-secondary leakage shall be monitored.

# Public Information on SG Inspections in Russia

- No regulatory requirements for SG inspections
- The SG manufacturer recommends that each SG be inspected every four years
  - 100% of tubes inspected within a 12-year interval
  - Bobbin coil probes are used
- If primary-to-secondary leaks are detected, additional SG inspections are performed using either visual or hydro-luminescent methods.
  - For visual inspections, the secondary side of the leaking SG is drained and pressurized with gas. Cameras would then be used to look for bubbles.
  - For hydro-luminescent inspections, a fluorescent substance is added to the secondary side, which would then be pressurized. The primary side would be drained, and the tube ends examined visually for signs of the substance.
  - Question: Is the hydro-luminescent method used in the US
  - Response: No, it is not used due to come contamination concerns.
  - Question: What level of leakage can be identified using a secondary side hydro test?
  - Response: We are not able to share exact levels but the US fleet has been successful finding leaking tubes.

# Public Information on SG Inspections in Slovakia

- All tubes were to be inspected prior to service.
- Subsequent inspections are performed every “4−6 years / fuel cycles.”
- Inspections typically performed using bobbin probes, with specialized probes (i.e., rotating or array probes) applied only in exceptional circumstances.

# Public Information on SG Inspections in Slovenia

- All tubes are inspected full length with bobbin coil probes.
- Rotating pancake coil probes are used for:
  - Row 1 and Row 2 bends
  - Hot leg transition zones
  - Preheater region
  - Confirm any bobbin indications at the TSPs.

# Public Information on SG Inspections in Spain

- Regulated by the Nuclear Safety Council
- Licensees are responsible for establishing and maintaining a program to confirm the function of safety-related equipment
- The Council reviews each program to verify that the program is in accordance with applicable regulations
- Every 10 years, the Council conducts period safety reviews of each nuclear plant
- Inspection Requirements
  - 100% preservice
  - 600TT units – 20% every outage
  - 800NG – 9% every outage

# Public Information on SG Inspections in Sweden

- Inspection Requirements
  - 100% preservice
  - Yearly inspections include a random sampling of 15 – 17% of the tubing
  - 20 – 100% of regions such as the hot leg top of tubesheet

# Public Information on SG Inspections in Switzerland

- Inspection requirements for Alloy 690TT tubing
  - 100% preservice
  - 100% of two of the three SGs every four years

# Summary

- Differences in safety standards
  - Different value judgments regarding both analysis methods and the degree of certainty required for safe operation have led to different performance criteria as well as different acceptance criteria
  - More conservative inspection requirements (e.g., shorter inspection intervals and/or larger inspection scopes) would allow for correspondingly less conservative acceptance criteria, permitting fewer repairs during a given inspection.
- Differences in SG design and materials
  - Improved materials and design features can allow less conservative fitness for service requirements
- Increased Experience
  - Required inspection scopes and frequencies can be increased with detected degradation or decreased with the lack of detected degradation over time (e.g., as has been implemented commonly in the US).

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# US Methodology for SG Aging Management

NUCLEAR

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Steam Generator Management and Technology Workshop
Shanghai, China
July 7-9, 2025

# US NRC Provides the Framework for License Renewal and Aging Management

- Generic Aging Lessons Learned (GALL) Report, NUREG-1801, R2
- Standard Review Plan for Review of Subsequent License Renewal Applications for Nuclear Power Plants, NUREG-2192
- Companion document to Generic Aging Lessons Learned for Subsequent License Renewal Report, NUREG-2191
- Review of these documents describe the US methodology for aging management
- Steam generators are addressed as one of the components that should be reviewed for aging management
  - Items of concern are covered in the following slides

# Generic Aging Lessons Learned (GALL) Report

- Provide aging management plans for steam generators
  - Section XI.M2, Water Chemistry
    - Lists the EPRI SGMP Water Chemistry Guidelines as the program to:
      - Mitigate loss of material due to corrosion
      - Mitigate stress corrosion cracking and related mechanisms
      - Mitigate the reduction of heat transfer due to fouling
      - Provide guidance for monitoring
  - Section XI.M19, Steam Generators
    - Lists NEI 97-06 and the SGMP Guidelines as the program to manage the aging of steam generator tubes, plugs, sleeves, and secondary side components

# SG Components Requiring Further Evaluation

- Table 3.1-1 in NUREG provides a summary of the aging management programs evaluated in the GALL-SLR Report pertinent to the reactor vessel, internals, and reactor coolant system.
- Specifically called out as needing further evaluation in a site-specific aging management plan:
  - Loss of material due to general pitting, and crevice corrosion in the shell assembly
  - Loss of material due to erosion
  - Cracking due to PWSCC in the channel head assembly and tubesheet

# Loss of Material Due to General, Pitting, and Crevice Corrosion in the Shell Assembly

- Most programs rely on the SGMP Secondary Water Chemistry Guidelines to mitigate corrosion
- Inspection is required if replacement of recirculating SGs create a new transition cone closure weld
  - Replaced only the bottom part of the SGs

# Loss of Material Due to Erosion

- Erosion could occur in steel SG feedwater impingement plates and supports exposed to secondary feedwater
- Evaluation is recommended to ensure aging effect is adequately managed.

# Cracking Due to Primary Water Stress Corrosion Cracking

- Foreign operating experience identified PWSCC in SG divider plate assemblies fabricated with Alloy 600 material and 600 weld materials even with proper water chemistry control
  - For units with divider plate assemblies fabricated of Alloy 690 and Alloy 690 type weld materials, a plant-specific aging management plan is not necessary.
  - For units with divider plate assemblies fabricated of Alloy 600 or Alloy 600 type weld materials, if the analyses performed by the industry (EPRI 3002002850) are applicable and bounding for the unit, a plant-specific aging management plan is not necessary.
  - For units with divider plate assemblies fabricated of Alloy 600 or Alloy 600 type weld materials, if the industry analyses (EPRI 3002002850) are not bounding for the applicant's unit, a plant-specific aging management program is necessary or a rationale is necessary for why such a program is not needed.
    - A plant-specific AMP (one beyond the primary water chemistry and the steam generator programs) may include a one-time inspection that is capable of detecting cracking to verify the effectiveness of the water chemistry and steam generator programs and the absence of PWSCC in the divider plate assemblies.

# Cracking Due to Primary Water Stress Corrosion Cracking

- Cracking due to PWSCC could occur in SG nickel alloy tube-to-tubesheet welds exposed to reactor coolant
- For Alloy 690TT SG tubes and cladding of Alloy 690 type material, a plant-specific aging management plan is not necessary
- For units with Alloy 690TT SG tubes and cladding of Alloy 600 cladding material, a plant-specific aging management plan is necessary unless the industry's analysis is applicable
  - Chromium in tube-to-tubesheet weld is approximately 22%
  - Tubesheet primary face is in compression
- SG program should include visual exams of channel head assembly including tubesheet and tube-to-tubesheet welds

# Questions

- What other inspections are recommended for channel head other than visual?
- Response: The industry provided results of testing in EPRI Technical Report 3002002850, publicly available, which determined that visual inspections were adequate to identify gross degradation. The NRC documented in LR-ISG-2016-01 that as long as plants are bound by the EPRI study, visual inspections are acceptable.

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# Discussion of Declining SG Performance and Deposit Effects

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Shanghai, China
July 7-9, 2025

# Background

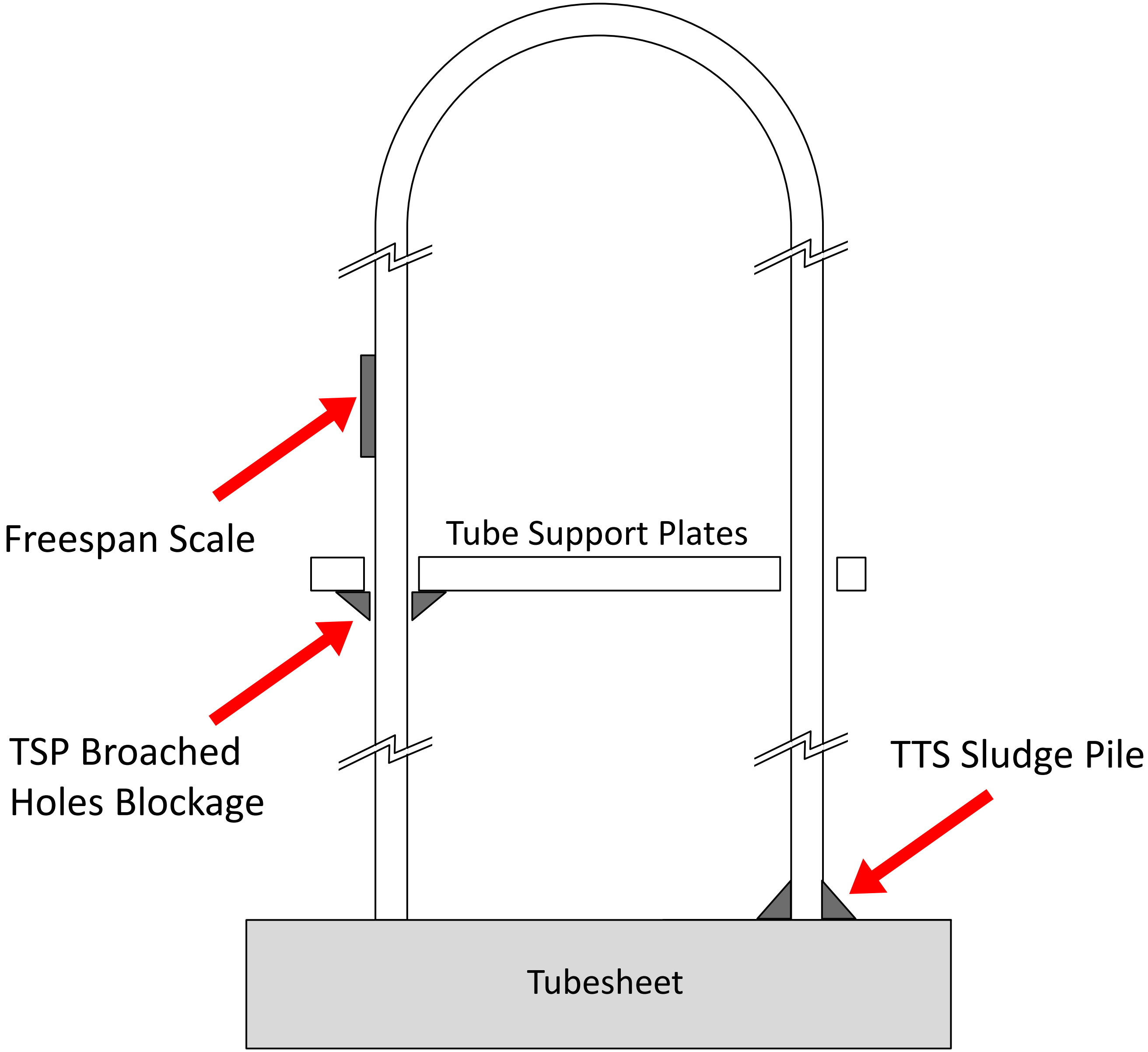
- SG Integrity is ensured through implementing a program such as NEI 97-06
  - NEI 97-06 does not govern issues regarding ability to generate output steam
- Performance declines in SG strongly affected by deposit buildup
  - Other factors, such as tube plugging, can affect performance but only when large number of tubes are plugged
- Deposit build up, if severe, can affect tube integrity

- United States Nuclear Regulatory Commission (US NRC) Letter IN-2007-37 States:
  - Although there is no specific requirement for licensees to monitor, assess, or remove deposit buildup, there are requirements for licensees to maintain steam generator tube integrity. These integrity requirements are contained, in part, in plant technical specifications. Therefore, it is important to assess the deposit buildup in a steam generator and the effects that deposits will have on steam generator performance and tube integrity during normal operation and design basis accidents. Promptly identifying and removing significant deposit buildup may prevent a loss of tube integrity and may improve the thermal performance of the steam generator.

# Locations of Deposits In SG

Primary Locations of Concern for Deposits:

1. Tube Scale on the Freespan
2. Top-of-Tubesheet Sludge (TTS) Piles
3. Tube Support Plate (TSP) Broached Hole Blockage



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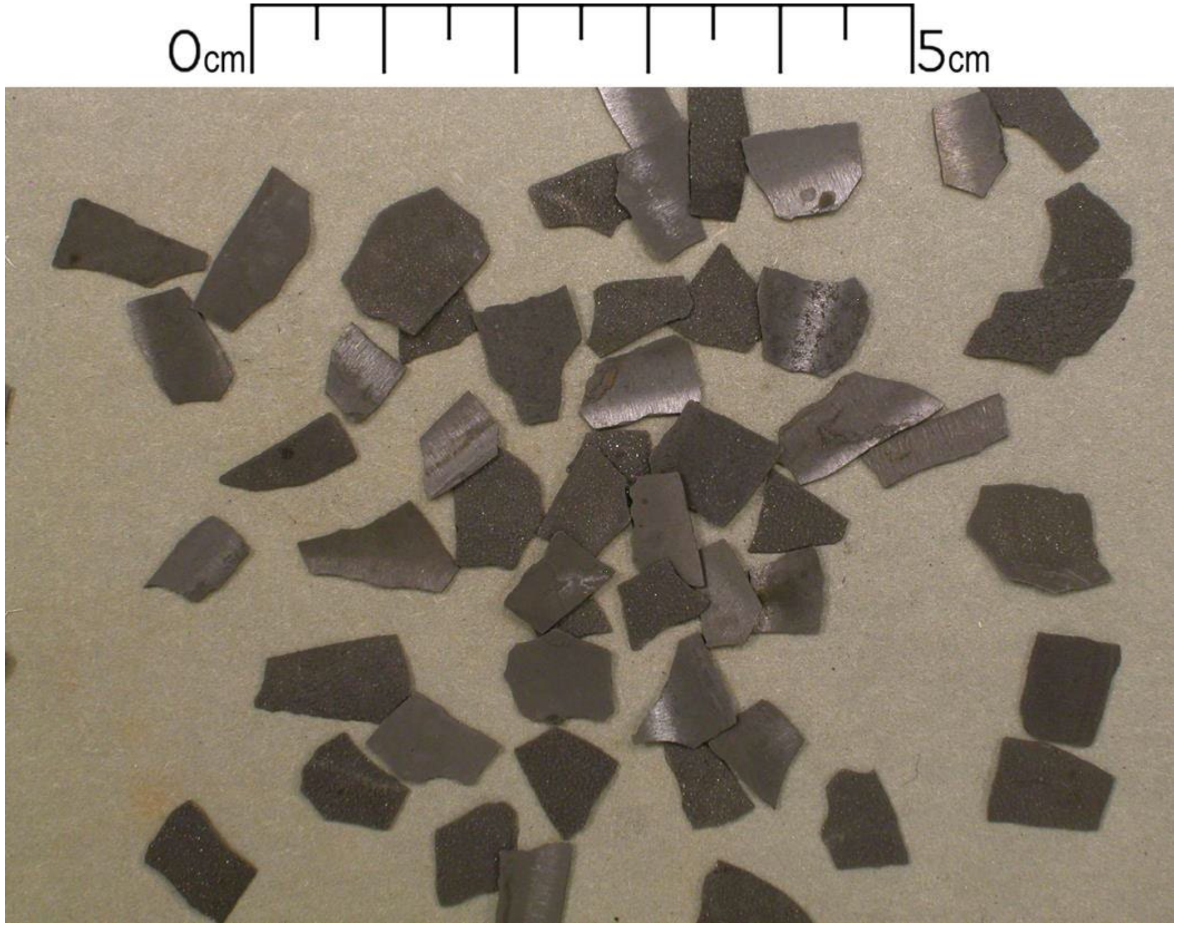
# Question on Slide 3

- Is there any ratio for the deposits at the three locations mentioned on Slide 3?
  - Response: No. The locations of deposits are design dependent and also depend on deposit management activities at units

# Tube Scale

- Tube scale is deposit buildup on the outer surface of a tube which is in contact with the secondary water
- As tube scale builds up, heat transfer can be reduced thus leading to decreased performance of SG
- Tube scale exfoliation occurs leading to production of scale flakes
  - These are typically very porous and break apart very easily
  - One plant has reported "hard" flakes which have caused wear on tubing
  - Analysis presented at a US NRC Meeting showed that of a sample of flakes from US plants, only 1 of over 60 flakes examined had similar characteristics (ML25079A163)




Images of Tube Scale Removed During Sludge Lancing

From 3002002794

# Top-of-Tubesheet Sludge Piles

- Deposits are known to form on the top-of-tubesheet (TTS) region on the intersection of the tube and TTS with a large collection often referred to as a sludge pile (EPRI Report 3002030563)
- Sludge piles are areas where contaminants can build up within the SG leading to increased risk of various contaminant related corrosion mechanisms
- Corrosion product formation at the TTS can expand into the tubes causing tube deformation (also known as denting)
- Denting is known to impact:
  - Increased risk of stress corrosion cracking (SCC) was observed in Alloy 600MA although no SCC has been observed in Alloy 690TT tubing (EPRI Report 3002002197)
  - Can limit the ability to pass eddy current probes through tubes impacting ability to inspect the entire SG

# Question on Slide 6

- Tubesheet sludge is typically controlled via slude lancing. How are tube scale deposits managed?
  - Response: That is the purpose of a plant’s Deposit Management Plan to layout how each plant will control all deposits.

# Tube Support Plate Broached Hole Blockage

- Broached tube support plates include flow holes near the tubes
- Deposits can preferentially form on these broached holes leading to decreased flow area and eventually complete blockage of flow holes
- When blockage occurs, flow within the SG is redistributed leading to increased flow in other areas of the SG
- This can lead to negative effects including:
  - SG liquid level oscillation
  - *Tube fatigue by flow induced vibration*
  - Reduced thermal efficiency

60% Blockage

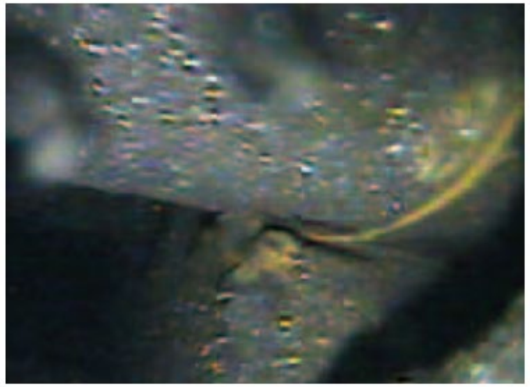
Partially Blocked STP Broached Hole

From 1022667

# Tube Fatigue Related to Broached Hole Blockage

- US NRC Information Notice 2007-37 (IN2007-37) discusses this topic
- A unit in France had a primary-to-secondary leak that was attributed to broached hole blockage
- Fatigue cracking, once initiated, can propagate rapidly over periods from hours to days

Cracked tube internal view



Cracked tube external view

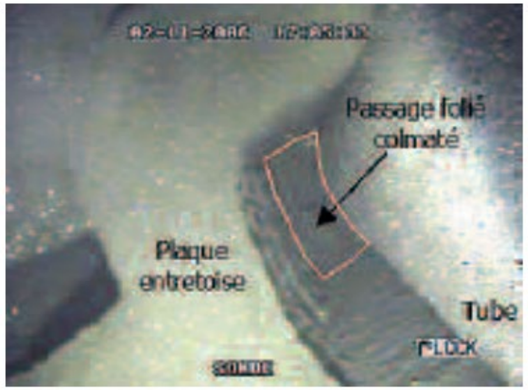



Illustration of clogging

Through-wall SG Tube Fatigue Crack Due to Blocked Broach Holes

From 2006 ASN Annual Report

# Deposit Management

- Given the potential impact of deposits, plants are recommended to have a plan to manage deposits
- Aspects of management include:
  - Estimating buildup of deposits in SG
    - Eddy current or visual examinations
    - Corrosion product measurement and tracking
  - Minimizing iron transport to SG (information in Secondary Water Chemistry GLs, EPRI Report 3002010645)
  - Looking for early indications of previously discussed issues or take actions to keep local deposits low such as SG water level oscillations
    - Exact onset of the phenomenon discussed is usually unit specific
  - Performing chemical cleanings (as needed)



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# Questions on Slide 10 (1 of 2)

- Which of the three locations mentioned is the most important?
  - Response: Each region can derive different consequences and in different designs different regions can be limiting. So EPRI would recommend evaluation all three to ensure that plant operators can find the most limiting.
- In EPRI's experience, what will be the most common approach to remove deposit? What is the best frequency for that?
  - Response: Sludge lancing is the most common method for deposit removal and focusses on the TTS location. Frequency varies by sites. So, there is no exact answer for this question.

# Questions on Slide 10 (2 of 2)

- What is the strategy for localized cleaning in the SG?
  - Response: For regions other than the TTS, there are not many effective methods for localized cleaning.
- When should chemical cleaning be performed?
  - Response: Chemical cleaning can be done at different times. Each plant should have a program to find the best time to perform the chemical cleaning.
- Any other actions to remove deposits other than chemical cleaning?
  - Response: None as effective for large scale deposit removal.

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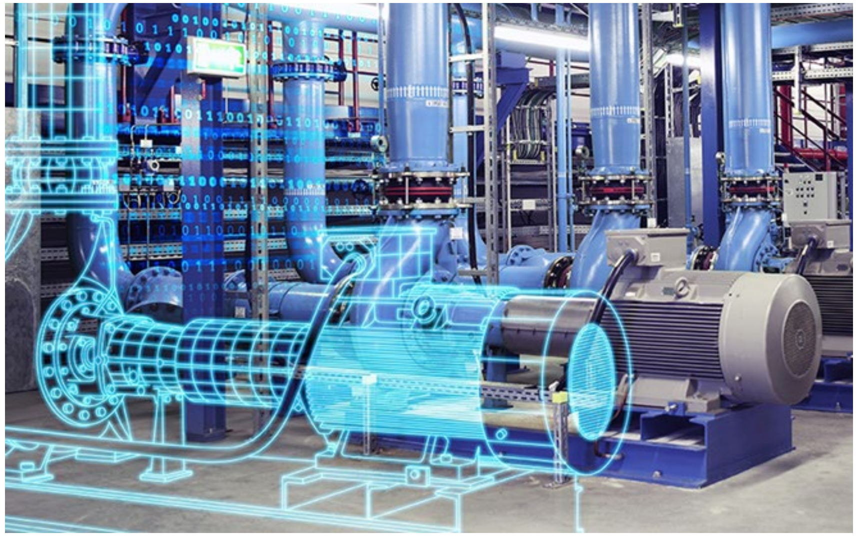
# Nuclear Plant Steam Generator Digital Twin

Brent Capell
Principal Team Lead

Steam Generator Management and Technology Workshop
Shanghai, China
July 7-9, 2025

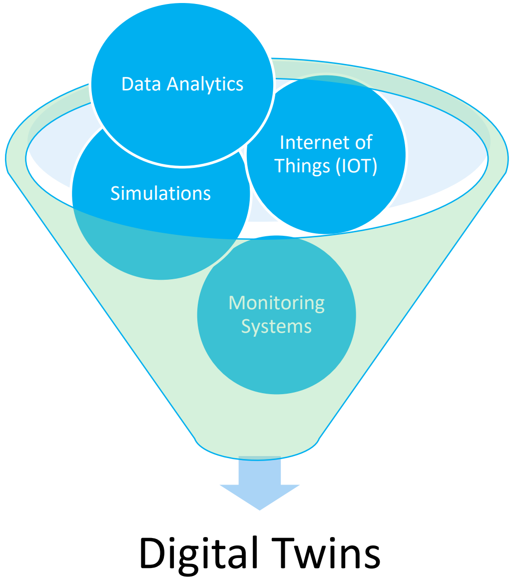
# What is a Digital Twin?

- A Digital Twin is a replica of the physical asset that is tracked and can undergo similar environmental and loadings conditions
  - A key attribute of a digital twin is that there is an exchange of information between a physical and the digital representations to take into account unique changes for each asset
- The Digital Twin is much more flexible to work with and can be used to simulate a variation of scenarios with much lower risk and confidence than the physical twin



# Simulation Vs. Digital Twin

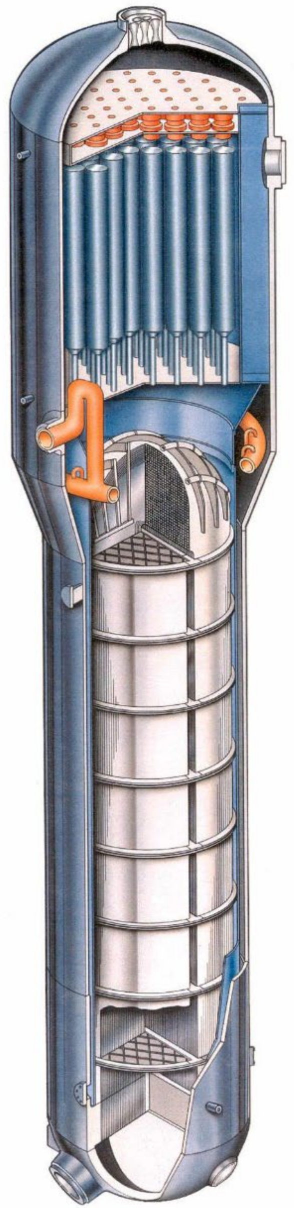
- Simulation is an essential and needed part of the Digital Twin to model the physical asset (physics based and/or data driven models)
- Simulation is typically used for design and uses assumptions to predict an outcome under various environmental and loading conditions
- Digital Twin is more than a simulation by taking advantage of monitoring technologies to interact with its physical asset
- Digital Twin can be used to mimic, learn, and predict physical asset behaviors to manage the various stages of the asset life cycle
- Digital Twin is a tool to understand what's happening vs. what could happen
- Elements of digital twins:
  - ✓ Data repository
  - ✓ Advanced modeling (physics based) or (data driven) analytics
  - ✓ Monitoring systems and data feed (Connectivity)



# Digital Twin Technology for Nuclear Plant Steam Generators

# Nuclear Plant Steam Generators Offer Opportunities for Digital Twins

- *Steam Generators* have many characteristics that make them a good target for Digital Twins
  - Want to make predictions of future performance/behavior
  - Operational differences make each steam generator unique
  - Available sensor data/design data
  - Simulation models available for many aspects
- The United States Nuclear Regulatory Commission (US NRC) has stated in meetings that they feel Steam Generators are a prime candidate for a Digital Twin
- But…



# Steam Generators are Also Very Complex

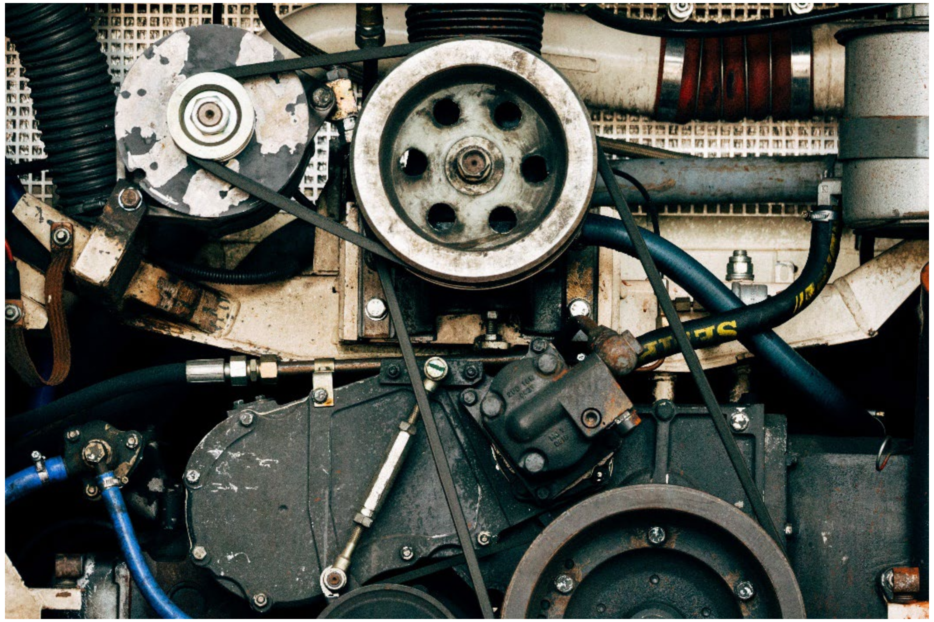



Photo by Michal Matlon on Unsplash

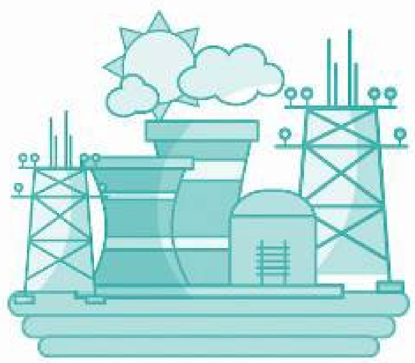
- What is really meant by a “Steam Generator Digital Twin”?
- *Some* aspects that could be included:
  - Steam output performance
  - Iron transport/deposition/removal
  - Broached hole blockage
  - Initiation/growth of SCC
  - Tube-to-Structure wear
  - Onset of water level instability
  - Secondary side component degradation
  - Other tube degradation mechanisms
  - NDE program optimization
  - Water Chemistry optimization
  - Physical modelling of components for maintenance planning

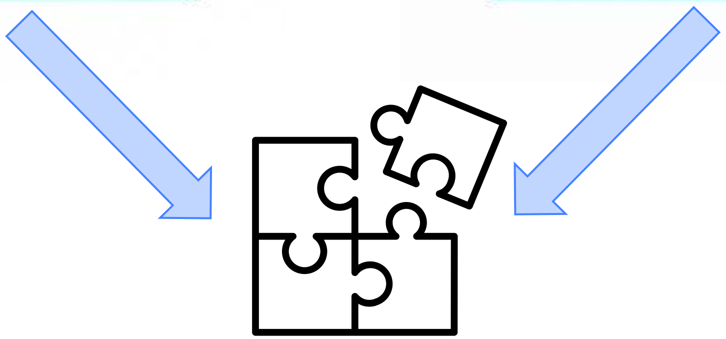
**To Do Everything at First Is Impractical!**

# SGMP Vision of SG Digital Twin

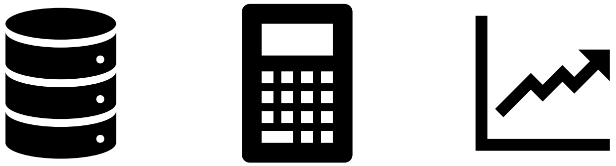
Physical Asset

Digital Twin





How to Make a Steam Generator Digital Twin? Role of *Central Repository* and *Predictive Models*?



- Problem:
  - Each SG has a unique operating history and requires individual care and tracking
  - Multiple different aspects such as SG integrity and performance could be tracked and the future state predicted
- Digital Twin Platform as a Solution:
  - A digital twin platform that allows to allow progressive construction of a SG digital twin is the most efficient path forward
  - This will allow:
    - *Storage system* for past relevant data
    - A platform for incorporation of *modelling and simulation* tools
    - Ability to use *data analysis* of past data to enhance predictive capabilities

# Evaluation of Digital Twin Framework for SG Digital Twin

- EPRI evaluated the needs for an SG digital twin framework in a report published in 2024
  - EPRI Report ID 3002029367

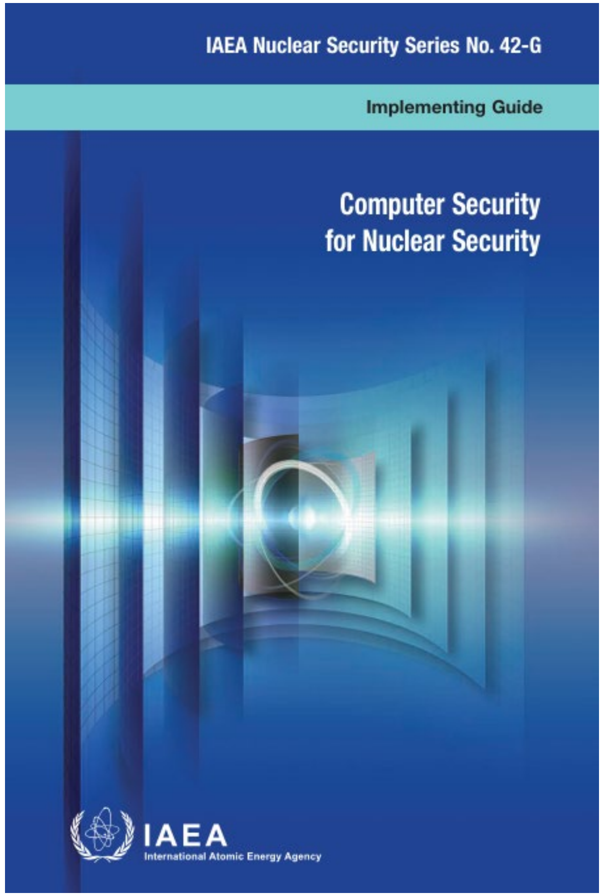
- Incorporates discussion of local storage as well as a cloud-based system

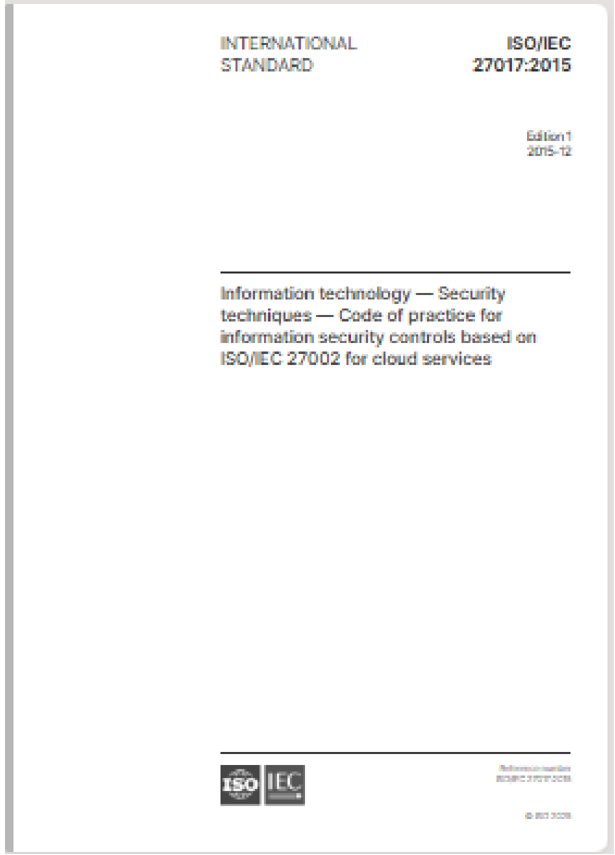
- The next few slides will cover aspects discussed in this report

# Regulations and Requirements

- Nuclear plant data, local and cloud storage based, is governed around the world by numerous data storage standards
  - IAEA Standards
  - ISO/IEC Standards
  - US Specific Regulations and Standards

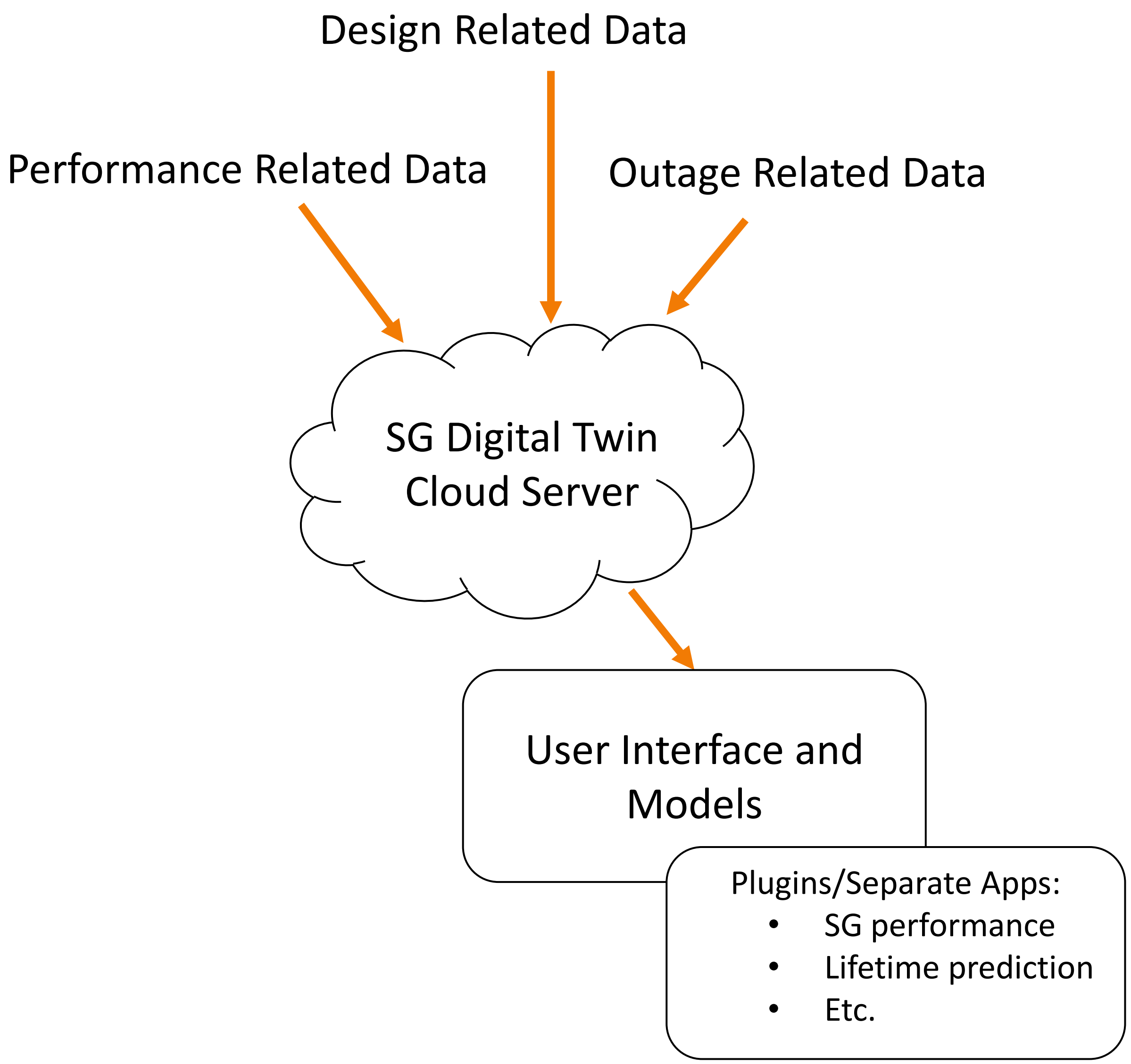
- Various applicable standards are presented so SG digital twin developers are aware



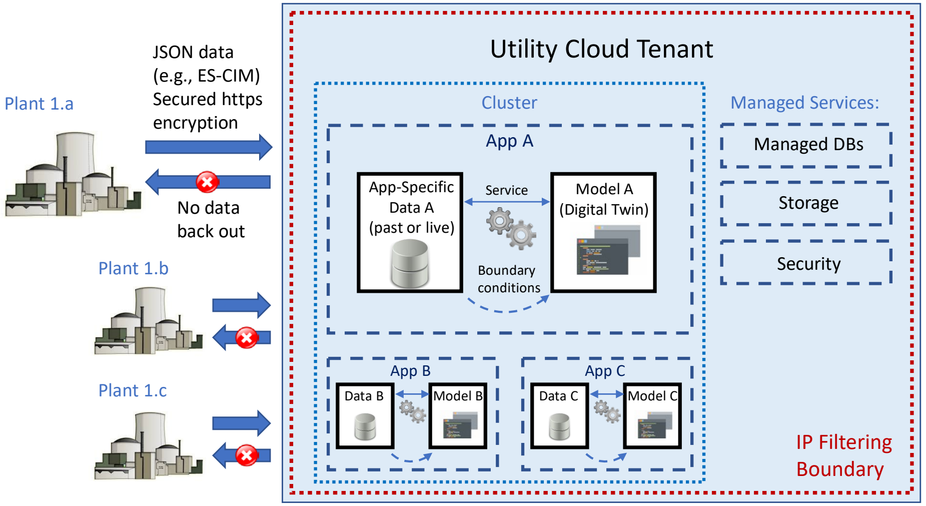



# Principles for SG Digital Twin Cloud Deployment

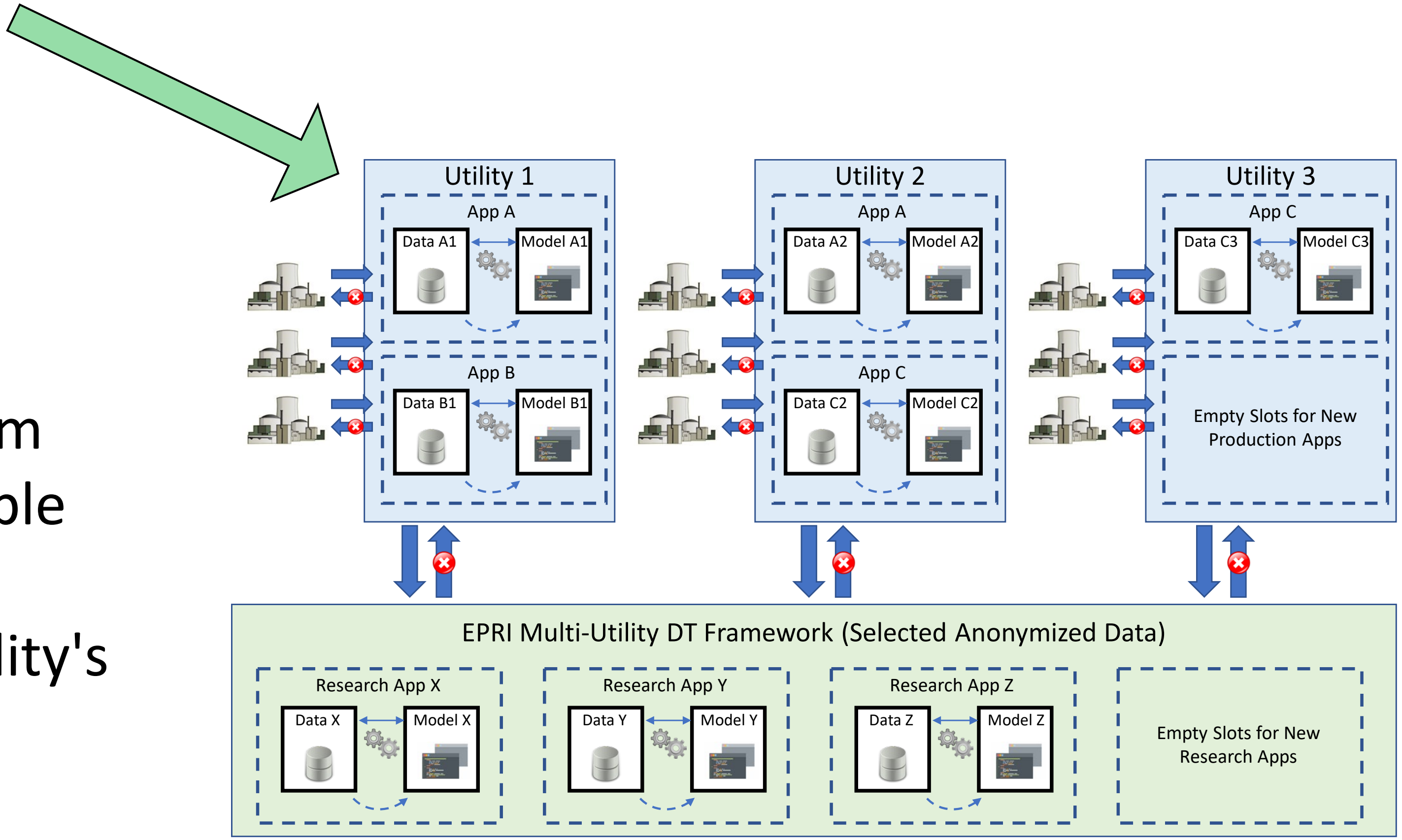
- Provides 13 principles as best practices to for a cloud-based system
  - Examples:
    - Data minimization and lifecycle control
    - Access controls
    - Software development lifecycle
- Discusses advantages of cloud-based module deployments and what additional resources are needed to implement them



# Discussion of Single and Multiple Utility Applications




- Presents discussion of how to setup a data storage system for a single utility with multiple units




- Discusses how a common platform could then be expanded to multiple utilities while maintaining data protection for each individual utility's data

# SG Digital Twin Summary

- SGMP has been investigating its role in making a steam generator digital twin platform
  - Need to define key first steps and focus work to prevent SG digital twin from being too much
- Report published:
  1. Summarizes data storage requirements and applicable international standards
  2. Describes principles for a successful cloud-based system
  3. Describes a system to store data for one utility with multiple units
  4. Discusses how EPRI could host a system and use multiple utilities data for research projects or simulation enhancements without jeopardizing data security


**EPRI Report ID 3002029367**

# Questions from Presentation (1 of 3)

- What is the current development status of digital twin in the US?
  - Response: EPRI is leading the industry effort.
- Is there a way to collaborate with EPRI for the digital twins? There is an on-going project in China starting in 2022.
  - Response: EPRI will investigate the ability to work together on SG Digital Twins
- Have there been any actual applications of digital twins for SGs?
  - Response: None that EPRI is aware of in the US.

# Questions from Presentation (2 of 3)

- Can you describe the main objective of the digital twins? What would EPRI like to achieve?
  - Response: Development of a system with a central location with data storage upon which additional modules can be added on various specific simulation tools for aspects such as predicting the changes in the SG performance.
- There are two ways to model for digital twins: data learning (machine learning or simulation models) and using historical data for projections. Which one is more applicable?
  - Response: It depends on the situation as each method has times when it works better. There is also a third option, hybrid methods. These combine the two but exactly how that is done is a still to be determined.

# Questions from Presentation (3 of 3)

- Another challenge is the data from the plant. Not all data can be monitored on-line. Do you have any recommendations?
  - Response: Data transfer is still an area where there are many open questions so there are not specific recommendations at this time.

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# Common Steam Generator Eddy Current Probes

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Steam Generator Management and Technology Workshop
Shanghai, China
July 7-9, 2025

# Principles of Eddy Current Testing

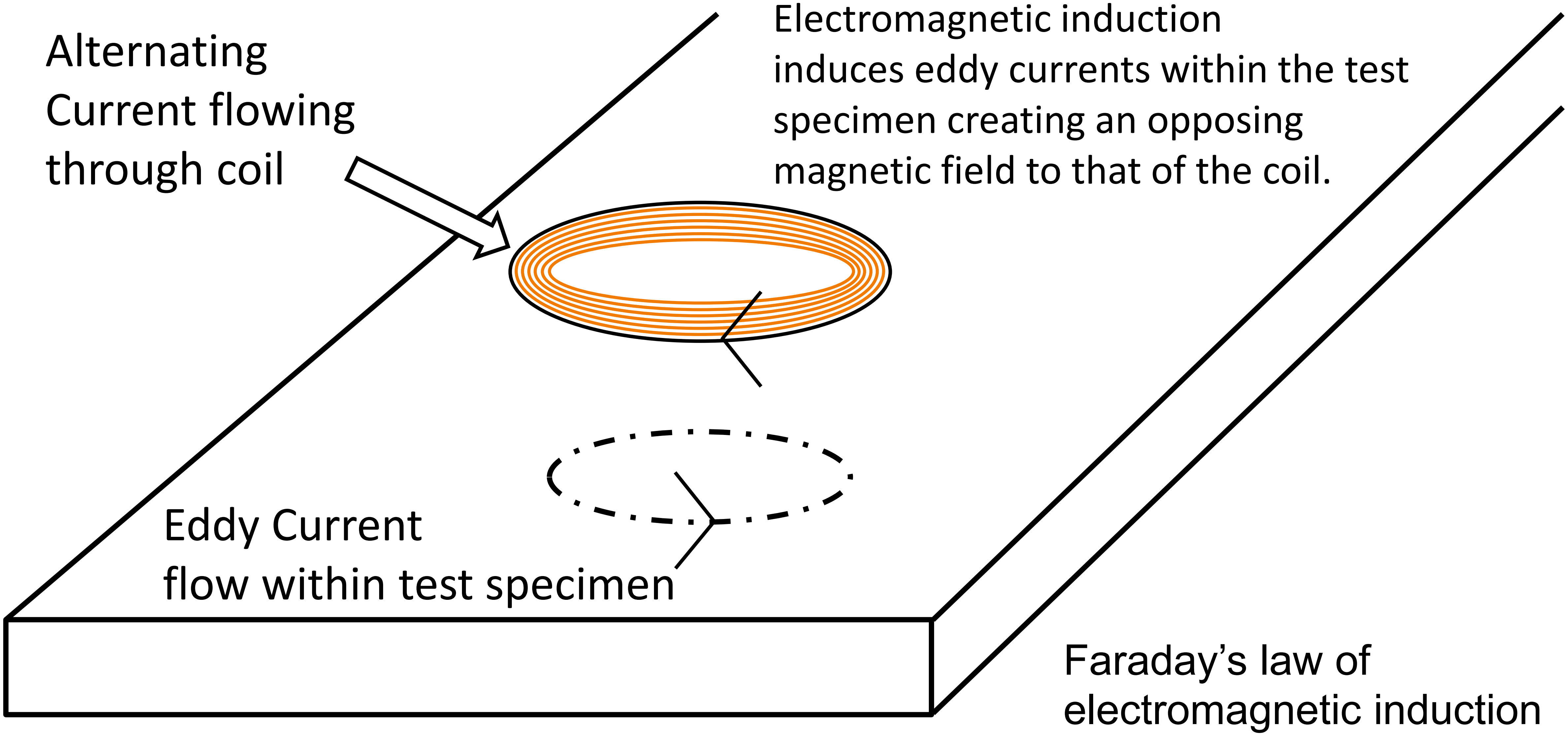
An alternating current flowing through a coil creates an alternating magnetic field.

When the coil is brought within close proximity to a conductor, the primary alternating magnetic field of the coil induces electrical currents in a closed circulatory pattern within the conductor (eddy currents).

The eddy currents flowing within the conductor generate a secondary alternating magnetic field, opposing that of the primary field which induced the current flow.

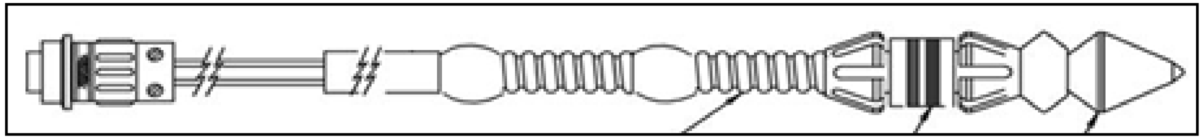
When a discontinuity (flaw) or inhomogeneity whose conductivity differs from that of the test specimen is present, the eddy current distribution is altered. Consequently, the impedance of the coil changes relative to its value obtained with an unflawed specimen.

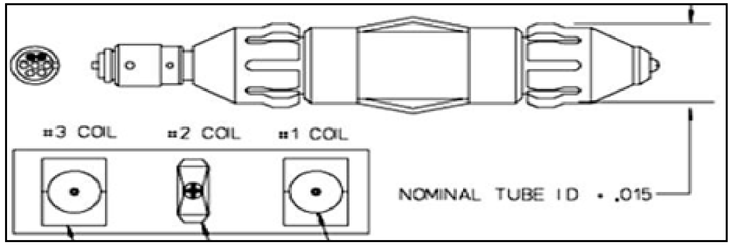
# Eddy Current Generation and Flow in a Conductor

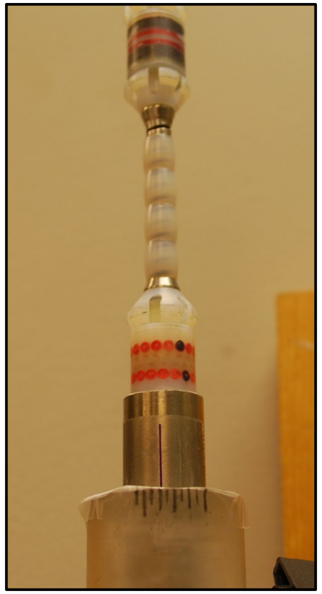


# Three Common SG Eddy Current Probes

- Bobbin Coil
- Rotating Probe Coils
  - Pancake coils
    - 115 and .080 High frequency
  - +Point™ coils
  - Rotating Ghent 3-4
- Array Probes
  - X-probe
  - Intelligent probe

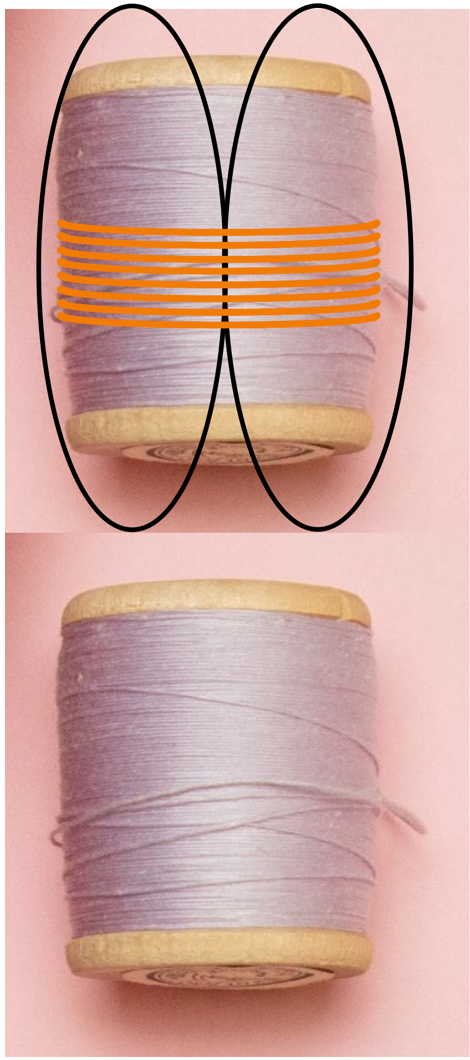




# Bobbin Coil Eddy Current Probes - Basics

- Bobbin probes consist of a pair of coils of magnetic wire wound circumferentially
- An excitor pulses the electric field in the coils which excites eddy currents in the SG tube
- When the circumferential fields produced interact with a defect (crack, surface volume flaw) the field in the excitor is altered and produces a signal that can be recorded and analyzed
- The Bobbin probe can operate in both differential or absolute mode.
  - In differential mode a comparison is preformed between the two coils for detection of quick acting (short) discontinuities within the material under test.
  - In absolute mode one of the coils is compared to an external reference for detection of slow acting (longer) changes in properties of the material under test.

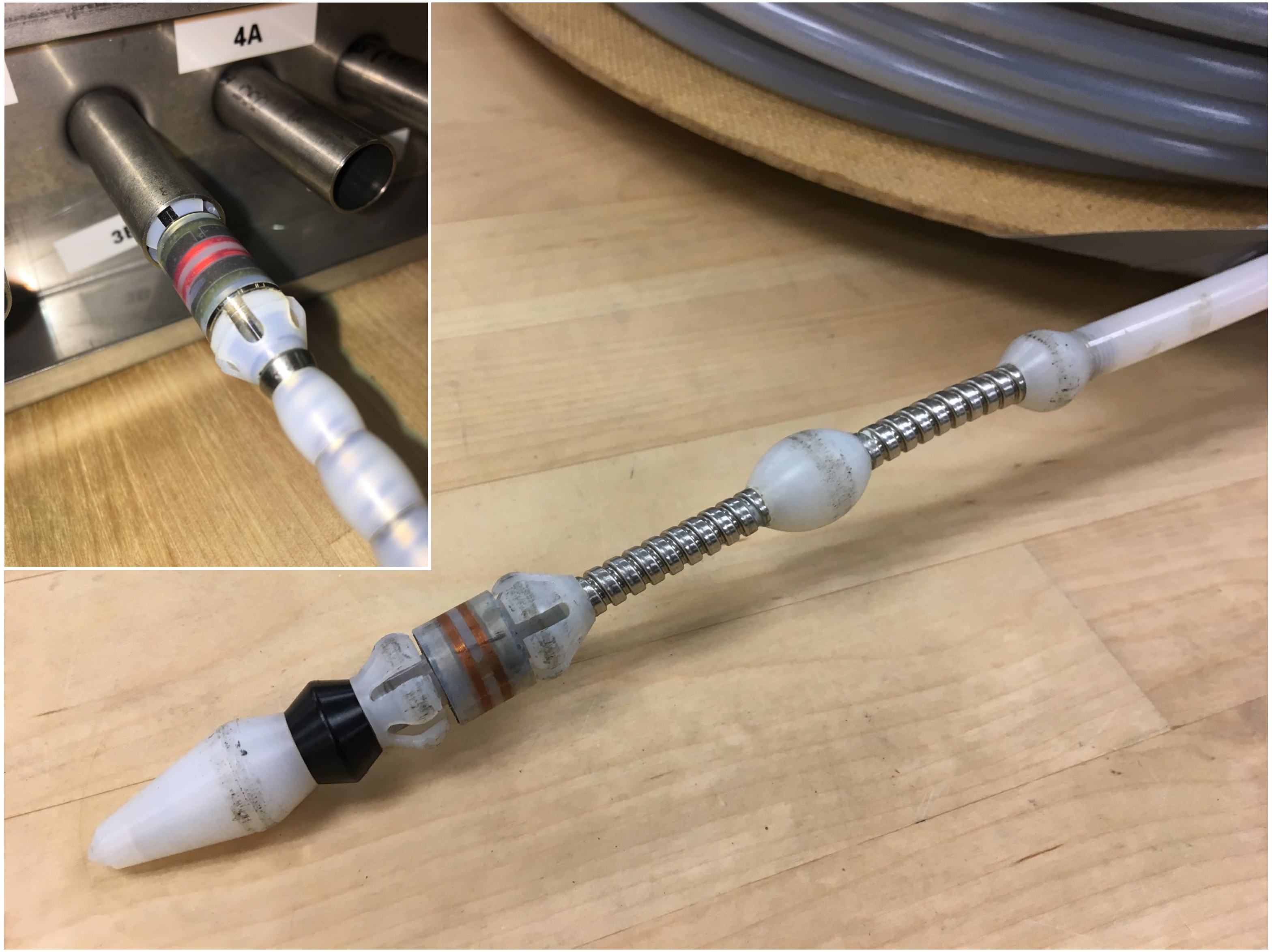


Magnetic Field created 90° to coil windings.

This induces an electrical current flow within the test material orientated In the same direction as the bobbin probe coil windings.

Sensitive to test material axial discontinuities, but not circumferential.

# Bobbin Coil Steam Generator Tube Probes



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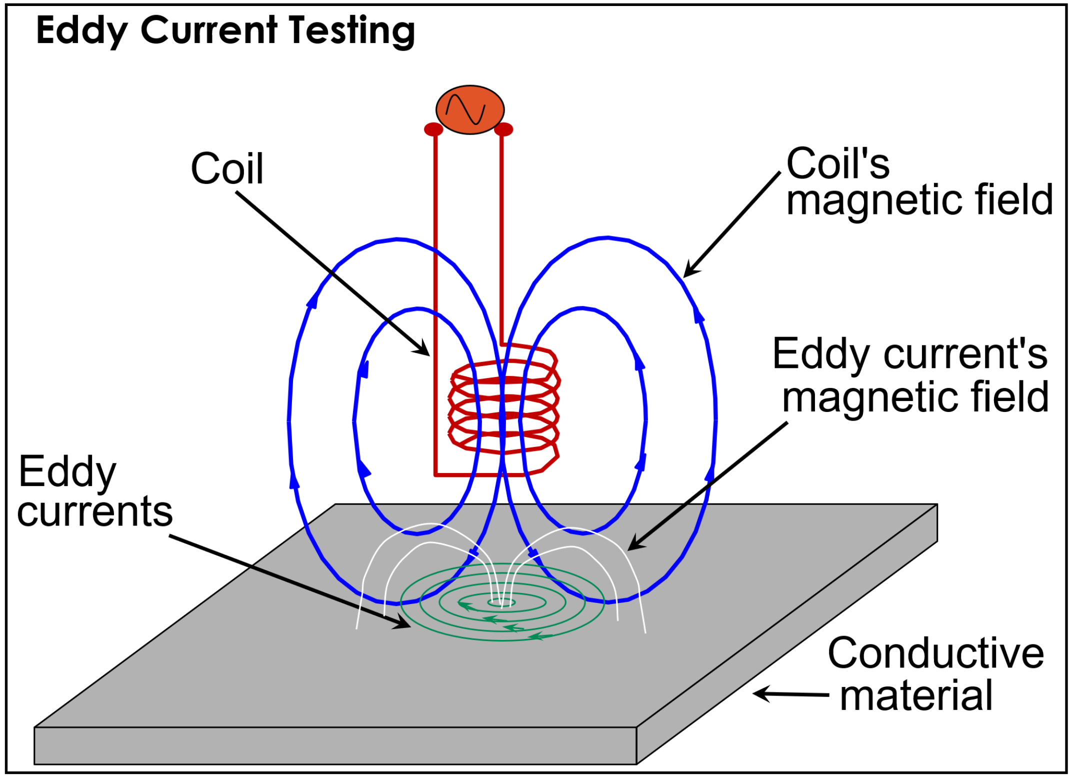
# Bobbin Coil Probes – Advantages and Disadvantages

- Advantages
  - Fast pull speed (near 3 m/sec)
  - Sensitive to axial and volumetric flaws
  - Single signal for analysis is relatively simple to process
  - Lowest cost of probe production

- Disadvantages
  - Limited detection capability for circumferential cracks
  - Cannot determine circumferential location of flaw
  - Large impact of tubesheet or tube support plates on signal which can make flaw detection difficult
  - Coil diameters need to fit through all of tubing including the u-bend region which has a decreased diameter that creates some “lift off” distance from surface that decreases signal strength

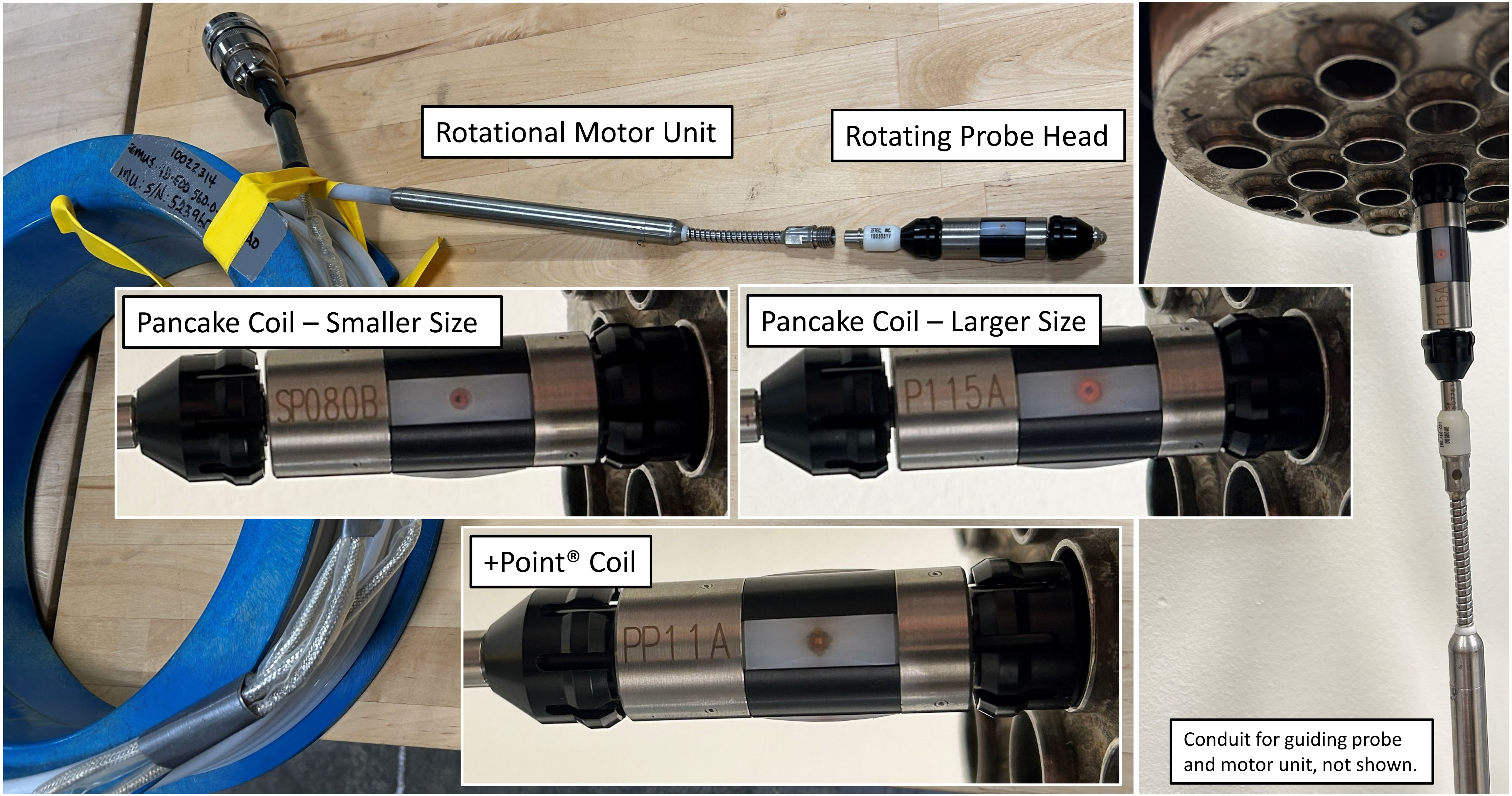
# Rotating Coils - Basics

- Two main types:
  - RPC coils include a circular coil positioned axially
  - +Point™ includes a pair of small coils with one pointing axially and one pointing circumferentially
- Excitation of the coils provides detection capability for axial, volumetric, and circumferential flaws
- Due to limited size of coils (few mm), they must be spun inside a tube to detect flaws around the whole circumference of the tube
  - For the length of the tube, this greatly decreases the pull speed since it must be slow enough to account for the spinning probe



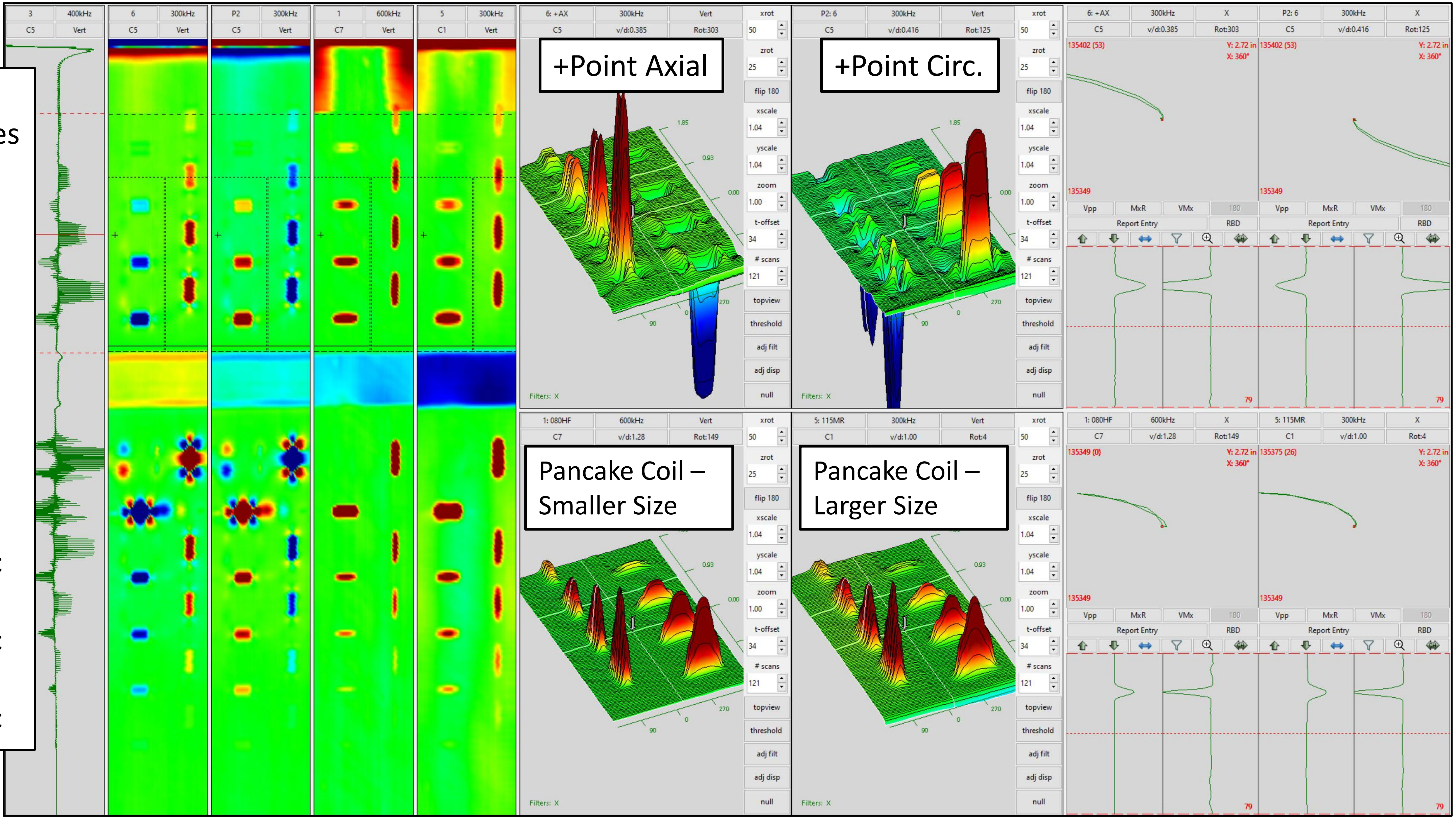

Area Being Examined limited to Coil Probe Size, Thus Coils Must be Rotated inside tubing to for Full Circumference Analysis

# Rotating Coil Steam Generator Tube Probes



# Example Data Visualization from Rotating Coil Probes

Cal. Std.
EDM Notches
20% ID Ax
20% ID Circ
40% ID Ax
40% ID Circ
60% ID Ax
60% ID Circ
TSP
100% Ax
100% Circ
60% OD Ax
60% OD Circ
40% OD Ax
40% OD Circ
20% OD Ax
20% OD Circ



# Rotating Coil Probes – Advantages and Disadvantages

- Advantages
  - Sensitive to axial and circumferential flaws
  - Highest flaw sensitivity for small flaws
  - Because probe rotates and is surface riding, coils are held in very close proximity to tube surface enhancing signal
- Disadvantages
  - Very slow pull speeds
    - Pull speeds reduced to ~12 mm/sec
    - Limit's ability to inspect full tube lengths or large numbers of tubes as required time would need to be significant longer than typical outages

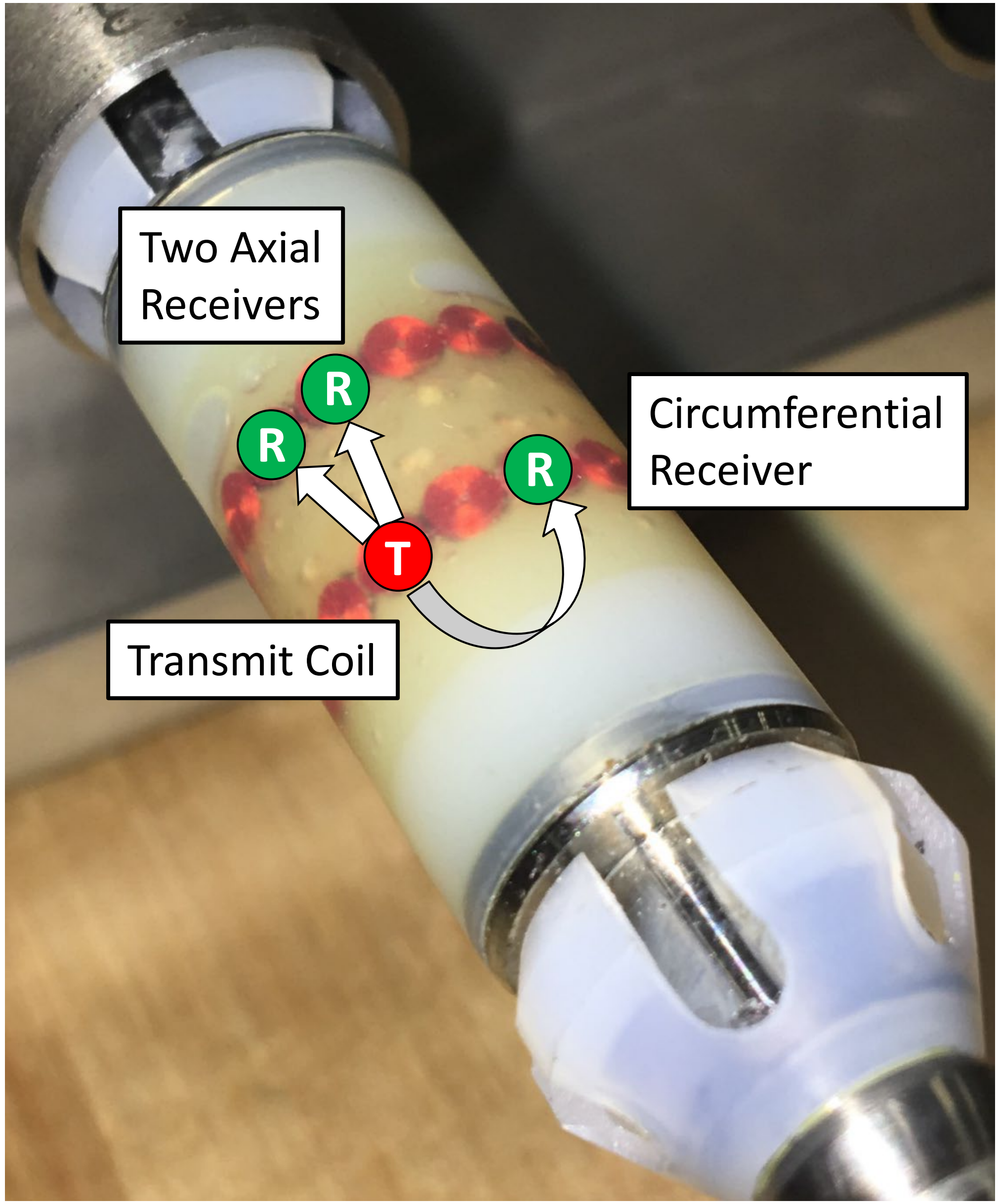
# Array Probes - Basics

- A series of small pancake coils are mounted in an array pattern and pulled within a tube
  - The coils are multiplexed together to simulate probe rotation
- The coils in the array are energized in a specific pattern where some coils act as transmitters and others are used as receivers which allows detection of axial, volumetric, and circumferential flaws
- A single probe with enough coil arrays to cover the entire circumference is pulled through the tube at a speeds approximately 1 m/sec

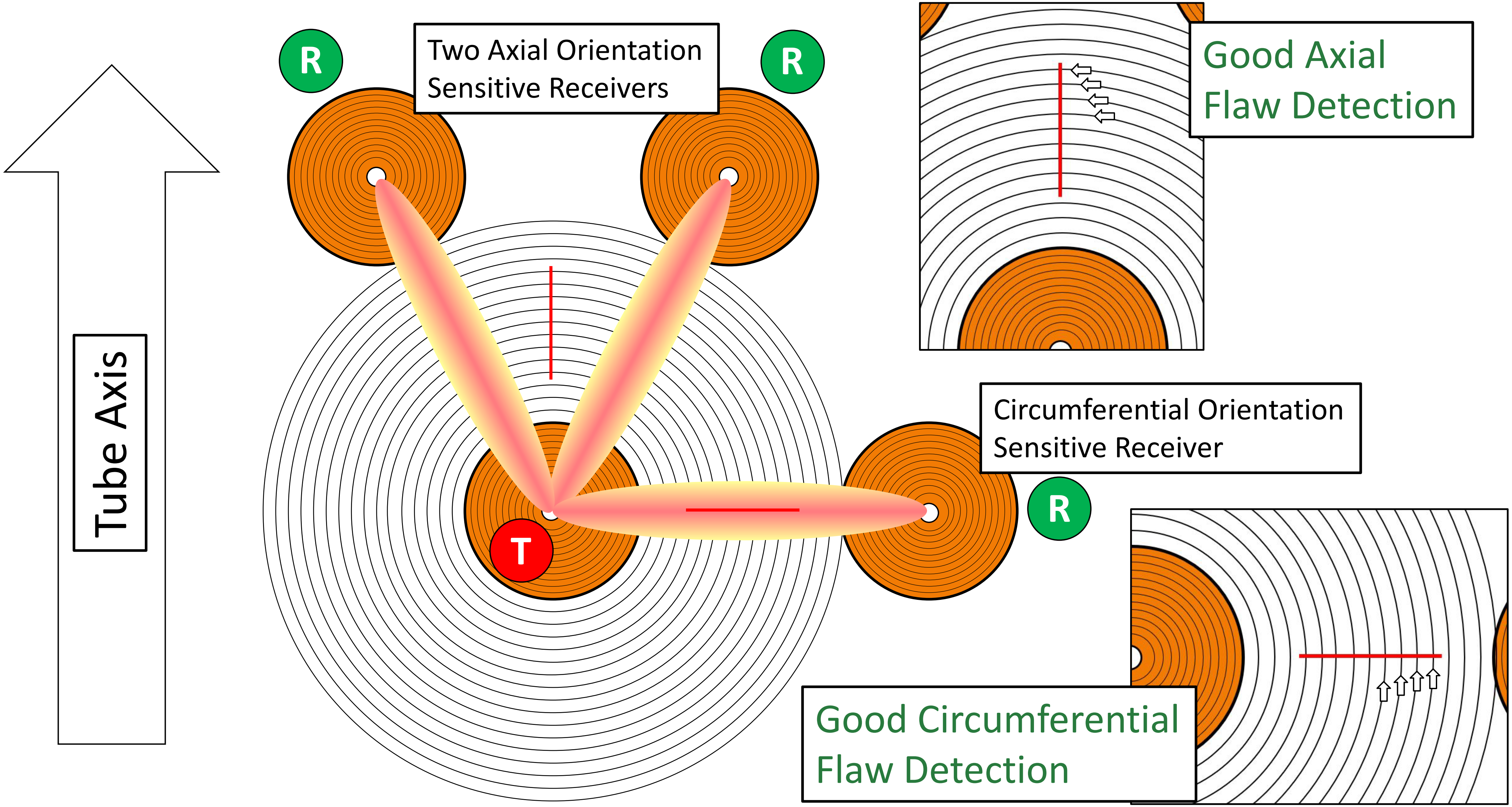
Array Coil Probe

# Array Coils

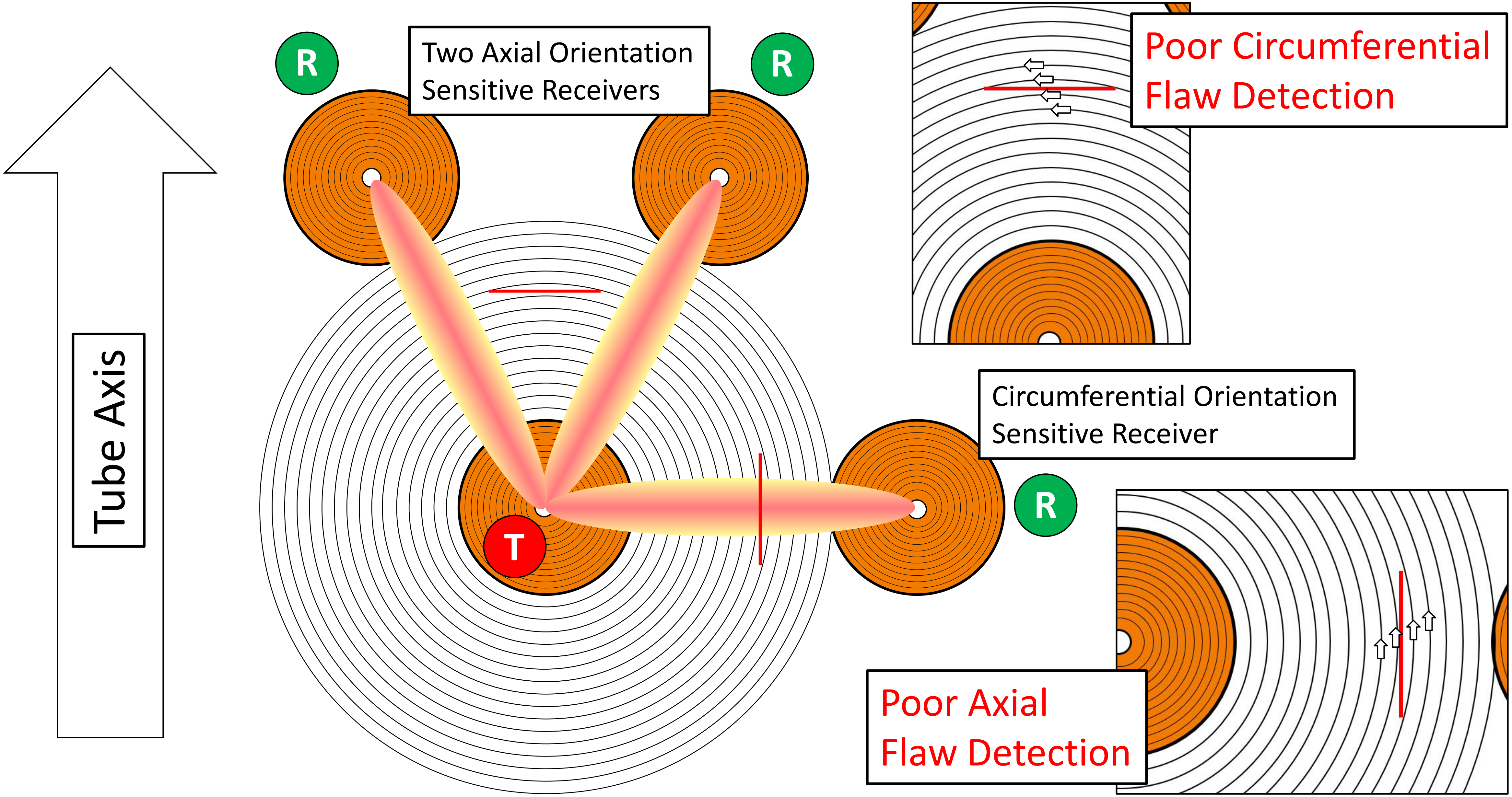

4A


Two Axial Receivers
R
R
R
T
Circumferential Receiver
Transmit Coil

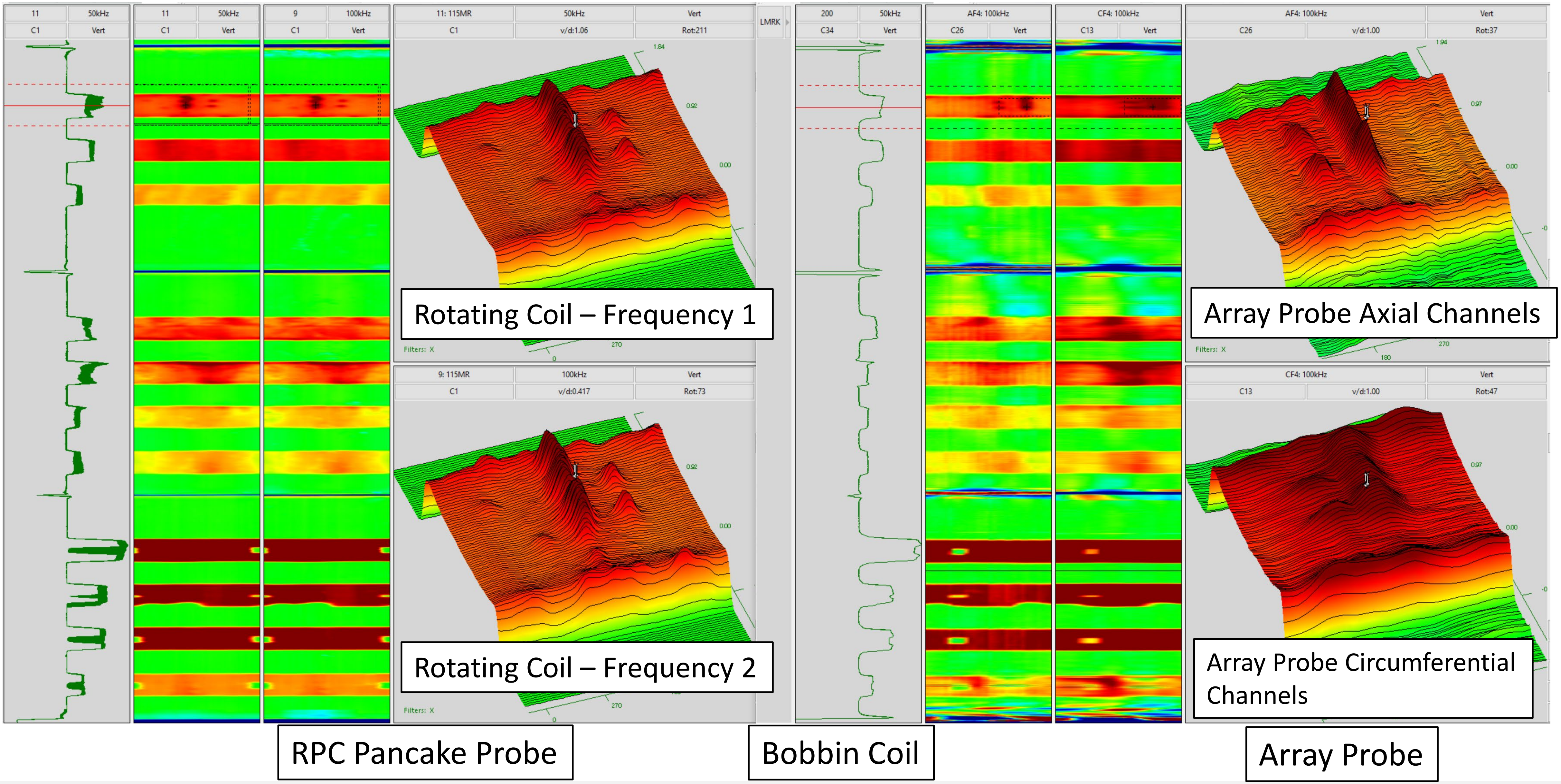
# Eddy Currents Flow Parallel to Coil Windings



# Eddy Currents Flow Parallel to Coil Windings



# Signal Strength Comparison – Rotating Versus Array Coils



# Array Probe – Advantages and Disadvantages

- Advantages
  - Sensitive to axial, volumetric, and circumferential flaws
  - Better flaw sensitivity than bobbin coils
  - Lower susceptibility to lift-off affect
  - Fast pull speed (approximately 1 m/sec)

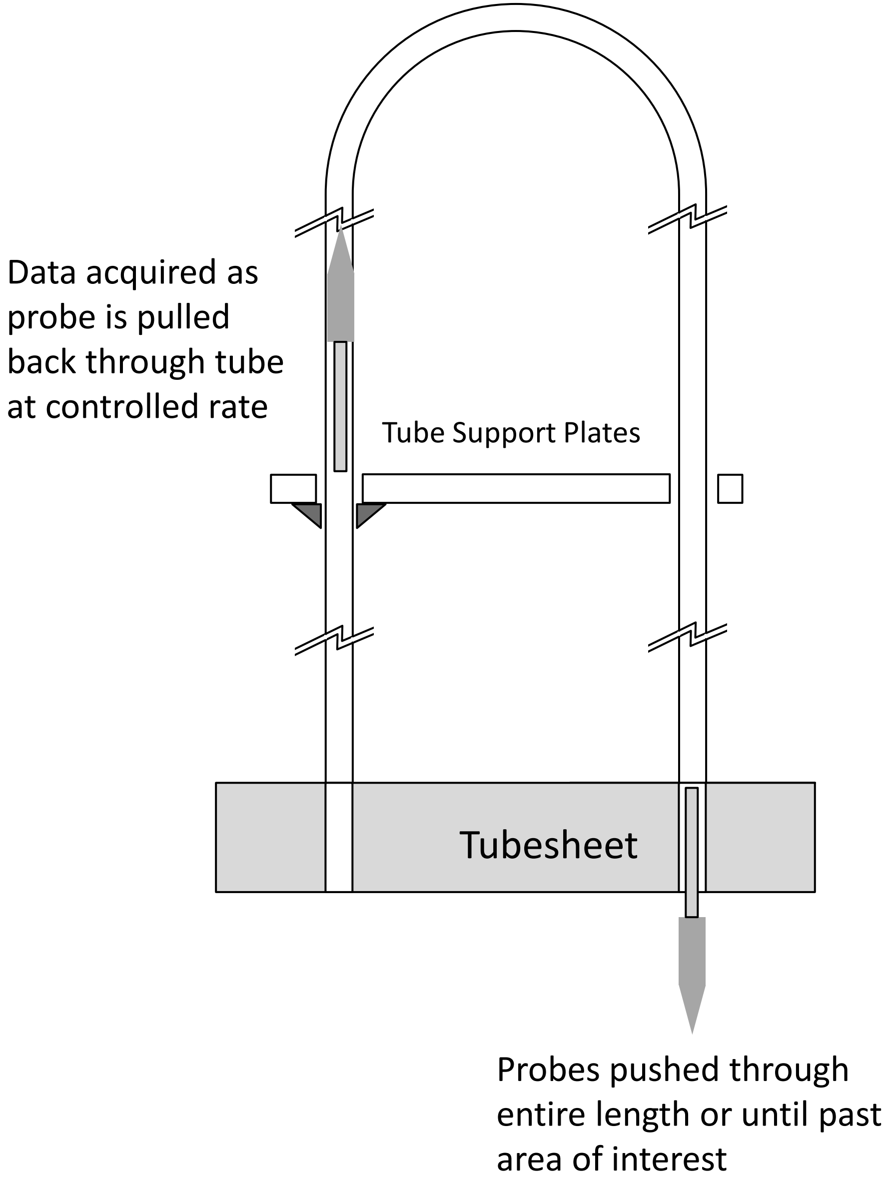
- Disadvantages
  - Use of arrays of coils creates areas of decreased sensitivity (amplitude crossover affect)
  - Flaw sensitivity could be slightly less than rotating probes
  - High probe cost
  - Large amounts of recorded data can make data storage and analysis more expensive

# Typical Eddy Current Data Acquisition Program

- Historically plants have used:
  - Bobbin coil probes for full length tube measurements
  - Rotating coils at top-of-tubesheet region if looking for cracking
  - Rotating coil probes at all special interest tubes (dents, dings, bulges)

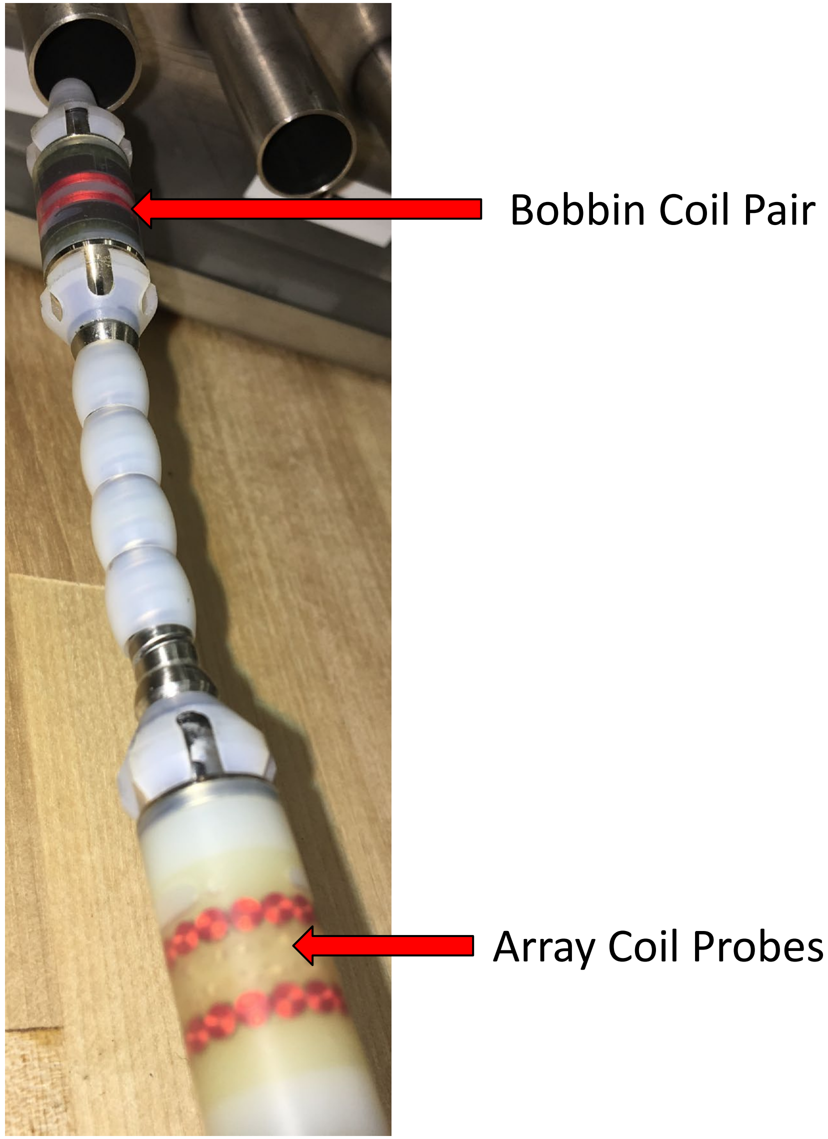
- Signal acquisition performed by

1. Probes are pushed mechanically through tube at high speed without acquiring data
2. Probes are pulled through tube for data acquisition with a controlled pull rate



# X-Probe Combination Probe

- The X-Probe can consist of a bobbin coil pair tethered to an array probe
- In some plants, data is acquired for both probe sets, but only the bobbin data is analyzed during initial inspection
  - If area of interest is located, array data can then be analyzed in that region to get more information
  - Plant can also choose to process full length array data and bobbin coil signals
- Rotating and seperate array coil probes are used at all special interest tubes (dents, dings, bulges)
- Rotating coil probes may also be used to verify or better characterize signals found by bobbin/array data



# Technical Specification Probe Type Requirements

- In general, technical specifications only require use of probes capable of detecting known or potential degradation
  - Up to plants to document why probes chosen meet this requirement
- Recent plant Technical Specifications changes allowed in the US by the US Nuclear Regulatory Commission (NRC) have increased reliance on “advanced probes”
  - “Advanced probes” defined as rotating or array probes
  - In some cases, plants looking for longer intervals between inspection must use 100% “advanced probes” inspections
    - Example, Alloy 600TT plants that have observed stress corrosion cracking (SCC) can skip one cycle after detection if “advanced probes” are used

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# In-service Inspections of Steam Generators

NUCLEAR

Sean Kil
Principal Technical Leader

Steam Generator Management and Technology Workshop
Shanghai, China
July 7-9, 2025

# Inspection Planning - Scope of Examination

- Identifying and documenting existing and potential degradation in planning for an upcoming outage
- Eddy Current Testing (ECT) scope is either 100% of all tubes during each inspection or <100% of all tubes during each inspection, however 100% of all tubes must be inspected prior to the end of the technical specification inspection period
- All tubing locations associated with existing and potential degradation mechanisms shall be inspected during each technical specification inspection period

2. Scope of Inspections

Inspections performed on all four SGs during the U2C28 refueling outage included:

- 100% eddy current testing (ECT) of all in-service tubes
- Visual inspection of channel head interior surfaces and all installed tube plugs
- Visual inspection of secondary side top-of-tubesheet region

Additionally, visual inspections were performed inside the steam domes of SG 22 and SG 23.

Example of inspection scope at 690 TT plant, Source: ML24295A135

# Inspection Planning – NDE Technique

- Select Non-Destructive Examination (NDE) technique to be utilized
  - For degradation mechanisms to be inspected, corresponding technique is selected
    - Examination Technique Specification Sheet (ETSS) is commonly used in the US.
    - Different ETSSs can be used for sizing and detection or degradation mechanism

| Table 2: NDE Techniques | | |
|---|---|---|
| **Degradation Mechanism** | **Detection Technique** | **Sizing Technique** |
| Support Wear - AVB | Bobbin<br>ETSS I96041.1 | Bobbin<br>ETSS 96004.1 |
| Support Wear - TSP | Bobbin<br>ETSS I96043.4 | Bobbin<br>ETSS 96004.1 |
| Support Wear - FDB | Bobbin<br>ETSS I96043.4 | Bobbin<br>ETSS 96004.1 |

Example of NDE Technique at 690 TT plant, Source: ML24295A135

# Tube Integrity Assessment

- Reported degradation indications by the ECT are assessed to
  - Check meeting Condition Monitoring (CM) limits for structural integrity
  - If dimensions of supporting structures are difference, each CM limit is estimated for each supporting structure

| Degradation Mechanism | Sizing ETSS | Sizing Probe | Assumed Axial Length, inch | Limiting Flaw Depth, %TW | Condition Monitoring Limit, %TW | Margin to Limit, %TW |
|---|---|---|---|---|---|---|
| Anomalous Indications due to Manufacturing | I96041.1, Rev. 8 | Bobbin | 0.62 | 11 | 50.0 | 39.0 |
| AVB Wear | I96041.1, Rev. 8 | Bobbin | 0.90 | 15 | 47.9 | 32.9 |
| TSP Wear, Flat | I96043.4, Rev. 1 | Bobbin | 1.125 | 31 | 46.5 | 15.5 |
| Secondary Side Components | Acceptable. No evidence of active degradation. | | | | | |

Example of Tube Integrity Assessment at 690 TT plant, Source: ML25139A554

# Tube Plugging

- Tubes to be plugged are determined based on the inspection results
- An administrative plugging limit of less than the technical specification limit can be applied in cases of aggressive degradation or to support multi-cycle operating
  – Tubes meeting the CM limit at the current outage can be plugged preventatively due to tube integrity until the next inspection outage
  – Percent and the total number of plugged tubes need to be tracked

| SG | Total Plugged Pre-3R1 | 3R1 Plugged | Total Plugged Post- 3R1 | # Tubes | % Plugging |
|---|---|---|---|---|---|
| 1 | 0 | 13 | 13 | 10,025 | 0.13 |
| 2 | 1 | 4 | 5 | 10,025 | 0.05 |
| **Total** | 1 | 17 | 18 | 20,050 | 0.09 |

Example of Tube Plugging List at 690 TT plant, Source: ML25139A554

# Tube Integrity Assessment until Next Inspection

- Operational Assessment (OA) is a process to project the tube integrity until the next planned inspection outage
  - Performed to assure that the performance criteria will not be exceeded until the next planned SG inspection
  - Depending on the region, growth rate can be different
  - Separate assessment would be needed for accurate and reasonably conservative assessment

**Table 6: Operational Assessment Summary**

| Degradation Mechanism | Growth Rate (% TW/EFPY) | Largest RTS Flaw (% TW) | U2C33 Projection (% TW) | Structural Limit (% TW) |
|---|---|---|---|---|
| AVB Wear | 0.97 | 17 | 33.9 | 45.5 |
| TSP/FDB Wear | 1.11 | 22 | 39.9 | 43.6 |

Example of Operational Assessment at 690 TT plant, Source: ML24295A135

# Questions

- Question:  How was the OA performed in ML24295A135?  The growth rate looks small, but the OA projection looks quite big
- Response:  We don't have the details of the operational assessment.
- Question:  Clarify what RTS means
- Response:  Return to service.  These are the flaws that are not plugged
- Question:  How is the max RTS depth determined?
- Response:  This is the maximum flaw depth of those left in service (not plugged).
- Question:  Clarify the outage numbering designation
- Response:  Plants can set their own numbering designation.  In this example it is Unit 2 Cycle 33 (U2C33).  This is common.

# Secondary Side Inspection

- Other components such as channel head, plug or upper internal system are examined during the outage
  - Visual inspection is a common practice for those component inspections
- Foreign Object Search and Retrieval (FOSAR) is also performed where tubes are susceptible to Foreign Object (FO) wear
  - Any FOs found in high cross flow area should be retrieved
- To remove deposits in the tube bundle, water lancing or chemical cleaning can be performed

# Summary

- Steam generator Inspection planning and activities at high level are addressed
- More details can be found in SGMP guidelines
- In US, all utilities are required to submit 180 day report after the steam generator inspections
  - All 180 day report can be downloaded using the link below
    - https://www.nrc.gov/about-nrc.html
- References
  - ML25139A554
  - ML25141A100
  - ML24292A032
  - ML24295A135

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# History of Steam Generator Regulation and Program Development in US

NUCLEAR

Brent Capell
Principal Team Lead

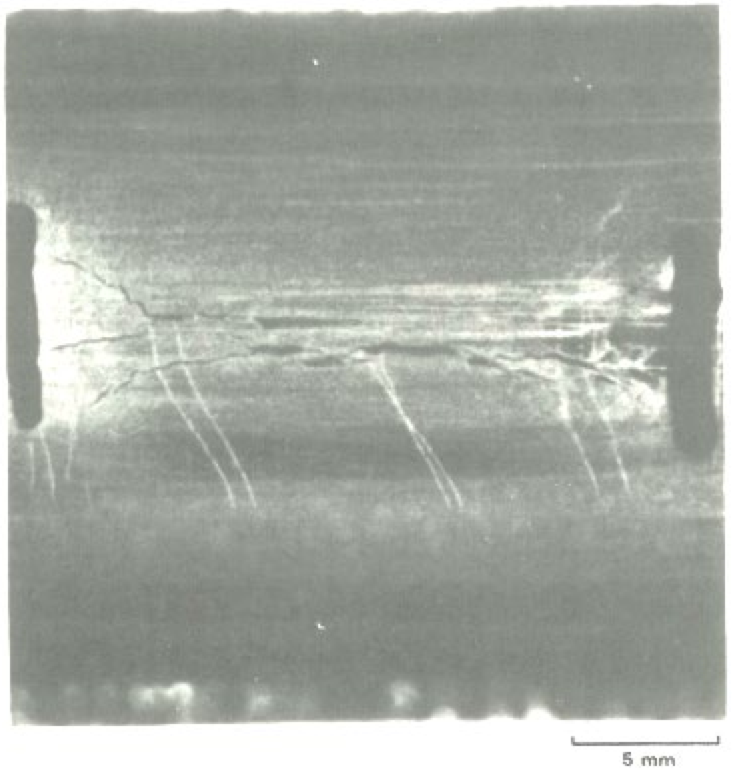
Steam Generator Management and Technology Workshop
Shanghai, China
July 7-9, 2025

# Thank You

- Thank you to Dan Mayes for providing much of the background information for this presentation

# Early Steam Generator (SG) Regulations and Operation

- The industry started with inspections with probes that couldn’t identify cracking
  - The material was very susceptible to cracking
- SG Technical Specifications required a 3% inspection every outage.
- The practice was in-service inspection, plug flaws indicated at 40% and greater, operate till next refueling outage or until a steam generator tube leak was found
  - It was common in the early years to manage the SG by leakage
- Industry formed the Steam Generator Owners Group (SGOG) to help manage SG issues




SCC Cracks Hot Leg in Alloy 600MA with Tubesheet Deposit Corrosion

From TR-103824-V1R1

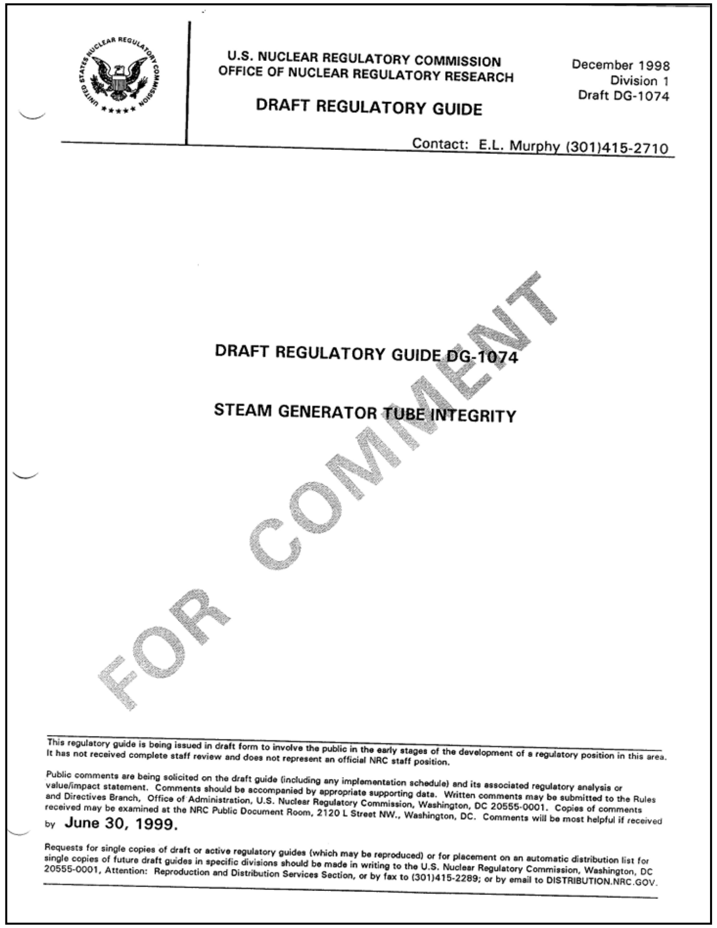
# Key Industry Operating Experience Events

- Millstone Unit 1 tube rupture March 7, 1989
  - Numerous SG leaks and other issues eventually led shutdown of Millstone Unit 1
- Surry plug top release event
- Palo Verde tube rupture
- Indian Point 2 large leak due to missed indication
- Axial Cracking detected at Oconee in 1994
- Severed plugged tube at Three Mile Island Unit 1 and Oconee
- Oconee missed indication in dent/ding that violated performance criterion
- Comanche Peak missed indication that violated performance criterion

**General Industry Performance Including These Events Lead to Greater Regulatory Involvement**

# US Nuclear Regulatory Commission (US NRC) Involvement

- The US NRC has regulatory authority in the US and a mandate to ensure safe nuclear plant operation
- Continued SG leak events, especially rupture events, meant US NRC began strong review of SG programs
- NRC publishes Draft Guide DG-1074 for comment
  - Provides an NRC view of an SG inspection and integrity program to curb concerns
  - Draft Guidance was very prescriptive and burdensome
  - Industry did not want to implement the draft guidance thus another way was needed



U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REGULATORY RESEARCH

DRAFT REGULATORY GUIDE

December 1998
Division 1
Draft DG-1074

Contact: E.L. Murphy (301)415-2710

DRAFT REGULATORY GUIDE DG-1074

STEAM GENERATOR TUBE INTEGRITY

FOR COMMENT

This regulatory guide is being issued in draft form to involve the public in the early stages of the development of a regulatory position in this area. It has not received complete staff review and does not represent an official NRC staff position.

Public comments are being solicited on the draft guide (including any implementation schedule) and its associated regulatory analysis or value/impact statement. Comments should be accompanied by appropriate supporting data. Written comments may be submitted to the Rules and Directives Branch, Office of Administration, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001. Copies of comments received may be examined at the NRC Public Document Room, 2120 L Street NW., Washington, DC. Comments will be most helpful if received by June 30, 1999.

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US NRC Draft Guide DG-1074 Available on US NRC Website Accession Number ML003739223

**US Industry Response Led to Development of SG Program**

# US Industry SG Response Program Development

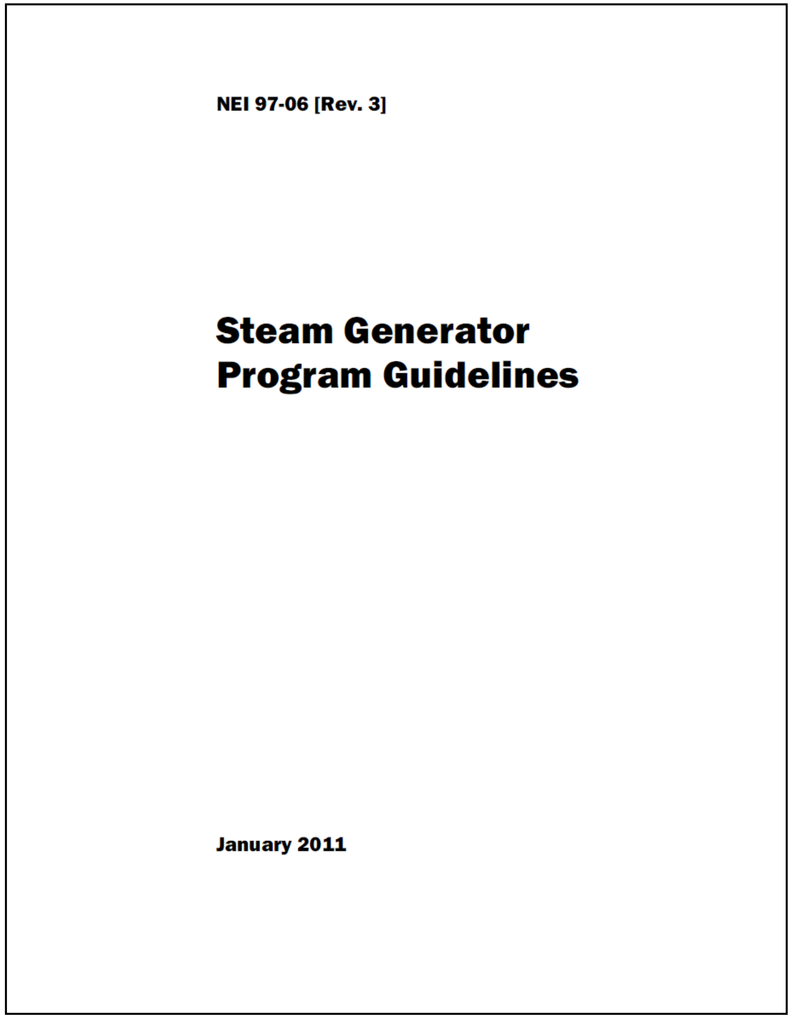
What is an NEI Document?

- NEI is the Nuclear Energy Institute
  - NEI is a nuclear energy organization in the US that includes utilities and vendors
- NEI produces high-level US industry-wide documents
  - Such documents are indicated with a code where the first two numbers indicate the year the document was first issued and the last two numbers are an identifier
- NEI documents require top-level management support for US industry actions

- US industry developed a program to reduce SG integrity concerns and avoid the overly prescriptive requirements in the US NRC Draft Guidance
- This program is the "Steam Generator Program Guidelines" issued as document NEI 97-06
  - Initial Revision 0 published in 1997
  - Endorsed by US Utility Nuclear Officers
    - All US utilities agreed to implement
  - Required initial implementation by January of 1999

# What is in NEI 97-06?

- Stated objective:
  - NEI 97-06 establishes a framework for structuring and strengthening existing Steam Generator Programs. It provides the fundamental elements to be included in a Steam Generator Program. These elements incorporate a balance of prevention, inspection, evaluation, repair and leakage monitoring measures.
- Establishes performance criterion
  - Structural integrity performance
  - Operational Leakage
  - Accident induced leakage
- Establishes content for an acceptable SG program


NEI 97-06 [Rev. 3]

**Steam Generator Program Guidelines**

January 2011

# Keys for NEI 97-06 Implementation

- Management Support
  - Plant managers need to understand goals of SG Program and support full implementation
  - US plants currently have good management support for SG related activities
- Personnel
  - There have been technically competent and knowledgeable people involved to help drive solutions
  - Training new engineers remains a top topic for SGMP
- Technology
  - Computers and other technologies have made in possible to manage SG issues that otherwise would not have been possible to mange
  - Computers allow for data storage to support large and complex inspections to prove tube integrity for plants even with severe degradation
  - Eddy current inspections can reliably detect degradation, and improvements continue to ensure cost-effective outages can be performed

# NEI 97-06 Impact on Plant Technical Specifications

- As stated earlier, initial plant requirements in Technical Specifications resulted in programs that often failed to prevent significant leakage events
  - The US NRC recommendations probably would have led to all plants having to implement very restrictive Technical Specifications to ensure integrity

- Instead, with NEI 97-06, the industry instead developed a "Generic License Change Package" (GLCP)
  - The GLCP included a collection of Technical Specification updates inline with implementing NEI 97-06
  - The US NRC forced all US plants to implement the changes in the GLCP
    - Implemented at plants as Technical Specification Task Force (TSTF) 449 (TSTF-449)
  - Since this was common, all US plants now have very similar Technical Specifications regarding SG integrity

# Technical Specification Task Force (TSTF) Documents

- The US Industry has supported other common sets of updates to SG related plant Technical Specifications
- These have been implemented as additional TSTF documents
- The NEI works with the Utilities to draft these documents and submits them to the US NRC to for approval
  - Once the US NRC approves the generic TSTF letter, plants can submit license changes to use the new Technical Specification rules through a simpler license change process
  - US Plants are often not required to update and use the most recently issued TSTF set of requirements

- Important SG Related TSTF Documents
  - TSTF-449 – Required for US Plants
    - Implement GLCP previously mentioned
    - Shifted to Performance Based Framework and included the performance criterion, inspection, repair, repair criterion requirements
  - TSTF-510
    - Changed inspection frequency to allow increased intervals between inspections for plants who could justify safe operation
  - TSTF-577
    - Most recent TSTF
    - Allows for plants to up to 96 EPFM between inspections when meeting specific criterion

# US NRC Response to NEI 97-06 SG Program

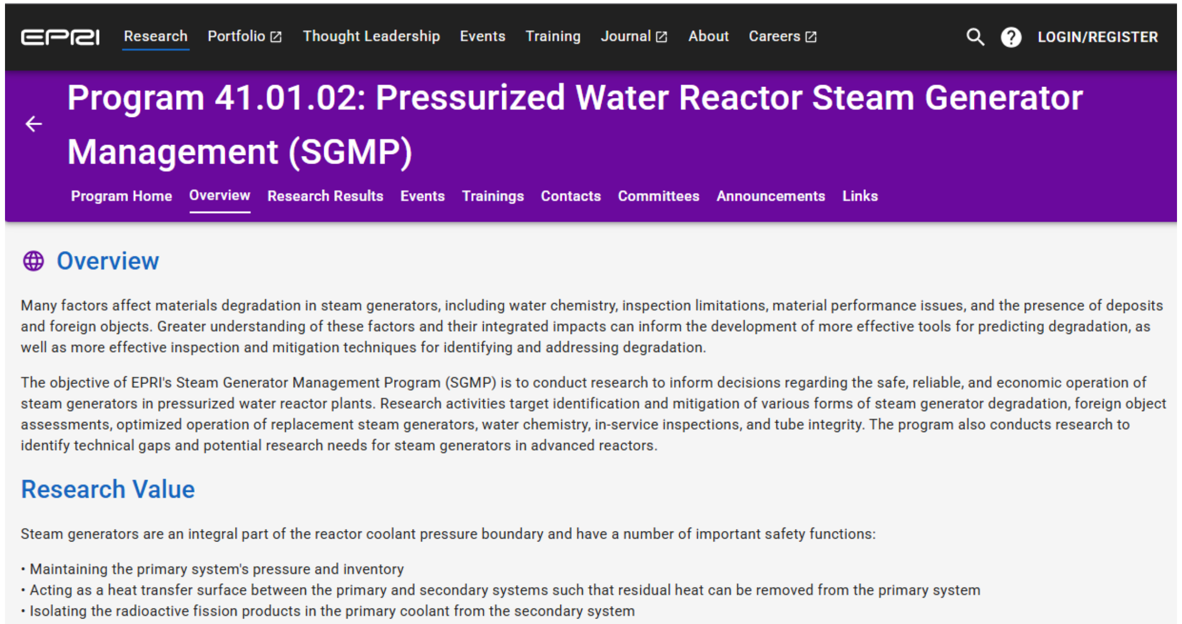
- The US NRC now recognizes NEI 97-06 as an acceptable SG Program to ensure integrity
  - US NRC never finalized their initial draft guidelines so the rules in DG-1074 were never required by plants
- All US plants incorporated needed changes into plant Technical Specifications via TSTF-449 thus the US NRC expects all US plants to be keeping up with NEI 97-06 activities
- US NRC remains actively involved with US industry through "Steam Generator Task Force" (SGTF) Meetings
  - SGTF coordinated by EPRI with US utility involvement and leadership
  - SGTF meets with twice a year with the US NRC
    - Normally public meetings so anyone can attend
    - Some sessions may be closed due to proprietary information exchange
  - Keeps US NRC aware of US industry activities and keeps industry aware of US NRC concerns

# NEI 97-06 Implementation Has Improved Performance

- US plants have far fewer leak events than 30 years ago
- Some reasons for improvement
  - Implementation of NEI 97-06 and the performance-based management criterion
  - SG replacements
    - Includes use of more corrosion resistant alloys
  - Better water chemistry control
  - Application of various other technologies including inspection technologies
- Plants recognize that proactively addressing SG integrity issues results in fewer unplanned outages
- The US Industry went from counting the number of leak outages per year to counting years between any leak outages

# Other Industry Groups – Evolution of SGOG into SGMP

- The Steam Generator Owners Group or SGOG has evolved into the Steam Generator Management Program (SGMP) managed by EPRI
- The SGMP allows for experience sharing and sponsorship of research to benefit members
  - Utility members currently meet twice a year to discuss experience and ongoing projects
- Provides training resource for new SG engineers and program owners



# Other Industry Actions – INPO and WANO

- INPO (Institute for Nuclear Power Operations) emphasis excellence in nuclear plant operations
- INPO organizes site visits to provide peer review of operations
  - Allows industry to review other plants processes and incorporate best practices or identify weaknesses
  - SG program related visits started in 1995 and continue today
- INPO model carried to WANO (World Association of Nuclear Operators)
  - Many INPO practices incorporated into WANO practices as well

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# Introduction to SGMP

Brent Capell
Principal Team Lead

Steam Generator Management and Technology Workshop
Shanghai, China
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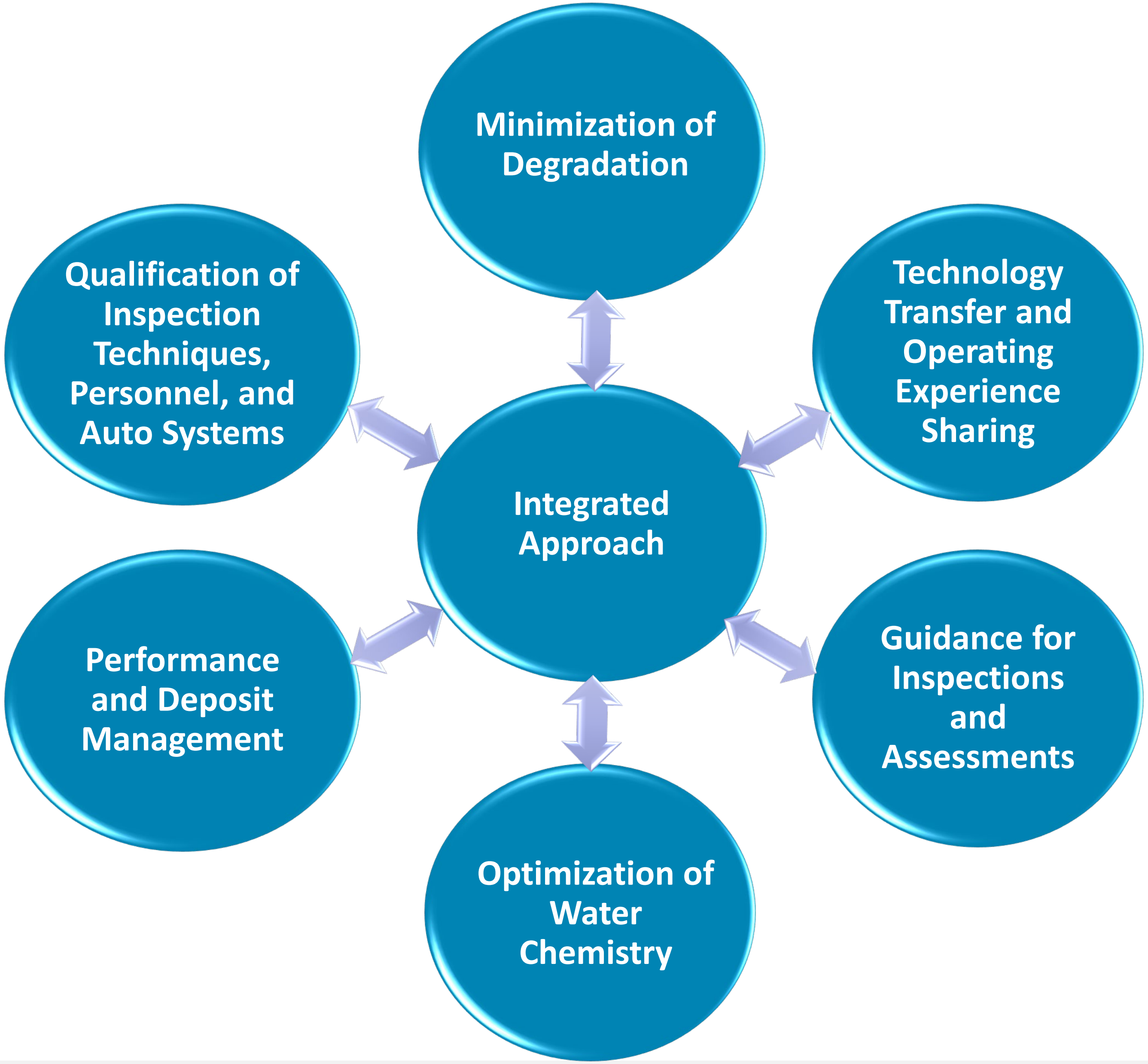
# EPRI Steam Generator Management Program

- **Began in the 1970's with focus on managing degradation of Alloy 600MA tubing and inspection issues**
- **Today we maintain six guideline documents aimed at developing and maintaining a strong steam generator program**



# SGMP Member Utilities for 2025

## Europe

- EDF Energy (UK)
- Foro-CEN (Spain)
- Rolls-Royce SMR (UK)
- Vattenfall (Sweden)
- Electrabel NV (Belgium)

## North America

- Ameren Services Company
- American Electric Power, Inc.
- CANDU Owners Group
- Constellation Energy Corp.
- Dominion Energy, Inc.
- Duke Energy Corp.
- Entergy Services, LLC
- Evergy Services (Wolf Creek)
- Fluor Marine Propulsion LLC
- NextEra Energy, Inc.
- Pacific Gas & Electric Co.
- Palisades Energy
- Pinnacle West Capital Corp.
- PSEG
- Southern Nuclear
- STP Nuclear Operating Co.
- Tennessee Valley Authority
- Vistra Energy Corp.
- Xcel Energy Services, Inc.

## Asia

- CGN Power
- China National Nuclear Power
- Emirates Nuclear Energy Corp.
- Japanese Utilities through CRIEPI
- Shandong Nuclear Power Company

## South America

- Eletrobras Termonuclear S.A (Brazil)
- Nucleoelectrica Argentina S.A

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# Primary SGMP Objectives for 2025

- Conduct research to inform decisions regarding the safe, reliable, and economic operation of steam generators
- Provide training and support for new engineers
- Supply analytical tools and guidance to support SG operability
- Provide consulting and peer review for utilities' SG programs and initiatives
- Pursue R&D to develop technology to identify and mitigate various forms of steam generator degradation
  - Assessment of foreign objects
  - Chemistry and deposit management
  - Steam drum component degradation
  - In-service inspections
  - Tube integrity

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