MATERIALS AGING MANAGEMENT PROGRAMS AT NUCLEAR POWER PLANTS IN THE UNITED STATES

T. J. Griesbach, B. M. Gordon, J. Zhang[a]
Structural Integrity Associates, Inc, San Jose, USA
[a]B&W Tech, Inc, Houston, USA / B&W Energy T&E (Shanghai), Ltd., Shanghai, China

E-mail address of main author: mherrera@structint.com

Abstract

Recent events regarding degradation of materials in nuclear power plants have been very costly to the industry and have implications for reliability, safety and performance. As a result, industry executives implemented a Nuclear Energy Institute Materials Initiative (NEI 03-08) for proactive management of materials aging issues at all plants in the United States. This Materials Initiative, which began in May 2003, will integrate and coordinate the industry resources devoted to the materials issues. Additionally, it requires that each plant supports this effort through funding and implementation of the applicable guidance documents with “mandatory” and “needed” actions. An overarching Materials Degradation Management Program (MDMP) must be in place at all plants (effective August 2006) that coordinates the many individual sub-programs affecting the reactor coolant system materials.

The key areas to be included are: BWR vessels and internals program, Alloy 600 management, reactor vessel integrity, PWR vessel internals, boric acid corrosion control, steam generator management program, primary and secondary system water chemistry, and fuel reliability. Other programs such as non-destructive examination (NDE) and inservice inspection, flow accelerated corrosion (FAC), fatigue management, and leak management may also be incorporated under the overarching program.

The success of the NEI 03-08 Materials Initiative will depend on how well each utility performs and how well these programs are adopted by the sites. Improvements in the overall performance should be recognized in the Program Health Reports and in the individual plant performance indicators such as fewer unplanned outages, improved reliability and increased capacity factors. This paper reviews the status of the NEI 03-08 Materials Initiative and implementation of aging management programs in the United States including recent activities and general approaches for managing materials degradation issues.

1. Introduction

Aging effects in nuclear power plants must be managed to ensure that the design functions remain available throughout the service life of the plant. From a safety perspective, this implies that aging degradation of structures, systems and components important to safety remain within acceptable limits. From an operability perspective, this also means that plants will take the necessary actions to prevent or control unplanned outages leading to reduced reliability caused by degradation or failures, including leaks or component failures. Long outages for repair or replacement of degraded components can lead to reduced capacity factors and loss of plant availability. Capacity factor losses in BWRs have mainly been the result of stress corrosion cracking (SCC) of piping and internals. After fairly high capacity factor losses in BWRs in the 1980s and 1990s due to SCC repairs, these issues have been fairly well managed to avoid further losses. Capacity factor losses in PWRs have been on the increase recently due to steam generator concerns leading to replacement and Alloy 600 dissimilar metal weld cracking. Because of this, the utility executives at all plants in the U.S. have embarked on an ambitious Industry Initiative to minimize the future impact of materials degradation on their plants. The Materials Initiative known as NEI 03-08 has been implemented voluntarily at all plants without the need for additional regulations, and compliance with the requirements is being monitored by the Institute of Nuclear Power Operations (INPO).

2. Background

The economic realities of the current electric power market makes it essential for nuclear power plants to achieve capacity factors in excess of 90% on a routine, continuing basis. Many of the nuclear plants in the U.S. have been able to meet this goal in recent years. However, maintaining this high level of performance may become more difficult in the future because as plants continue to age when time-dependent aging effects are on the increase. This could in turn lead to plant derating, forced or extended outages for inspections and repairs, and higher operations and maintenance costs. For plants approaching the license renewal stage of plant life, this poses additional concerns for reliability and safety to meet the goals for extended plant life.

Understanding the plant aging mechanisms and taking steps to prevent unanticipated failures is a primary objective for dealing with the aging concerns. The initial operation of the early commercial light water reactors encountered few corrosion and age-related degradation problems. Corrosion was considered in all plant designs, and corrosion was not considered as a serious problem since materials were chosen to be corrosion resistant. Any problems discovered in service were quickly repaired and did not have a major impact on plant availability. As more plants entered service and more operating time was accumulated on existing plants, more corrosion-related incidents appeared in the piping, reactor internals and other components. Eventually, the corrosion of the plant and fuel materials did seriously impact plant availability, economics, reliability, and, in some cases, plant safety. Table 1 presents a brief summary of the corrosion history of LWRs. Figure 1 shows the trends in capacity factor losses in BWRs in the United States through 2004. After the initial problems were discovered and corrected, the improvements in capacity factor losses were significant. However, new aging mechanisms related to steam generator degradation and the cracking of Alloy 600 dissimilar metal welds have posed additional problems for the nuclear industry.

To quantify the fiscal impact of these types of corrosion incidents on the cost of operating nuclear power plants, the Federal Highway Administration (FHWA), Office of Infrastructure Research and Development funded an economic evaluation [1]. The annual nuclear power costs of corrosion were divided into three main categories:

1. Corrosion-related causes of partial LWR outages - $5M/year
2. Corrosion-related causes of zero power LWR outages - $665M/year
3. Contribution of corrosion to LWR operation and maintenance (O&M) - $2B/year

As can be seen in Table 2, which presents the ten most expensive operating and maintenance (O&M) costs of corrosion for one particular reactor site, i.e., Oconee 1, 2 and 3 PWRs, the cost of corrosion in the nuclear power industry is extremely high.

In the past six years there have been several materials degradation events at U.S. plants that were unexpected, and these events caused the industry to reevaluate the need to be more proactive to avoid more serious consequences from age-related degradation of materials. In 2003 the utility executives made a management policy commitment involving all nuclear plants in the United States to ensure that the management of materials degradation and aging is forward looking and coordinated to the maximum extent possible. The industry also committed to rapidly identify, react, and effectively respond to emerging issues on aging of materials. The Industry Materials Initiative is known as NEI 03-08 [2], and it has now been implemented at all plants in the United States.

2.1 The NEI 03-08 Materials Initiative

The NEI 03-08 Materials Initiative requires that every PWR and BWR in the United States shall establish and maintain a Reactor Coolant System (RCS) Materials Degradation Management Program (MDMP) that incorporates the following key elements:

- A high level program that ensures the utility implementation of the requirements of NEI 03-08, and
- Implementation of the "Mandatory" and "Needed" elements of the reference documents listed in the "Materials Initiative Guidance". The "Mandatory" and "Needed" elements include inspections, evaluations, and repairs as recommended in the published documents; additional "Good Practice" elements may also be incorporated.

In addition, the Initiative requires that each utility participate in the management groups, fund the various programs, contribute the technical leadership and executive leadership to these efforts, share all materials operational experience, implement appropriate guidelines and expectations, and develop a long-term strategic plan for managing the aging issues.

3. Aging Management Programs

The Reactor Coolant System Materials Degradation Management program must include the following sub-programs where applicable:

- PWR reactor vessel integrity management program
- BWR vessel and internals management program
- Alloy 600 management program
- Boric acid corrosion control program
- PWR steam generator management program

Other sub-programs may also be linked to the RCS MDMP, including:

- In-service Inspection (ISI) program
- Nondestructive Examination (NDE) program
- Chemistry control program
- Fatigue management program (thermal and environmental)
- PWR reactor internals aging management program
- Reactor fuel performance program

These sub-programs may already be in place, or they may need to be created as part of an overall approach to managing aging effects in plants.

3.1 PWR Reactor Vessel Integrity Management

Resistance to brittle fracture is of primary concern to ensure the integrity of the reactor pressure vessel (RPV). Failure of the RPV is beyond the design basis, and therefore, protecting the integrity of the vessel is of the utmost importance to plant safety.

Furthermore, radiation-induced embrittlement is the dominant aging concern that may limit the useful life of a nuclear plant. Neutron irradiation reduces the toughness of the ferritic steel base metal and welds, and this effect must be monitored to assure that the intended safety margins are maintained. An embrittlement management program must be in place to manage pressure-temperature operating limits, pressurized thermal shock, low Charpy upper shelf energy materials, and low temperature overpressure protection (LTOP) system setpoints. These areas must be reevaluated whenever a surveillance capsule is tested, or when fluence in the vessel beltline is recalculated, or for plant license renewal.

3.2 BWR Vessel and Internals Management

The BWR Vessel and Internals Program (BWRVIP) has been operative since the early 1990s when the evaluation of BWR core shrouds revealed an industry-wide problem with intergranular stress corrosion cracking (IGSCC) and irradiation-assisted stress corrosion cracking (IASCC) associated with core shroud welds. The BWRVIP was chartered to support a program addressing the problems of BWR reactor internals, internals attachments, vessel welds, and vessel nozzles. The BWRVIP inspection and evaluation guidelines supplement the Code and regulatory mandated inspections to assure the safety and operability of these plant components. The BWRVIP document "Guidelines for the Management of Materials Issues," BWRVIP-94, Revision 1 [3] outlines the specific actions for BWR utilities to follow in managing the BWR vessel and internals materials issues under the NEI 03-08 Materials Initiative.

3.3 Alloy 600 Management

Under the NEI 03-08 Materials Initiative, each PWR plant must develop and document an Alloy 600 management plan, defining the process it intends to use to maintain the integrity and operability of each Alloy 600/82/182 component for the remaining life of the plant. This plan should include consideration of mitigation (zinc injection, mechanical stress improvement process (MSIP), etc.), inspection (type and frequency), repair (weld overlay, overlay, or mechanical clamp), and replacement (substitute with stainless steel or Alloy 690/52/152) options. This requirement was to be completed within eighteen months from the date of issuance of the implementing guidance document, MRP-126 [4]. The inspection plan for Alloy 600 butt-welds is contained in MRP-139 [5]. These inspections and/or mitigation measures are now being completed at each PWR plant. One of the primary measures being used to mitigate the effects of Alloy 600 cracking is a full thickness weld overlay.

3.4 Boric Acid Corrosion Control

Boric acid corrosion (BAC) represents a significant maintenance concern at many pressurized water reactor (PWR) plants because of the large number of potential leakage sources -- flanged joints, valve packing, mechanical seals, and fittings. PWRs use borated water in their primary coolant system to control reactor criticality. Under certain conditions, leakage of borated water from primary system gaskets, seals, valve packing, and primary water stress corrosion cracking (PWSCC) can result in significant BAC of associated carbon steel or low-alloy steel components. Under extreme conditions, BAC can compromise the integrity of plant primary system components. In 1988, the U.S. Nuclear Regulatory Commission (NRC) issued Generic Letter 88-05, which required all operators of PWRs to develop and implement programs to address BAC issues in their plants. EPRI published Boric Acid Corrosion Control Guidelines [6] for PWRs to manage BAC, and each plant is required to have a BACC program.

3.5 PWR Steam Generator Management

The purpose of a Steam Generator Management Program (SGMP) is to ensure steam generator tube integrity and extend the life of PWR steam generators. The program must contain a balance of prevention, inspection, evaluation and repair, and leakage monitoring measures. Each plant owner must document and implement their SGMP through plant procedures and other licensee-controlled documents. The program must contain these elements:

(a) *Degradation Assessment.*

- Prior to planned steam generator inspections, each plant owner must perform a degradation assessment of the reactor coolant boundary within the steam generator that includes:
  - Choosing techniques to test for degradation based on the probability of detection and sizing capability
- Establishing the number of tubes to be inspected
- Establishing the structural limits
- Establishing the flaw growth rate or a plan to establish the flaw growth rate

(b) *Inspections*
Each PWR owner must plan inspections according to the expected tube degradation and follow the inspection guidance contained in the EPRI PWR Steam Generator Examination Guidelines [7].

(c) *Integrity Assessment*
Each PWR owner must assess tube integrity after each steam generator inspection to account for uncertainties and to evaluate condition of the tubing relative to performance criteria.

(d) *Tube Plugging and Repairs*
Each plant owner must qualify and implement plugging and repair techniques in accordance with industry standards.

(e) *Primary-to-Secondary Leak Monitoring*
Each plant owner must establish primary-to-secondary leak monitoring procedures.

The SGMP must be developed in accordance with the EPRI Steam Generator Management Program Guidelines and NEI 97-06 [8], the documents that define the requirements for each program.

3.6 Fatigue Management

Fatigue of piping systems is an age-related degradation mechanism requiring aging management. Unanticipated transients, thermal stratification and striping can result in fatigue cracking at the locations of high cycling. A thermal fatigue screening evaluation is required for all PWR plants under NEI 03-08, and any actions indicated by the evaluation must be undertaken in a timely manner consistent with normal plant operation and refueling outages. For example, an assessment of non-isolable normally stagnant branch lines in the reactor coolant system is required. A screening approach is provided in MRP-146 [9] that may be used to eliminate the requirement for further evaluation, monitoring, or inspection of qualifying lines. These screening evaluations were completed for all PWR plants by June 2007. Additional fatigue management guidelines are available for managing the long-term effects of thermal fatigue in nuclear power plants, and many plants have implemented on-line fatigue monitoring systems such as FatiguePro [10] to manage fatigue during the initial 40-year license life and for plant license extension.

3.7 PWR Internals Aging Management

Aging concerns and degradation in PWR vessel internals must be adequately managed to assure functionality for plant license renewal. Cracking and other aging effects could lead to loss of function of critical internals components. UT indications and cracking have been detected in baffle-former bolts in some French plants. A few indications have been observed in baffle bolts in U.S. plants. Safety analyses during a LOCA or seismic event requires that a certain number of baffle bolts remain intact to assure core coolability during safe shutdown. Possible aging mechanisms include:

- Irradiation Embrittlement of Wrought or Forged Stainless Steel
- Irradiation Embrittlement/ Thermal Aging of Cast Austenitic Stainless Steel
- IASCC/SCC
- Stress Relaxation of Bolted Connections
- Void Swelling

There are currently no industry guidelines for aging management of internals. However, Inspection & Evaluation Guidelines are currently under development through the EPRI Materials Research Program (MRP), and when published in 2008, these guidelines will contain mandatory and needed elements for all PWRs under the NEI 03-08 Materials Initiative.

4. Summary

An effective Reactor Coolant System MDMP should have technical, cultural, and programmatic aspects for successful implementation. From a technical standpoint, the RCS materials should be managed to meet structural, leakage, and functional performance objectives. The cultural aspects are important to adopt a corporate philosophy for managing materials degradation that is proactive and maintains a long-term view of the aging mechanisms. This includes personnel development, succession planning, and industry participation. The programmatic aspects are clear; the RCS MDMP should be defined by written programs or procedures that define the scope, objectives, process, organizational structure and performance objectives for each plant. These programs are being audited by INPO for adequacy and completeness to assure that materials degradation issues are being managed properly for the long term.

REFERENCES

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[6] "Boric Acid Corrosion Guidebook, Revision 1: Managing Boric Acid Corrosion Issues at PWR Power Stations," EPRI, Palo Alto, CA: 2001. 1000975 (Proprietary).

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[8] *NEI 97-06, Revision 2, Steam Generator Program Guidelines,* Nuclear Energy Institute, May 2005.

[9] "Materials Reliability Program: Management of Thermal Fatigue in Normally Stagnant Non-Isolable Reactor Coolant System Branch Lines (MRP-146)," EPRI, Palo Alto, CA: 2005. 1011955 (Proprietary).

[10] *FatiguePro: On-Line Fatigue Monitoring Program*, Structural Integrity Associates.

Table 1. A Brief Summary of the Corrosion History of LWRs

Corrosion Event	Time of Detection
Alloy 600 IGSCC in a laboratory study	Late 1950s
IGSCC/IASCC BWR stainless steel fuel cladding	Late 1950s and early 1960s
BWR IGSCC of Type 304 stainless steel during construction	Late 1960s
IGSCC of furnace sensitized Type 304 during BWR operation	Late 1960s
IGSCC in U-bend region of PWR steam generator	Early 1970s
Denting of PWR Alloy 600 steam generator tubing	Mid 1970s
PWSCC of PWR Alloy 600 steam generator tubing	Mid 1970s
Pellet-cladding interaction failures of BWR zircaloy fuel cladding	Mid 1970s
IGSCC of BWR welded small diameter Type 304 piping	Mid 1970s
IGSCC of BWR large diameter Type 304 piping	Late 1970s
IGSCC of BWR Alloy X-750 jet pump beams	Late 1970s
IGSCC of BWR Alloy 182/600 in nozzles	Late 1970s
Accelerating occurrence of IGSCC/IASCC of BWR internals	Late 1970s
PWSCC in PWR pressurizer heater sleeves	Early 1980s
Crevice-induced IGSCC of Type 304L/316L in BWRs	Mid 1980s
FAC of single phase carbon steel systems in PWRs	Mid 1980s
PWSCC in PWR pressurizer instrument nozzles	Late 1980s
IGSCC of BWR low carbon (304L/316L) and stabilized stainl steels (347/321/348) in vessel locations	Late 1980s – present
IGSCC of BWR internal core spray piping	1980s – present
Axial PWSCC of Alloy 600 of PWR top head penetration	Early 1900s
Circumferential PWSCC of j-groove welds	Early 1900s
PWSCC of PWR hot leg nozzle Alloy 182/82	Early 2000s
PWSCC induced severe boric acid corrosion of a PWR head	Early 2000s

Table 2. Ten Most Expensive O&M Costs of Corrosion for the Oconee 1, 2 and 3 PWRs [1]

Work Activities	Cost	Cost %	% Attributed Corrosion	Cost of Corrosi
Steam Generators	$22,757,765	8.26	95	$21,619,877
Maintenance Engineeri Support	$13,204,783	4.79	33	$4,357,578
Radiation Protection	$12,116,142	4.40	80	$9,692,912
Mechanical Components	$10,709,285	3.89	33	$3,534,064
Maintenance Function Support	$10,675,567	3.87	33	$3,522,937
Work Control	$6,073,111	2.20	33	$2,004,127
Chemistry	$5,570,659	2.02	60	$3,342,395
Piping	$2,391,285	0.87	60	$1,434,771
Coatings and Painting	$2,279,358	0.83	45	$1,025,771
Decontamination	$1,216,689	0.44	80	$973,351
Remaining Activities	$188,590,607	68.43		$17,122,624
Total	$275,585,251	100.00	25	$68,896,313

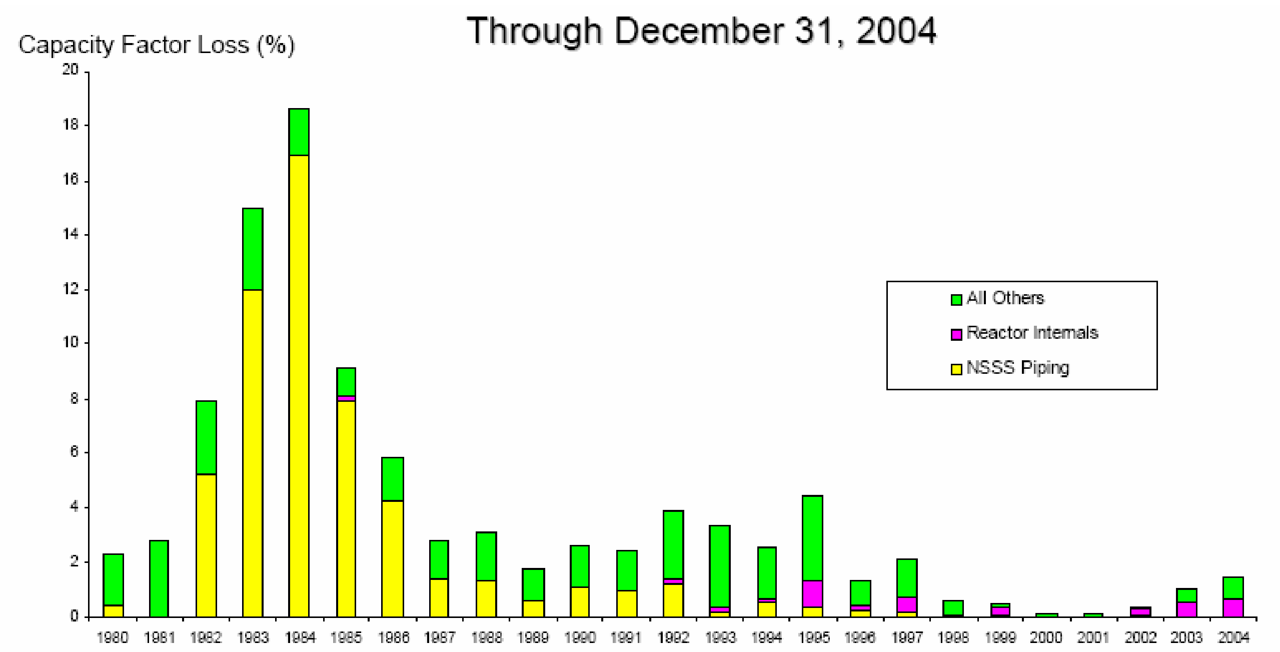

FIG. 1. Capacity Factor Losses due to Corrosion-Related Damage in BWRS
(Source: Electric Power Research Institute)