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Plant Engineering: Impact of Electric Power Uprates on Flow-Accelerated Corrosion

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Technical Update, July 2011

EPRI Project Manager

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ABSTRACT

This report describes a study done to examine the impacts of stretch power uprates and extended power uprates on flow-accelerated corrosion (FAC). Power uprates generally change the operating conditions, and such changes are reflected in the rates of FAC. Prior to uprates, utilities perform calculations using the Electric Power Research Institute computer program CHECWORKS[1] to estimate the impact of the changes of conditions on the rates of FAC of the modeled components. Because there have been some anecdotal reports of anomalous behavior following upgrades, a study was performed to document and examine such occurrences.

All U.S. nuclear units that have experienced a power uprate of 6% or more—a total of 22 units—were surveyed. The maximum power uprate was 20%. The results of the survey showed that only one of the 22 reported some limited anomalous behavior following the uprate. This experience was examined and discussed.

Based on this work, the use of CHECWORKS to estimate the impact of the changes of conditions on FAC following an uprate has been validated through the operating experience of the units surveyed.

Keywords
CHECWORKS
Flow-accelerated corrosion (FAC)
Power uprates

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[1] *CHECWORKS* is a trademark of the Electric Power Research Institute.

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INTRODUCTION

1.1 Flow-Accelerated Corrosion

Flow-accelerated corrosion (FAC) is a degradation mechanism that attacks carbon steel material under certain, specific circumstances. Unfortunately, these conditions are often found in fossil and nuclear power plants. FAC results in global wall thinning, and if unchecked can lead to component failures. There have been several catastrophic failures of piping in nuclear power plants notably at Surry in 1986 and in Mihama (Japan) in 2004.

Because of its importance, FAC has been the subject of a large amount of research. This research has resulted a fundamental understanding of the nature of the attack as well as the parametric influences.

1.1.1 Parametric Influences

As described in depth in the FAC book [1], the parametric effects can be divided into three categories:

- Water Chemistry – The concentration of oxygen and the pH at the operating temperature have been shown to be the most important parameters. The greater the concentration of dissolved oxygen and the higher the pH at the operating temperature the lower the rate of FAC.
- Hydrodynamics – The liquid velocity, the local geometry, and the steam quality are also important parameters. Generally, geometries that produce turbulence (e.g., a flow orifice) result in higher rates of FAC.
- Materials – The alloying elements of chromium, copper and molybdenum have been shown to lower the rate of FAC. In particular, the influence of chromium is the strongest.

1.2 Utility Programs to Deal with FAC

To deal with the wall thinning caused by FAC, utilities have developed inspection programs. In the United States, NSAC-202L [2] is the document that is universally used for program guidance. Because of differences between and among systems, operating conditions and types of components nuclear utilities have divided their programs into three areas. Note that different utilities have somewhat different definitions for the boundaries between the categories.

- Large Bore - Modeled – Piping systems with known operating conditions and nominal diameters usually greater than 2 inches (~ 50 mm) are modeled using a computer program to help prioritize the large number of components for inspection. In the U.S., the program that is used is CHECWORKS™ Steam Feedwater Application [3].
- Large Bore - Susceptible Non-Modeled – Piping systems with unknown operating conditions and nominal diameters greater than 2 inches (~ 50 mm) are not modeled. Rather, engineering judgment tempered by operating experience is used to select inspection locations.

- Small-Bore – Piping systems that are 2 inches (~50 mm) and smaller or systems constructed using socket welded fittings are normally treated separately from the other two categories. This is because the inspection techniques are normally different and the fact that program strategies are often different between small-bore and large bore systems. Inspection locations are determined by engineering judgment and operating experience.

1.3 Modeling FAC with CHECWORKS™

Because of the large number of susceptible components, computer modeling of large-bore susceptible piping has become common, and in fact, is universally done in the U.S. nuclear industry using CHECWORKS™. It should be stressed that CHECWORKS™ models are used only for large-bore piping that has a well defined set of operating conditions including the time of operation. Thus there are significant portions of the steam/feedwater systems that are not modeled with the program. The inspection locations for these portions of the plant are selected using a combination of engineering judgment, the guidance found in NSAC-202L [2] and operating experience.

1.4 Power Uprates

In recent years, due to favorable economics, many plants in the United States have performed a power uprate to increase the licensed power of the unit. As uprates increase the power level they are a licensing issue, and as such the Nuclear Regulatory Commission (NRC) is responsible for ensuring that the new power is acceptable under their regulations. As such, the NRC has defined three types of uprates – Measurement Uncertainly Recapture, Stretch Power Uprate, and Extended Power Uprate. They are defined as:

- **Measurement uncertainty recapture** (MUR) power uprates are less than 2 percent and are achieved by implementing enhanced techniques for calculating reactor power.
- **Stretch power uprates** (SPU) are typically up to 7 percent and are within the design capacity of the plant. Stretch power uprates usually involve changes to instrumentation set points but do not involve major plant modifications.
- **Extended power uprates** (EPU) are greater than stretch power uprates and have been approved for increases as high as 20 percent. These uprates require significant modifications to major balance-of-plant equipment.

A complete list of approved power uprates and their approved dates can be found at the NRC website [4].

1.4.1 Implications of a Power Uprate

A SPU or an EPU will involve changes to the operating conditions (i.e., pressures, temperatures, flow rates and steam qualities) and possibly the water chemistry as well. EPU’s may also involve change in plant design and hardware modifications. Consequently, the FAC implications of an uprate should be considered.

1.4.1.1 Excerpt from NSAC-202L

As mentioned above, NSAC-202L [2] is the industry consensus document. In it, it is recommended that:

> It is recognized that even small power uprates can have a significant affect on FAC rates. This can be caused by changes to equipment and changes to system operating conditions such as flow rates, temperature, dissolved oxygen, and steam quality. When power uprates are being considered, it is recommended that the proposed changes to operating conditions and any possible changes to the plant heat balance diagram be fully reviewed and evaluated using the Predictive Plant Model.[2] Potential changes to the Susceptible-Not-Modeled lines should also be considered. This should include identification of any piping areas and equipment where FAC rates are predicted to significantly increase such that material upgrades can be considered and changes to the plant inspection plan can be made.
>
> It is recognized that power uprates can be very minor or quite significant. It is recommended that each change to the plant heat balance diagram be evaluated for its effect on FAC in the susceptible systems.[3]

1.4.2 Licensing Considerations

The significance of FAC is recognized by the NRC, and an applicant for a power uprate normally has to demonstrate that it has considered the impact of the power increase on the FAC program. Utilities often will perform a detailed CHECWORKS™ analysis to examine the impact of the uprate on the predicted rates of FAC. Based on this analysis, the inspection programs are normally adjusted to account for the higher predicted rates in portions of the systems. As plant configurations, amounts of resistant material and way in which the uprate is performed vary greatly, the CHECWORKS™ analysis is plant specific.

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[2] Author's note – the "plant predictive model" normally refers to the CHECWORKS™ model.

[3] Section 4.3.1, "FAC Analysis of Power Uprates," from *Recommendations for an Effective Flow-Accelerated Corrosion Program (NSAC-202L-R3).* EPRI, Palo Alto, CA: 2006. 1011838.

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OBJECTIVES

The objectives of this work were to:

- Review US Experience with FAC in plants that have had experience a significant power uprates.
- Present and examine any anomalous behavior found. That is, occasions where the pre-uprate CHECWORKS™ predictions did not match the post-uprate experience.
- Discuss any inadequacies found in the modeling approaches used.

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APPROACH

In order to meet the above objectives, a two-step approach was taken using a survey with follow-up analysis as needed.

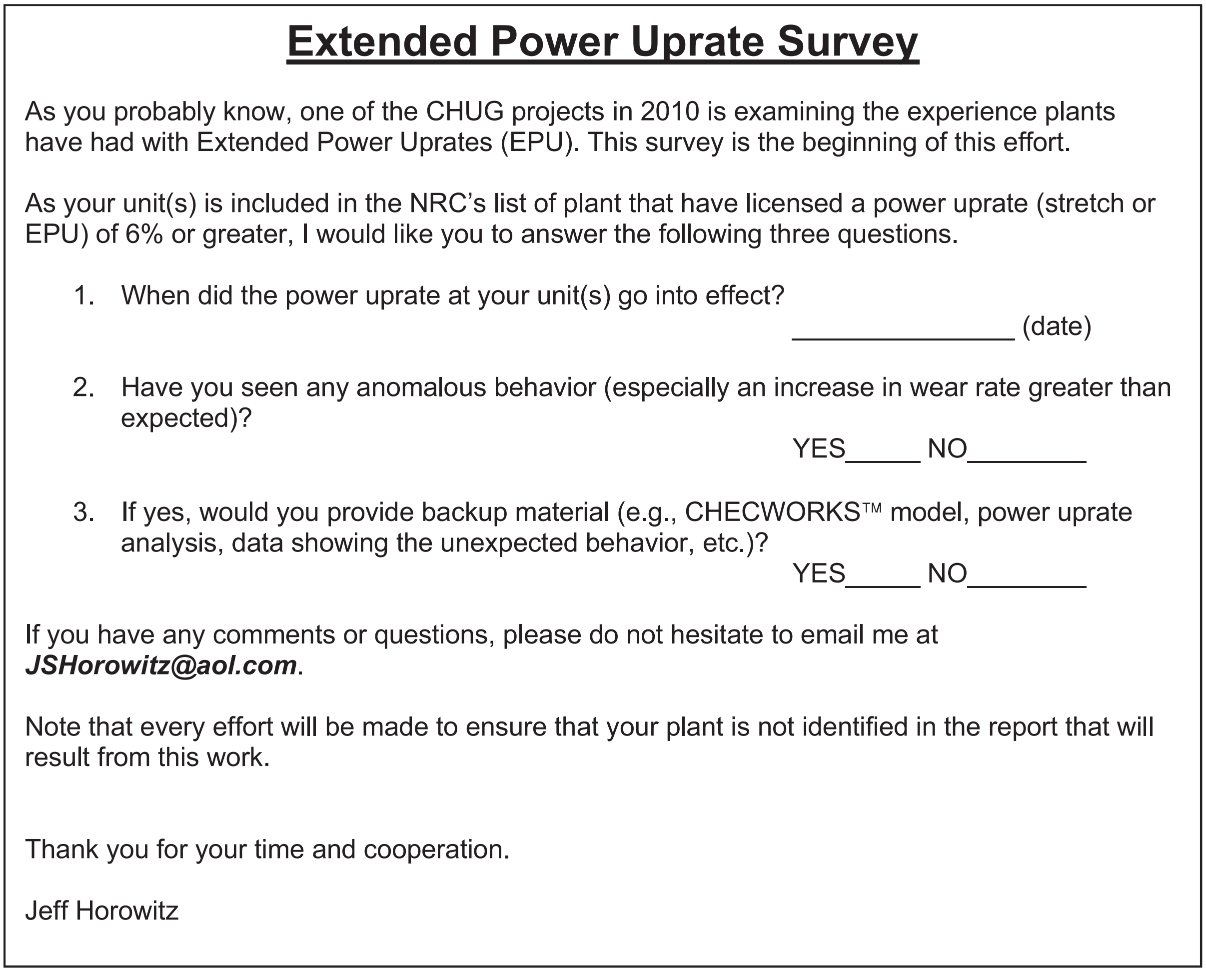
3.1 Units Surveyed

The complete list of uprates published by the NRC [4] was examined. All units with an approved uprate of greater than 6% were selected. This yielded 22 units with an increased power level ranging from 6 to 20%. These units are listed in Table 3-1. Each of these units was sent a simple survey – shown in Table 3-2.

Table 3-1
List of Plants Surveyed – Data from Reference 4

Plant	Type	Percentage	Date Approved	Stretch (S) or Extended (E)
Kewaunee	PWR	6	2/27/2004	S
Monticello	BWR	6.3	9/16/1998	E
Millstone 3	PWR	7	8/12/2008	S
ANO-2	PWR	7.5	4/24/2002	E
Hatch 1	BWR	8	10/22/1998	E
Hatch 2	BWR	8	10/22/1998	E
Waterford	PWR	8	4/15/2005	E
Beaver Valley 1	PWR	8	7/19/2006	E
Beaver Valley 2	PWR	8	7/19/2006	E
Susquehanna 1	BWR	13	1/30/2008	E
Susquehanna 2	BWR	13	1/30/2008	E
Brunswick 1	BWR	15	5/31/2002	E
Brunswick 2	BWR	15	5/31/2002	E
Hope Creek	BWR	15	5/14/2008	E
Duane Arnold	BWR	15.3	11/6/2001	E
Ginna	PWR	16.8	7/11/2006	E
Dresden 2	BWR	17	12/21/2001	E
Dresden 3	BWR	17	12/21/2001	E
Quad Cities 1	BWR	17.8	12/21/2001	E
Quad Cities 2	BWR	17.8	12/21/2001	E
Clinton	BWR	20	4/5/2002	E
Vermont Yankee	BWR	20	3/2/2006	E

Table 3-2
Survey Used



Extended Power Uprate Survey

As you probably know, one of the CHUG projects in 2010 is examining the experience plants have had with Extended Power Uprates (EPU). This survey is the beginning of this effort.

As your unit(s) is included in the NRC's list of plant that have licensed a power uprate (stretch or EPU) of 6% or greater, I would like you to answer the following three questions.

1. When did the power uprate at your unit(s) go into effect?
   _______________ (date)
2. Have you seen any anomalous behavior (especially an increase in wear rate greater than expected)?
   YES_____ NO________
3. If yes, would you provide backup material (e.g., CHECWORKS™ model, power uprate analysis, data showing the unexpected behavior, etc.)?
   YES_____ NO________

If you have any comments or questions, please do not hesitate to email me at ***JSHorowitz@aol.com***.

Note that every effort will be made to ensure that your plant is not identified in the report that will result from this work.

Thank you for your time and cooperation.

Jeff Horowitz

3.2 Follow Up Analysis

Of the total of 22 units surveyed, only one unit reported anomalous behavior. This unit is a BWR that had experienced an EPU. This unit will be denoted as BWR-A.

3.3 BWR-A

3.3.1 Operating Experience

This unit initially reported unanticipated damage to a feedwater heater nozzle – denoted in the unit as 4B. This experience was first reported at a CHUG meeting, and this material is summarized below.

- **Geometry** – A 16 inch (406.4mm) by 18 inch (457.2mm) with a 3/8 inch (9.525mm) nominal wall extraction steam expander welded to an 18 inch (457.2 mm) with a ½ in (12.7 mm) carbon steel nozzle. The nozzle has a stainless steel liner that starts 1 inch (25.4 mm) downstream of the attachment weld.

- **Replacement history –** The carbon steel piping immediately upstream of this nozzle was replaced with P-22 chrome-moly (i.e., FAC-resistant) material in 1994.
- **Operating conditions** – The conditions before and after the EPU are presented in Table 3-3. Note that for the changes of conditions expected for the EPU, a CHECWORKS™ analysis predicted an increase in FAC rate of 31% over the pre-EPU conditions with a projected wear rate of 60.9 mils per year (1.55 mm per year). Note that this prediction was for a "typical" component in this area as the unusual geometry of the nozzle itself could not be modeled using CHECWORKS™.
- **Inspection history –** The nozzle area was inspected in 2006. This inspection was aimed at detecting a possible entrance effect at the attachment weld.[4] The readings at the toe of the weld were approximately 0.450 to 0.525 inches (11.4 to 13.3mm).

  This area was inspected again in 2009 after the EPU. The readings at the toe of the weld were approximately 0.150 to 0.225 inches (3.8 to 5.7 mm). Due to this significant wear, an internal weld build up was used to restore the damaged area.
- **Extent of condition** – As a result of this unexpected wear, the nozzles of the two sister feedwater heaters (4A and 4C) and the nozzles of the next lower pressure feedwater heaters (3A, 3B, and 3C) were examined at this time using a 4" by 4" (101.6 mm x 101.6 mm) grid. Nothing significant was seen at this time.

Table 3-3
BWR-A Operating Conditions

	Before EPU	**After EPU**
Pressure – psig (MPa)	104 (0.717)	106 (0.731)
Temperature – °F (°C)	330 (165.6)	342 (172.2)
Steam Quality	96.78%	96.7%
Relative wear rate from CHECWORKS™	100%	131%

3.3.2 2010 Re-Inspections

Because of this experience, the sister feedwater heater nozzles and the next lower pressure set of nozzles were re-inspected in 2010. These inspections were performed using a 1" by 1" (25.4 mm x 25.4 mm) grid as opposed to the larger grids used in the earlier inspections. The inspected areas started at the toe of the pipe/nozzle weld and covered the 360° around the nozzle. The grid extended 4" (101.6 mm) downstream. Wall loss was found at the toe of the weld for the 3C, 4A, and 4C nozzles. Wall thickness was near nominal 1 inch (25.4 mm) downstream of the weld. As the thicknesses measured were at or below the minimum acceptable thickness, weld build up was

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[4] The FAC entrance effect can occur when flow passes from a FAC-resistant material to a FAC-susceptible material. Damage immediately downstream of the transition is sometimes observed. This effect is discussed in detail in [5].

performed over the entire nozzle for a distance of 1 inch (25.4 mm). All of the nozzles are scheduled for re-inspection in the 2012 outage.

3.3.3 Assessment by the Plant FAC Engineer

In answering the question, “Is the experience caused by the EPU?” the plant FAC engineer stated that these nozzles were inspected using the larger grid in the outage prior to the EPU and everything was close to nominal. The 4B nozzle was inspected in the outage following the EPU and the damage was uncovered and the scope of the inspection increased. As the CHECWORKS™ modeling had indicated that the lines that would see the most increase in FAC wear rate were the extraction steam to the #4 and the #3 feedwater heaters.

Thus, his conclusion was that the EPU caused the anomalous behavior.

3.3.4 Independent Assessment of this Experience

While it is likely that the EPU did contribute to, or even cause, the anomalous behavior reported, there are other factors that should be kept in mind.

- **Difference in grid sizes –** The use of the smaller grid size in the 2010 inspections almost certainly showed more degradation than using the larger grids. While it was a prudent choice, the use of different grid sizes does complicate the quantification of the degradation between inspections.

- **Entrance effect –** Although it has been described and documented for over 10 years, the entrance effect [5] is still not fully understood particularly in two-phase (i.e., steam-liquid) flows. It is possible that some of the degradation seen was caused by this effect.

Additionally, the question of the relevance of this experience to the objectives of this work should be discussed. The overall objective of this project was to examine the adequacy of using CHECWORKS™ modeling to predict the impact of power uprates on rates of FAC. The experience of BWR-A will now be examined using this focus.

- **Non-modeled component –** As the piping upstream of the affected nozzles had been replaced with resistant material, this line would not have been an active part of the CHECWORKS™ model. Therefore, there was not a prediction of the change of wear rate for the nozzle itself; rather a general prediction was made for the line. This will be discussed in greater depth below.

- **Unusual geometry** – As noted above, the presence of the stainless steel liner in the nozzle makes the geometry non-standard as far as CHECWORKS™ modeling is concerned.

- **NSAC guidance** – A portion of the excerpt from NSAC-202L, Revision 3, quoted in Section 1, bears repeating here (with emphasis added):

  > Potential changes to the Susceptible-Not-Modeled lines should also be considered. This should include **identification of any piping areas and equipment where FAC rates are predicted to significantly increase** such that material upgrades can be considered and changes to the plant inspection plan can be made.

This is exactly the situation here. The extraction lines to the #4 heaters were predicted to have the largest increase in FAC rates due to the EPU. Although this area was non-modeled, the FAC engineer re-inspected the nozzles based on this observation and thus found a potential problem. This experience should certainly not be regarded as a failure of CHECWORKS™ or the programmatic procedures recommended by NSAC-202L.

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CONCLUSIONS

The following conclusions are drawn from this project:

- A survey of the 22 U.S. nuclear units that have had a power uprate of 6% or more was conducted. The maximum power uprate was 20%.
- The results of this survey indicated that only one of the 22 units reported that the CHECWORKS™ predictions did not match their experience.
- A detailed examination of this experience shows that this experience was not a program failure; rather it indicates that the programmatic practices of NSAC-202L were successful in locating a potential problem area.
- This project demonstrates that through the examination of user experience, CHECWORKS™ modeling properly accounts for the changes of FAC rates that occur because of power uprates.

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