REVIEW OF EPRI'S STEAM GENERATOR R&D PROGRAM

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ABSTRACT

EPRI has carried out an extensive R&D program on SG technology since the mid 1970's. Very early efforts under the auspices of the Steam Generator Owners Group (SGOG) focused on developing remedial actions for the critical SG corrosion issues of denting, wastage and pitting. Fundamental work was also carried out in the development of thermal hydraulic models for vibration and wear, chemical cleaning and tube repair techniques. In the late 1980's and continuing through today, the program has shifted emphasis towards management of steam generator degradation, primarily stress corrosion cracking of the SG tubes on both the primary and secondary sides. The current Steam Generator Management Program (SGMP) carries out R&D in four areas; materials, chemistry, thermal hydraulics and non-destructive testing. The strategic goals of this program and projects put in place to achieve these goals will be reviewed in detail in this paper.

INTRODUCTION

Steam Generator degradation has caused substantial losses of power generation, resulted in large repair and maintenance costs, and contributed to significant personnel radiation exposures in Pressurized Water Reactors (PWRs) operating throughout the world. EPRI recently the revised Steam Generator Reference Book[1], which reviews all of the major forms of SG degradation. Competitive pressures are causing utilities to strive to reduce operations and maintenance (O&M) and capital costs. SG corrosion is a major contributor to the O&M costs of PWR plants, and therefore US utilities are evaluating and implementing the most cost effective solutions to their corrosion problems. Mitigation strategies developed over the past few years reflect a trend towards plant specific solutions to SG corrosion problems. Since SG degradation is in most but not all cases an economic problem and not a safety problem, utilities can focus their mitigation strategies on their unique financial situation. Accordingly, the focus of R&D has shifted from the development of more expensive, prescriptive solutions to corrosion problems to providing the utilities with a number of mitigation options, for example; molar ratio control, boric acid treatment, iron reduction and chemical cleaning. An additional focus of the R&D program in the future will be more cost effective and accurate NDE of SG tubes.

Figure 1 shows the loss of capacity factor attributed to corrosion problems in US PWRs for the years 1980 through 1996. Pressurized water reactors (PWRs) experienced an average capacity loss of more than 5% and a peak of nearly 8% in 1982. It is estimated that SG corrosion problems have cost the US nuclear utility industry billions of dollars. The data in Figure 1 shows that despite the fact that the PWR fleet is aging, capacity factor losses have continually improved, although the levels have somewhat stabilized over the past few years. It is anticipated that further improvements will be realized as a result of the implementation of steam generator management practices such as improved water chemistry, inspection and repair techniques.

STEAM GENERATOR TUBE DEGRADATION

Steam generators are large and expensive components that were designed for an expected service life of up to 40 years. Some service-induced damage to steam generator tubes was anticipated, however, by the mid-1970s, steam generator tubes in many RSGs were being plugged at a rate which indicated that the design margin would be exceeded well before their 40 year design life. Since 1977, EPRI under the direction of the US and foreign utilities has conducted a major research program to help utilities improve the performance of their steam generators. As a result, most of the initial types of damage have been eliminated. Improved steam generators incorporating design enhancements derived from both laboratory and field R&D have operated for well over a decade with virtually no corrosion related problems. Current new and replacement steam generators are anticipated to operate for the remaining life of the plants and will support life extension in many cases. However, many older design units remain in service. While some operate successfully with minimum degradation, others have deteriorated to such an extent that some utilities now face a particularly difficult and expensive decision: whether to replace their current steam generators at costs of around $100-200 million per plant, to de-rate the plant due to a reduction in heat removal capability as steam generator tubes are plugged, or to shut down certain plants entirely.

SGMP TECHNOLOGY R&D PROGRAM

In recent years, EPRI's Steam Generator Management Program (SGMP) has evolved into a number of Issue Resolution Groups (IRG's) which focus on resolving critical issues such as; alternate plugging criteria and the SG rule (now deferred by the US regulator) and a SG technology R&D program. This paper discusses the ongoing activities of the R&D program which is divided into four disciplines; materials research, advanced water chemistry, thermal hydraulics (including vibration and wear) and non destructive examination (NDE) research.

Materials Program

Secondary side steam generator tubing degradation continues in both recirculation and once through steam generators with mill annealed Alloy 600 despite plant operation with reduced impurity ingress (ALARA chemistry), boric acid, molar ratio control as well as reduced iron transport, elevated hydrazine and chemical cleaning among other efforts. It is important to know why degradation of Alloy 600 tubing continues so steam generators can be managed to maximized their service life and to prevent steam generators with Alloy 690 from experiencing the equivalent fate.

Earlier R&D programs have defined the improvement to be gained by materials and design changes for replacement steam generators. The current materials program addresses products in the areas of inhibitor applications and the identification of factors influencing the continued IGA/SCC of original steam generators where materials and design changes cannot be made. An understanding of Alloy 600 corrosion is considered important to prevent corrosion in replacement units.

Primary Side Corrosion

Degradation of the SG tubing occurs on the primary side. Primary side corrosion has effectively been limited to stress corrosion cracking (SCC) of the tubing in regions of high tensile stresses, including the tube to tubesheet expansion zone and inner row u-bend regions. Operationally induced stresses associated with denting and sleeving have also resulted in PWSCC. From a mechanistic view, PWSCC or pure water cracking is not completely understood. Primary water chemistry is however, believed to have at most a second order effect on PWSCC. The motivation for optimizing primary water chemistry is to control radiation fields in the primary system.

R&D programs conducted throughout the world have led to the identification of materials and heat treatments that are much more resistant to PWSCC than the mill-annealed Alloy 600 used in most original equipment generators. These improved materials including Alloy 690 and Alloy 800 are being used in new and replacement units. To date these materials have not yet experienced PWSCC. These materials also have proved to be more resistant to secondary side attack in plants that have replaced SG's. To prolong the life of the older generators, stress improvement processes (annealing and shot peening) have been developed and widely used. PWSCC is very temperature sensitive, and at some plants the primary system temperature has been reduced to further extend generator life. Sleeving also has been employed as a repair method to avoid the need to plug damaged tubes. Another repair method which looks promising involves insitu welding of the tube at the damage location and also nickel plating.

Secondary Side Corrosion

Major activities in the materials program has focused on the development of inhibitors. Boric Acid Treatment (BAT) was originally used to control SG tube denting. Subsequent laboratory work[2-4] indicated that the use of boric acid may also be beneficial in controlling secondary side IGA and/or SCC. The exact mechanism for inhibition is not known. It may be neutralization of a caustic environment and/or modification of the oxide film on the tubing making it more protective. Approximately 30 percent of US PWRs are currently using BAT. Most of these plants indicate that they are using BAT for IGSCC control. Although data from the laboratory testing of BAT is quite positive, the field data is less clear. Weibull statistics have been used to evaluate the time to failure of SG tubes before and after BAT application[5]. The interpretation of the field data in reference 5 suggests that on average a small benefit has been realized due to the use of BAT.

More recently, Lumsden[6] has shown that the use of titanium oxides strongly inhibit caustic IGSCC. Since titanium compounds have extremely low solubilities, it was postulated that the inhibitor would not be able to penetrate fouled crevices. In fact, the titanium additives were found to be less effective in the model boiler testing when the crevices were prepacked to simulate fouling. The titanium additives were more effective at inhibiting cracking in initially open crevices. These results suggest that implementation of a titanium based inhibitor may be more effective immediately following a chemical cleaning or before the crevices are significantly fouled. Several plants have gone forward with full scale additions of titanium oxides. To address the question of access of the crevice to titanium, a destructive examination of a tube support/tube intersection removed from a recently retired SG at Ringhals was conducted (9). Titanium was injected prior to shutdown of the plant, but the examination indicated that titanium was unable to penetrate the crevice. As with BAT, the potential benefits of adding the inhibitor greatly outweigh the small risk of deleterious side effects. To date there is no firm data on whether titanium has been effective in any of the plants.

The major new initiative in the materials program will address the influence of startup/shutdown on producing oxidizing conditions which may have a major influence on IGA/SCC in steam generators. The hypothesis that IGSCC may be significantly influenced by startup/shutdown conditions is based on several observations including; 1)Belgian correlations of damage being influenced by number and frequency of shutdowns, 2) known ingress of oxidants during startup, 3) direct measurement of SG ECP during startup of non-commercial plants. The program will be designed to test this hypothesis through both laboratory testing and field tests. This work will result in the development of steam generator layup/startup guidelines. A basis document, to be available by the end of 1998, will provide the available field experience and laboratory testing results to demonstrate that the most significant growth of initiated SCC occurs during the early phases of startup when the electrochemical potential at the degraded location(s) has been raised because of oxidation reactions occurring during layup/startup. Follow-up programs will be carried out.

In addition, two other mechanisms for IGSCC have recently been proposed that will be addressed in the materials program. The first, associated with the presence of aluminum silicates in crevices is being addressed by other R&D programs, primarily EDF. The results from their program will be available to the SGMP and some laboratory work will be carried out by EPRI. The other mechanism, steam phase attack has been postulated for both OTSG's in the superheated region and RSG's in steam blanketed crevices. This mechanism will be investigated by a laboratory test program over the next several years.

Advanced Chemistry Program

Improved water chemistry control is essential to reduce corrosion damage within the SG's, and the input of corrosion products into the SG's where it can foul tube surfaces and crevices. An improved understanding of the relationship between bulk chemistry parameters and local chemistry parameters where the corrosion is occurring is needed to improve corrosion control strategies. New approaches are required to control corrosion product deposition and transport within the SG's. Secondary water chemistry control is a compromise between conflicting requirements in the Balance of Plant (BOP) and the SG. Data is needed to define the optimum chemistry considering the SG and BOP on a plant specific basis.

EPRI has developed Secondary Water chemistry guidelines and revised them at 2-3 year intervals to reflect technology developments and plant experience. These guidelines are derived from work carried out in this program. Advanced technology developments are incorporated in application guidelines, which provide assistance to the plant chemists on water chemistry control, including improved amines, molar ratio control and IGSCC inhibition (Boric Acid and TiO2 Addition).

Crevice Chemistry

Most forms of secondary side SG degradation have been associated with the concentration of impurities locally in flow starved regions, such as the crevice formed between the tube and support plates, or underneath corrosion product deposits which form on tube supports, tube sheet surfaces, and free span surfaces. The concentration of impurities in these regions can be orders of magnitude greater than the bulk water. These aggressive solutions have caused a number of forms of corrosion. Since changing the material properties in situ is difficult, most of the remedial actions have focused on modifying the crevice chemistry to control the corrosion of the SG tubing. An understanding of the crevice solution is necessary to mitigate corrosion, so much effort has focused on developing insights into how crevices concentrate solutions, what chemistries exist in crevices and how potential inhibitors might work in the crevice. A major initiative within the SGMP over the past several years has been the development of a highly instrumented device for monitoring SG crevice chemistry (7) . A heated crevice monitor (HCM) has been developed and tested in the laboratory at Rockwell International. The device contains a prototypical SG tube support crevice instrumented for temperature, electrochemical and solution composition measurements. A second less complicated device has been constructed and is in operation at SJSU (8) to complement the studies at Rockwell. The development work and subsequent construction of a second instrumented heated crevice for installation at the OHI plant had been co-funded by Kansai Electric and the other Japanese PWR utilities. The autoclave was installed at OHI 1 in September 1997 and will be operational over the next 18 months.

The work at OHI will provide critical data on the development of crevice chemistry in an operating PWR. This data from a plant operating at sub-ppb impurity levels in conjunction with the laboratory data from the HCM at much higher impurity levels will provide a more complete picture of the relationship between crevice chemistry and bulk water chemistry. A crevice T/H model has been developed and initial benchmarking using the laboratory data from Rockwell has been accomplished (9), but the model also needs to be tested with actual plant data from OHI. An ECP model coupled with the T/H model (10) will also be benchmarked with the laboratory and plant data.

The results from this program will lead to improved chemistry control practices with better definition of appropriate molar ratio control practices and guidelines for the use of elevated hydrazine to optimize reducing conditions. The program will be completed by 2000 to support the next revision to the Secondary Water Chemistry Guidelines.

Recent reports of FAC of SG support plates in a few French and US plants requires an understanding of the influence of SG chemistry parameters on this damage mechanism. A report detailing the root cause and corrective actions at the Graveline plants of EDF will be completed by the SGMP in late 1997. Internal investigations by EDF are leading to new recommendations for lower hydrazine limits in some EDF plants. In addition to hydrazine, which is suspected to enhance the FAC rate, the influence of the SG pH on FAC must be better understood so that the SG chemistry can be optimized to control IGSCC of the SG tubing and to minimize the potential for FAC of carbon steel materials in the SG. Two investigations will be conducted to determine the influence of SG chemistry parameters and the SG design on FAC in PWR SG's. The first investigation will be a detailed survey of US PWR inspections for SG internals corrosion. This survey will include both inspection and chemistry data with an attempt to develop correlations between operating chemistry and damage. In parallel, a laboratory program will be conducted to directly measure the influence of SG chemistry parameters on FAC. This work will also support the next revision of the EPRI Secondary Water Chemistry Guidelines.

SG Sludge/Fouling

Corrosion product fouling of crevices and tubes is clearly related to SG corrosion. Tube fouling is implicated in the longer term decay of SG pressure performance. And, the extent of fouling determines the frequency of required chemical cleanings. Robust, measurable standards for the success of the programs in this area, therefore, are plant observables such as an increased blowdown iron (indicating improved control over corrosion product deposition), a flattening in the long term downtrend in steam pressure, and a reduction in chemical cleaning costs.

Over a number of years, chemistry interventions for SG sludge/fouling control have been focused on methods for reducing corrosion product transport into the generator. Several alternative amine programs have been developed and applied successfully in the field as a result of these efforts. At some point, however, one recognizes that a finite level of iron ingress seems likely to be unavoidable. Continued competitive pressures to improve heat transfer efficiency while holding down SG cleaning costs therefore demand an alternative approach be formulated in order to enable further improvement in iron control.

The SG Sludge/Fouling Control Program is directed at developing chemical technologies to reduce the rate of corrosion product deposition in the generator and to improve the use of wet layup and sludge lancing opportunities for achieving tube defouling and sludge removal. This program began with loop studies at AECL which demonstrated a clear effect of amine choice on the rate of iron oxide deposition onto Alloy 600 tubes under heat flux conditions. For 1998 through 2002, a significant expansion of the program is proposed to leverage the likely surface chemistry modes of action behind those results.

In the next 1 to 2 years, the program consists of two main thrusts: (1) development of surface chemistry interventions for tube fouling control based on tailoring amines to advantage the effect on deposition rate already observed at AECL; (2) investigation of polymeric dispersants as possible additives to inhibit tube fouling during operation; and, (3) investigation of wet layup treatment and sludge lancing chemistries to promote tube defouling and more efficient sludge removal. The second area began this year in collaboration with a number of utilities should culminate in a trial of a dispersant in an operating PWR. In addition, an industry guideline for qualification of any additive to the secondary cycle during operation (such as a dispersant) or during layup (such as a defouling agent) will be developed to support other new secondary chemistry initiatives.

Advanced NDE R&D Program

Improved methods for examining steam generators are needed to accurately assess the condition of tubes, sleeves, plugs and tube support structures. Only by having a thorough understanding of steam generator conditions can continued operation be justified. Improvements in the ability of NDE techniques to more reliably detect and more accurately size degradation can lead to a better understanding of degradation type, degradation growth rates and tube structural integrity. Greater accuracy of the examination measurements will provide higher confidence in the determination of the maximum allowable operating period between inspections and may provide a basis for justifying a full cycle of steam generator operation without having to perform a mid-cycle inspection. Increases in the Probability of Detection (POD) of degradation could provide the basis for decreasing the size of the inspection sample without reducing the maximum interval between inspections.

As greater numbers of inspections are required to gain a thorough understanding of the steam generator condition, the duration and cost of the examination increases. Often, the steam generator inspection is the critical path task at some point during a refueling outage. Unfortunately, the inspection techniques which are currently considered as the most comprehensive, are also typically the slower of the available NDE techniques. Although much work has been performed in the development of methods to acquire data from several probes inserted simultaneously in one channel head, rotating probe technology is significantly slower than the generally less accurate pull through techniques. There is a need to develop faster inspection techniques which provide the detection accuracy of the slower rotating probe techniques. Faster techniques would provide the opportunity to reduce the duration of the inspection and, in so doing, would result in a reduction in the inspection costs and would help to minimize the time that the steam generator inspection was the critical path activity.

The analysis of data is another area where there is need for improvement.. Two areas in which improvements in data analysis methods, for currently available NDE techniques, can benefit utilities include: 1) the development of improved techniques for measuring degradation parameters and 2) the development of automated data analysis. The development of data analysis methods for more accurately measuring degradation (e.g., crack depth profiles) could assist utilities in justifying the use of alternate tube repair criteria or could provide more precise flaw growth information for use in predicting the future steam generator condition. This information would be included as a vital part of the steam generator assessment.

The development of automated data analysis would reduce utility reliance on data analysts and would result in a more reliable and consistent assessment of the steam generator inspection data. During peak outage periods, there is often a shortage of qualified data analysts. This situation often leads to longer working hours for the data analysts and an analyst staff that often includes several less experienced individuals. Automated data analysis will lead to a reduction in both analyst staffing levels and in the number of computer workstations needed during an examination. There is also a need to improve data analyst consistency in reporting results. The use of automated data analysis will provide consistent results, not only during a given examination, but from examination to examination. The time intensive effort to investigate and resolve discrepancies between data analysts can be minimized due to the consistency provided by automated data analysis.

Improvements in steam generator NDE have the potential of providing utilities with significant benefits, including: reducing inspection costs, reducing inspection duration, providing data to justify cycle length, providing data to justify alternate repair criteria and providing data to justify steam generator operation. The first action to address NDE improvements is to evaluate existing NDE capabilities and to assess other NDE R&D efforts that that may be ongoing. NDE methods that exist, but require some improvements to meet utility needs, will be further developed. NDE methods that are in an R&D phase should be further developed if a thorough assessment of the NDE method results in a favorable status. In those areas where no useful method either exists or is under development to address utility needs for improved NDE, R&D activities will be initiated.

Thermal Hydraulic Program

Improved methods for characterizing the current condition of installed Steam Generators and of predicting and controlling their future rate of degradation are needed to minimize future capacity losses and further extend life. In addition, the improved technology can be used in the design of replacement and new SGs and assure that future SGs meet utilities' reliability and service life requirements. This requires advanced technology to perform detailed plant-specific thermal and hydraulic analysis, needed to evaluate the effects of tube plugging, sleeving, degradation mechanisms such as under-deposit corrosion, flow induced vibration, tube wear and fatigue, and the assessment of design fixes, modifications such as flow split, T(hot) reduction, etc. Analysis of fouling and sludge deposition as a function of operating conditions and water chemistry provides the needed input to design inspection and mitigation methods.

EPRI's Thermal hydraulics workstation version 1 was developed and released in 1996. Its applications include calculation of thermal and hydraulic conditions in operating steam generators to evaluate the effects of plugging, sleeving, and other degradation mechanisms, thermal performance under different operating conditions, identification of susceptible regions to fouling and deposition to provide information for in-service inspection. The workstation software will be improved and implemented on a PC (Windows 95, NT). Improvements in the future will include a deposit model based on combining thermal hydraulics with water chemistry capable of calculating the growth of fouling and deposits on tube surfaces and other regions. This information is useful for scheduling chemical cleaning, sludge removal, and evaluation of performance degradation. Combination of this advanced method with other tools such as CHECWORKS will provide utilities with an analysis method to evaluate corrosion product ingress and deposition within the steam generator and regions susceptible for under deposit corrosion. The fatigue and wear analysis methodology, which couples the tube vibration response with fatigue and wear rate correlation and material property data base, will be implemented on a computer work station. Practical use of the improved and validated workstation methodology will help in extending the life of existing steam generator units by providing information for economical preventive maintenance actions and in service inspection requirements.

STATUS AND FUTURE PROSPECTS FOR STEAM GENERATOR TUBE DEGRADATION

R&D to develop remedies for the various forms of steam generator tube degradation has been very beneficial to US utilities. Average capacity factor losses (see Figure 1 have been decreased from 5.5% (1980-1984) to 3% (1987-1994), average steam generator life has been substantially extended and the forced outage rate due to tube leaks has been reduced by a factor of ~7 from its peak in 1976. US utility estimates put the present value of these improvements at several billions of dollars.

However, for the past several years, worldwide tube plugging rates which were trending down in the early 1980s, have been increasing slowly and currently are at values which suggest that the average steam generator life will be 20 to 25 years. Thus, most original equipment steam generators may have to be replaced within the 40-year plant license life. Because the average age of installed steam generators in the US currently is ~15 years, many replacements may be necessary in US plants within the next 10 to 15 years unless remedial measures and/or improved repair methods can be developed and deployed for ODSCC/IGA, which currently appears to the damage form that will limit the life of most generators.

The challenge for the near future is to make further improvements in capacity factors as the nuclear fleet continues to age. As competitive pressures continue to influence decisions that effect corrosion damage in PWRs, the challenge is to make further improvements in a cost-effective manner. This means that utility remedial actions will become more plant specific as individual utilities weigh the risks and benefits of the remedial actions available to them..

The R&D program in the materials and chemistry programs so far have led to a good but incomplete knowledge of the mechanisms for concentrating impurities in SGs and the underlying corrosion processes themselves. Mitigation strategies and techniques for evaluating what conditions exist in the SG crevices have been developed and are now being implemented based on the current understanding of these phenomenon. Work in the area of NDE research should lead to more accurate and less expensive inspections. This will become especially important as US utilities will be required to perform condition monitoring and operational assessments during each refueling outage. Improved NDE will also allow operators to more quickly identify initiation of damage mechanisms so that mitigation strategies can be implemented before the problem becomes too severe. The work in the T/H area has been effectively used in designing new and replacement SG's. Additionally, the eventual coupling of chemistry and T/H models will allow for more accurate predictions of SG fouling and the development of improved mitigation strategies.

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Figure 1