Steam Generator Management (QA)

Program Overview

Program Description

Many factors affect materials degradation in steam generators, including water chemistry, inspection limitations, material performance issues, and the presence of foreign objects. Greater understanding of these factors and their integrated impacts will lead to more effective tools to predict the potential for degradation and more effective inspection and mitigation techniques to identify and address degradation.

The Steam Generator Management Program (SGMP) conducts research to ensure the safe, reliable, and economic operation of steam generators in pressurized water reactor plants. Research activities target identification and mitigation of various forms of steam generator degradation, foreign object assessments, optimized operation of replacement steam generators, water chemistry, in-service inspections, and tube integrity.

Research Value

The Steam Generator Management Program drives greater consistency in managing steam generator issues across the nuclear fleet. The program develops guidance for existing issues such as degradation in steam generators with original Alloy 600 MA tubes, as well as emerging issues such as managing degradation in steam generators with the more corrosion-resistant Alloys 600 TT, Alloy 690 TT, and Alloy 800 tubes. SGMP participants gain access to the following:

- Strategic roadmaps outlining research gaps confronting key issues—such as foreign object management and steam generator life management—and the collaborative actions needed to address these gaps
- Guideline documents that reduce the potential for steam generator tube ruptures and forced leakage outages, which can cost an estimated $5 to $20 million per event
- Better tools for integrity assessments, reducing unnecessary examinations that can cost an estimated $1 to $2 million per plant
- Chemistry controls that can delay the onset of corrosion and mitigate steam generator fouling
- A database of worldwide steam generator information related to degradation, used to assist utilities with decisions on steam generator operation and maintenance

Approach

The Steam Generator Management Program applies an integrated approach for managing steam generator materials degradation in pressurized water reactors. The program develops guidance through improved understanding of how multiple variables impact steam generator operation and maintenance, including thermal hydraulics, water chemistry, tubing materials, inspection techniques, and tube-plugging/repair criteria.

SGMP closely collaborates with other EPRI programs, including Materials Reliability, Nondestructive Evaluation, and Chemistry, to ensure appropriate technologies and technical guidance are effectively integrated into research activities.

There are both base and supplemental components of the Steam Generator Management Program. The base portion encompasses nondestructive evaluation (NDE) research and development (R&D), water chemistry, materials performance/thermal hydraulics, and the Steam Generator Degradation Database.

- Nondestructive Evaluation R&D: This project develops tools such as software algorithms, improved inspection techniques, and database libraries to enhance the accuracy and efficiency of steam generator inspections. Improved flaw detection and flaw-sizing accuracy capabilities, for example, could better inform decisions regarding operating intervals between inspections.

- Water Chemistry: This project develops guidelines, chemistry technologies, and predictive models to minimize steam generator tube corrosion and fouling, and to optimize chemistry for safe, reliable, and long-term steam generator operation. Advanced technology developments are incorporated into application sourcebooks to inform water chemistry control actions, including the use of improved amines, dispersants, molar ratio control, and intergranular stress corrosion cracking inhibition.
- Materials Performance and Thermal Hydraulics: Foreign objects and tube wear can threaten safe and reliable steam generator operation. This project conducts experiments and develops computational simulations that more accurately estimate foreign object movements and tube wear rates from steam generator foreign objects. Prediction tools and on-line measurement techniques also are needed to manage issues resulting from buildup on tube support plates. Finally, corrosion studies can help determine the effect of various steam generator environments on tube degradation rates.
- Steam Generator Degradation Database: This project maintains a web-accessible database of steam generator information. This database contributes to the safe and reliable operation of steam generators by providing data to inform decisions regarding inspection scope, tube repair activities, and the effectiveness of steam generator corrective actions, such as chemical cleaning.

To address strategic objectives established for each of its programs, the Electric Power Research Institute (EPRI) has developed roadmaps to plan, coordinate, and execute needed research among multiple entities. For the Steam Generator Management Program, roadmaps have been developed to address the technical barriers confronting foreign object detection and characterization and effective steam generator life management. Additional roadmaps will be developed as conditions warrant.

The supplemental portion of the Steam Generator Management Program provides mechanisms for responding to emerging issues and for developing effective monitoring and assessment programs.

- Supplemental Research and Emerging Issues: This project enables EPRI to conduct research to address emerging technical, operational, and regulatory issues not anticipated in annual research planning. This project also facilitates research in specific areas that may not be of interest to the broader base program participants. Such research could include additional capabilities for software products, database maintenance for alternate tube repair criteria, and review of newly developed chemical additives.
- Structural Integrity Assessment and Nondestructive Evaluation Field Support: This project develops products to ensure steam generator tube integrity through thorough inspections, condition monitoring, and operational assessments. Cornerstone products include the *Steam Generator Examination Guidelines* and its qualification program, the *Steam Generator Integrity Assessment Guidelines*, the *Steam Generator Primary-to-Secondary Leakage Guidelines*, and the *Steam Generator In-Situ Pressure Test Guidelines*.

Accomplishments

The Electric Power Research Institute's (EPRI's) Steam Generator Management Program supports nuclear power industry efforts to minimize the potential for steam generator tube ruptures, forced leakage outages, and other steam generator integrity issues. Accomplishments include both technology development and technical support, spanning more cost-effective nondestructive evaluation techniques for steam generators to technical justification for regulatory issues.

- Updated guideline and supporting technical documents implementing the requirements of nuclear industry initiative NEI 97-06, which imposes requirements for a nuclear plant's steam generator program
- Developed new applications for dispersant use beyond online addition to significantly reduce steam generator fouling: dispersant addition during steam generator wet layup as well as during the long-path recirculation cleanup of the condensate and feedwater systems just prior to plant startup
- Developed software algorithms for automatic eddy current data analysis, demonstrated high levels of performance for detection of steam generator tube degradation, and transferred the technology to NDE organizations for field application.

- Developed eddy current data analysis guidance for detection of various types and sizes of steam generator foreign objects
- Completed an engineering study of divider plate cracking for 40-year plant life.
- Performed an assessment of potential mechanisms for lead transport to steam generator tube crack tips
- Developed a prioritization strategy for managing foreign objects in square pitch and triangular pitch steam generators
- Analyzed the impact of advanced amine use on iron transport, flow accelerated corrosion, and steam generator fouling in pressurized water reactor secondary systems

Current Year Activities

Steam Generator Management Program research and development for 2012 will focus on continued development of dispersant applications; advanced inspection and inspection analysis methods; root causes of steam generator degradation; and guideline revisions related to water chemistry. Specific efforts include the following:

- Update the *Primary-to-Secondary Leak Guidelines*, which define needed requirements and provide guidance in optimizing a plant's primary-to-secondary leak program
- Update the *In Situ Pressure Test Guidelines*, which define needed requirements and provide guidance in performing pressure tests of degraded steam generator tubes to directly demonstrate tube integrity
- Provide a significant update to the *PWR Dispersant Application Sourcebook*, incorporating significant industry experience and additional application technologies
- Continue development of advanced software algorithms for automated eddy current data analysis for detection of steam generator degradation and foreign objects.
- Update *Generic Predictions,* which includes predicting the future extent of tube degradation in steam generators with Alloy 800NG, Alloy 600TT, and Alloy 690TT tubes
- Continue research to understand the safety significance of divider plate crack propagation during extended periods of performance.

Selected reports and products may be prepared in whole or in part in accordance with the EPRI Quality Program Manual that fulfills the requirements of 10CFR50 Appendix B, 10CFR21 and ANSI N45.2-1977. Reports and products developed under the EPRI QA program will be marked and identified as such.

Estimated 2012 Program Funding

$7.7 million

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Summary of Projects

Project Number	Project Title	Description
P41.01.02.01 (Roadmap)	Steam Generator Foreign Object Management (Roadmap)	
P41.01.02.02 (Roadmap)	Steam Generator Life Management (Roadmap)	

Steam Generator Foreign Object Management (Roadmap)

Key Research Question

Corrosion was the dominant tube degradation mode for steam generators manufactured with Alloy 600MA tubing. Most steam generators with Alloy 600MA tubing have been replaced with steam generators that have more corrosion resistant tubing such as Alloy 600TT, 690TT or 800NG. As a result, corrosion of steam generator tubing is decreasing and other degradation modes are becoming more important.

Foreign objects on the secondary side of steam generators cause tube wear that can challenge tube integrity and can lead to primary-to-secondary leakage and unplanned outages. This is currently the number one cause of steam generator forced outages. Foreign objects include material that is accidentally left in the secondary system during installation or repairs and material from degraded components in the secondary system. Although foreign material exclusion programs are in place at plants to minimize the number of foreign objects in the secondary system, it is not possible to eliminate all foreign objects. As such, a strategy to manage foreign objects and the associated degradation on the secondary side of a steam generator is needed.

Approach

This work is divided into three essential areas. These areas are needed in conjunction with each other to adequately manage the issues and the associated consequences related to foreign objects within steam generators.

Effective Inspection
Existing primary side eddy current techniques for managing foreign objects are limited. The goals of the research are to improve foreign object primary side eddy current detection and sizing capabilities and to develop a secondary-side inspection method that can assess tube damage from a foreign object. The secondary side inspection technique will enable utilities to size wear without accessing the primary side. This will be useful if tube wear is observed from a visual inspection on the secondary side during an outage when primary-side inspections are not conducted or after primary side inspections are complete.

Development of new primary side inspection techniques requires experienced eddy current analysts to propose and test innovative methods to acquire and analyze eddy current data. The eddy current data will be collected in a laboratory with tubes that have tube wear and with parts in locations that are expected in the steam generators. This will be done using several different probe designs. Each successful method will be added to the library of accepted eddy current inspection methods that are used by the inspection vendors.

A promising secondary side sizing technique based on optical depth measurement will be developed and evaluated for its ability to measure tube wear on the secondary side of a steam generator. Upon completion, the technology will be transferred to a vendor for commercialization and then it will be offered as a service to the utilities.

Evaluation
During an outage, many foreign objects can be located in the steam generator. A structured process will enable the steam generator engineer to decide the action needed when foreign objects are detected and assist with the prioritization of foreign object retrieval. EPRI will develop a first-principled-based method to predict potential wear from a foreign object and will qualitatively confirm the results using experimental data. This method will be applied generically to develop a prioritization scheme for removal of foreign objects (size and mass) that are located in a steam generator. Prediction of potential foreign object wear using this methodology will be used for tube integrity assessments.

Foreign Object Handbook
EPRI will maintain and update the *Foreign Object Handbook* which provides an overall strategy for managing foreign objects. This handbook will capture operational experience, recommended inspection practices, foreign materials exclusion practices, prioritization schemes, and tube wear prediction methods.

Impact

Operational Drivers: In the worst cases, tube degradation from foreign objects can lead to unplanned outages due to primary-to-secondary leakage. From a more practical standpoint, foreign objects and associated tube wear may lead to an unplanned expanded eddy current inspection scope, an unplanned tube plugging campaign, and/or an inability to operate multiple cycles between inspections. In addition, inability to accurately size foreign object wear leads to unnecessary in-situ pressure tests to demonstrate tube integrity. These activities can significantly increase worker radiation exposure, outage costs, and schedule.

Regulatory Drivers: Regulators are concerned that existing eddy current inspection practices may not adequately identify foreign objects or foreign object tube wear indications. Undetected foreign objects or tube indications that are missed or inaccurately sized during inspection may lead to a degraded tube that causes a primary-to-secondary leak.

How to Apply Results

Upon completion of this work, the following can be expected:

- Improved eddy current inspection techniques and new secondary side wear sizing techniques will be integrated into vendor services that are provided to the utilities. These techniques will better identify and size tube wear, and locate foreign objects.
- EPRI's *Foreign Object Handbook* (EPRI Product 1014981) will serve as the basis for utilities and steam generator vendors to implement a plant-specific strategy for managing foreign objects. This document will include a method to prioritize the order in which objects should be removed from the steam generator, an industry accepted method to predict tube wear, and a summary of relevant operating experience.
- Utility foreign materials exclusion program managers in conjunction with utility steam generator engineers will maintain a foreign materials exclusion program that is based on EPRI's *Nuclear Maintenance Applications Center: Foreign Material Exclusion* (EPRI Product 1016315 and subsequent revisions) and INPO's *Achieving Excellence in Foreign Material Exclusion* (INPO 07-008 and subsequent revisions).

NEI 03-08 steam generator guideline documents will be updated by EPRI and implemented by the utilities to address research results and operating experience related to foreign objects.

Steam Generator Life Management (Roadmap)

Key Research Question

Steam generator life-cycle management must balance the implementation of measures to mitigate or repair existing degradation and the application of techniques to reduce the likelihood of future degradation against the associated costs. Recent operating experience demonstrates that current knowledge of relevant degradation

mechanisms and existing mitigation options may be inadequate to accurately project and maximize steam generator life:

- Fatigue failure and primary-to-secondary leaks have occurred in three steam generator tubes caused by significant deposit accumulation on the tube support plates.
- Denting of steam generator tubes at the top of the tubesheet has occurred at seven plants. Denting occurred in as many as 1500 tubes in a single plant and caused stress corrosion cracking and tube repair in three of the plants.
- Stress corrosion cracks are being detected in Alloy 600TT and Alloy 800NG steam generators.
- In plants that have implemented power uprates, deposit accumulation has limited thermal performance.

Approach

The project plan is shown in the flowchart. The primary focus is on strategic planning to maximize steam generator life and optimize steam generator performance. The work is divided into four areas:

Deposit Management
Secondary side water chemistry in conjunction with deposit removal techniques control the deposit accumulation on steam generator tubes and tube support plates.

EPRI will update the *Dispersant Application Sourcebook* to include lessons learned and recommendations from plants using on-line dispersant application. Dispersants suspend corrosion products in the steam generator bulk water and repel corrosion products away from the tubes/deposits, thereby preventing corrosion products from adhering to the tubes/deposits. Ongoing research and field trials are exploring the possibility of using dispersants during outages (steam generator wet lay up) to remove deposits from steam generator tubes and during startup (long-path re-circulation) to prevent corrosion products from reaching steam generators.

Crystal habit modifiers can be used to control or tailor deposit properties. Results from preliminary experiments look promising. If specific amines or their degradation products are found to significantly affect the crystal habit of corrosion product particles, this would allow utilities to engineer heat transfer enhancing deposit layers on steam generator tubes and to facilitate removal of the deposit from the tube. The EPRI Steam Generator Management Program and the EPRI Chemistry Program plan to explore the application of this technology to nuclear power plants.

Techniques to mitigate denting of the tubes at the top of the tubesheet will be developed based on an assessment of the underlying mechanism. The operational effects of deposit accumulation at tube support plates will be assessed using a new transient analysis method. An online monitoring technique that uses existing plant measurements to estimate the accumulation of deposits on the tube support plates is under development.

The *PWR Steam Generator Deposit Control and Removal Strategies Sourcebook* will evaluate the characteristics of deposit samples removed from steam generator tubes, historical deposit removal activities, and secondary chemistry that can be used to develop recommendations for an overall deposit control and removal strategy.

Prediction
Two empirical models are under development to estimate deposit accumulation. One will predict deposit accumulation on the tubes in the tubesheet region and the second will predict deposit accumulation on the top tube support plate. In addition, another empirical model will relate deposit accumulation on the tubes to stress corrosion cracking. Generic predictions (*Pressurized Water Reactor Generic Tube Degradation Predictions*) will be developed to estimate the future extent of tube degradation in steam generators based on existing degradation. The results of these two models and the generic predictions are used as input to the overall steam generator life strategy.

The new steam generator thermal-hydraulics software code and deposit formation module will be used to predict the location of deposit accumulation in the steam generator. The new steam generator thermal-hydraulics software code also will overcome deficiencies in the current code (ATHOS/SGAP) by removing geometry constraints to enable evaluation of modern and future steam generator designs.

Thermal Performance
A plant's thermal margin decreases when it implements a power uprate, makes other operational changes, or when deposits accumulate on steam generator tubes. A new *Thermal Performance Handbook* will provide a method for factoring thermal performance into a steam generator life management strategy. In addition, utilities and vendors will be able to predict thermal performance using the new steam generator thermal hydraulics code.

Lead-induced Stress Corrosion Cracking Inhibitors
Advanced alloys such as 800NG and 690TT are significantly more resistant to stress corrosion cracking than 600MA. However, stress corrosion cracking is possible in 800NG and 690TT in an environment that contains lead. Autoclave testing will be used to develop a fundamental understanding of lead-induced stress corrosion cracking mechanism. Subsequently, mitigation options will be developed.

Impact

Operational Drivers: Unacceptable levels of deposit accumulation can result in stress corrosion cracking, water level oscillations, less than optimal thermal performance, and/or fatigue failure of steam generator tubes. At the plant level, this can lead to an unplanned outage, an unplanned tube plugging campaign, a reduction in power output, reduction in the maximum allowed power level, and/or primary-to-secondary leakage. These activities can significantly increase worker radiation exposure and plant operating costs.

Asset Management: Asset management decisions associated with power uprates, license renewal, and life extension should consider the operating life of a steam generator and the possibility of a first and second steam generator replacement. The models used today to assess steam generator management options and mitigation options will influence decisions if a plant chooses to uprate power or extend the license.

Regulatory Drivers: Regulators are concerned that deposit accumulation in steam generators may reach levels that adversely affect steam generator performance prior to implementation of deposit removal activities by utilities. For example, the U.S. Nuclear Regulatory Commission raised this issue in NRC Information Notice 2007-37.

How to Apply Results

Upon completion of this work, it is expected that utility program managers and steam generator vendors will have robust models and an adequate knowledge base to develop plant-specific steam generator life management strategies that effectively balance the risk of deposit accumulation, stress corrosion cracking, and thermal performance against other costs and benefits and inform long-term reliability decisions. Specific implementation plans include the following:

- Developing the basis for a plant-specific strategy for managing steam generator deposit accumulation using the new report *PWR Steam Generator Deposit Control and Removal Strategies Sourcebook.*
- Predicting thermal performance consequences of deposit formation on the tubes using the new report *Thermal Performance Handbook* and new steam generator thermal-hydraulic software code.
- Assessing the risk of lead-induced stress corrosion cracking and implementing inhibitors using information in a new report, *Lead-induced Stress Corrosion Cracking: Mechanism and Inhibitors.*