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Proceedings of the U.S. NRC/EPRI/ANL Heated Crevice Seminar

Held at
Argonne National Laboratory
October 7-11, 2002

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

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Prepared by
J. Park*, K.Fruzzetti**, J. Muscara***,
D.W. Diercks*

* Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

** Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304

*** Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

J. Davis, NRC Project Manager

Abstract

An international Heated Crevice Seminar, sponsored by the Division of Engineering Technology, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Argonne National Laboratory, and the Electric Power Research Institute, was held at Argonne National Laboratory on October 7-11, 2002. The objective of the seminar was to provide a working forum for the exchange of information by contributing experts on current issues related to corrosion in heated crevices, particularly as it relates to the integrity of PWR steam generator tubes. Forty-five persons from six countries attended the seminar, including representatives from government agencies, private industry and consultants, government research laboratories, nuclear vendors, and electrical utilities.

The seminar opened with keynote talks on secondary-side crevice environments associated with IGA and IGSCC of mill-annealed Alloy 600 steam generator tubes and the submodes of corrosion in heat transfer crevices. This was followed by technical sessions on (1) Corrosion in Crevice Geometries, (2) Experimental Methods, (3) Results from Experimental Studies, and (4) Modeling. The seminar concluded with a panel discussion on the present understanding of corrosive processes in heated crevices and future research needs.

FOREWORD

This seminar was co-sponsored by the Nuclear Regulatory Commission, Argonne National Laboratory, and the Electric Power Research Institute and was held at Argonne National Laboratory on October 7-11, 2002. This seminar provided an exchange of information on corrosion in heated crevices in steam generator tubes of pressurized water reactors. Much of the corrosion that occurs in steam generator tubes occurs in crevices created at the top of the tube sheet and at tube support plates on the secondary side of the steam generator.

The seminar started out with a keynote address on the environments found in heated crevices and how they contribute to intergranular corrosion and stress corrosion cracking of steam generator tubes. The keynote address was followed by four technical sessions: (1) Corrosion in Crevice Geometries; (2) Experimental Methods; (3) Results from Experimental Studies; and, (4) Modeling. Forty-five persons from six countries attended the seminar.

The Steam Generator Tube Integrity Program has been ongoing for the past several decades. The previous work concentrated on quantifying and improving in-service inspection reliability and on development of methods for predicting failure pressures and leak rates for degraded steam generator tubes under normal, accident, and severe accident conditions. The current program will continue the work on improved inspection techniques but will place more emphasis on the degradation of steam generator tubes on the secondary side of the steam generator in crevices. Key to the understanding of the degradation processes is better knowledge of the physical and chemical conditions within crevices. The purpose of this seminar was to gain an understanding of the state-of-the-art of crevice conditions and the corrosion that occurs as a result of those conditions. The long term goal is to use the results of the crevice studies to predict the behavior of steam generator tubes under field operating conditions.

Carl J Paperiello, Director
Office of Nuclear Regulatory Research
United States Nuclear Regulatory Commission

Contents

Abstract iii

Foreword iv

Acknowledgments viii

Meeting Agenda 1

List of Participants 5

Location of Seminar: Argonne National Laboratory 6

Seminar Minutes 7

Introductory Comments (K. Fruzzetti, EPRI) 23

Introductory Comments (J. Muscara, USNRC) 24

Introduction (R. W. Staehle, Staehle Consulting) 26

Presentation Handouts:

Session 1: Corrosion in Crevice Geometries; Chairman: W. J. Shack

An Overview of Recent French Studies of Possible Secondary Side Crevice Environments Causing IGA/IGSCC of Mill Annealed Alloy 600 PWR Steam Generator Tubes [Keynote Talk] (P. M. Scott and F. Vaillant) 28

Approach to Predicting Corrosion of SG Tubes Based on Quantifying Submodes of SCC in a Statistical Framework [Keynote Talk] (R. W. Staehle) 64

Session 2: Experimental Methods; Chairman: K. Fruzzetti

Heated Crevice - Design, Experimental Methods, and Data Interpretation [Keynote Talk] (J. B. Lumsden and K. Fruzzetti) 98

Experimental Simulation of Crevice Chemistry Evolution (C. B. Bahn, S. H. Oh, and I. S. Hwang 137

Experience of Heated Crevice Experiments at Studsvik (H.-P. Hermansson, A. Molander, P.-O. Andersson, and H. Takiguchi) 160

High Temperature pH Probes for Crevice/Crack Tip Solution Chemistry Applications—A Preliminary Study (S. Rangarajan, Y. Takeda, and T. Shoji) 187

Session 3; Results from Experimental Studies; Chairman: F. Vaillant

Limits to Crevice Concentration Processes [Keynote Talk] (A. Baum) 203

My Conclusions after 25 Years of Model Boiler Testing (J. Daret) 241

Inferences Regarding PWR SG Crevices from Plant Operating Experience [Keynote Talk] (J. Gorman) 247

Inferences Regarding PWR SG Crevices from Model Boiler Results [Keynote Talk] (J. Gorman) 286

Laboratory Experiments on Steam Generator Crevice Chemistry (P. V. Balakrishnan and G. L. Strati)........ 319

The Hideout and Return in a Sludged Ringhals TSP Crevice (P-O. Andersson, A. Molander, J. Chen, and P. Gillén) 346

Experimental Study of Concentrated Solutions Containing Sodium and Chloride Pollutants in SG Flow Restricted Areas (D. You, S. Lèfevre, D. Féron, and F. Vaillant) 375

Some Effects of Steam Generator Deposits on Crevice Chemistry (C. Marks) 392

Evaluation of the Effect of Startup Oxidants on the ECP of a Crevice Filled with Deposits (J. B. Lumsden and A. McIlree) 431

Session 4: Modeling; Chairman: Peter King

Mechanisms for Concentrating Impurities at Line Contact Tube Support Crevices in PWR SG's [Keynote Talk] (P. Millett and D. Hussey) 448

Hideout and Hideout Return in PWR Steam Generators: Predictions of Crevice Chemistry [Keynote Talk] (S. Sawochka) 473

Status of EPRI Software Tools for Evaluating Crevice Chemistry (T. Gaudreau) 515

Modeling and Analysis Supporting Argonne Model Boiler Facility Development (K. E. Kasza) 528

Numerical Modeling of Steam Generator Crevice Thermal-Hydraulics (S. Bajorek and D. Helton) 550

Application of Chemical Equilibrium Model to the Evaluation of Magnetite-Packed Crevice Chemistry (C. B. Bahn, I. H. Rhee, and I. S. Hwang 557

The Conditions Known to Produce Crevice Corrosion by the *IR* Mechanism and Those Yet to Be Investigated (H. W. Pickering) 575

Panel Discussion (R. W. Staehle, Discussion leader)

Panel Discussion Agenda 592

Panel Discussion Outline (A. Baum) 594

Ongoing/Future SG Research in Canada (P. King)........ 597

Future SG Work in Sweden (P. Andersson) 598

Hydrazine Ratio and Na-24 Hideout Studies (S. Odar) 599

Ongoing/Future SG Research in France (F. Vaillant) 607

Proposed 2003 EPRI Programs addressing
SG Fouling and Crevice Issues (K. Fruzzetti) 608

Discussion Notes (D.R. Diercks) 619

Written Questions/Answers and Comments 623

Post-Seminar Comments (J. A. Gorman) 638

Acknowledgments

The Heated Crevice Seminar was sponsored by the Division of Engineering Technology, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Argonne National Laboratory, and the Electric Power Research Institute. and was hosted by Argonne National Laboratory. The seminar was organized by Jangyul Park of Argonne National Laboratory and Keith Fruzzetti of the Electric Power Research Institute. Roger W. Staehle of Staehle Consulting assisted with the program development.

Additional administrative assistance was provided by Denise Moores, Zhongquan Zhou, David Kupperman, Jonathan Meagher, Marianne Adair, and Joan Brunsvold, all of Argonne National Laboratory. Dwight Diercks of Argonne National Laboratory recorded the meeting minutes.

Meeting Agenda

October 7 (Monday) 6:00 pm – 8:00 pm Registration and Reception

Meeting for session chairmen and keynote speakers at 8:00 – 8:30 pm.

October 8 (Tuesday) 8:30 am – 5:30 pm Technical Session

Topic: Corrosion in Crevice Geometries Chairman: W. J. Shack

Presentations: 8:30 am – 10:30 am

An Overview of Recent French Studies of Possible Secondary Side Crevice Environments Causing IGA/IGSCC of Mill Annealed Alloy 600 PWR Steam Generator Tubes [Keynote Talk]	P. M. Scott [Framatome-ANP] F. Vaillant [EDF R&D]
Approach to Predicting Corrosion of SG Tubes Based on Quantifying Submodes of SCC in a Statistical Framework [Keynote Talk]	Roger W. Staehle [University of Mennesota]

Discussions: 10:30 am – 12:00 pm

Topic: Experimental Methods Chairman: K. Fruzzetti

Presentations: 1:00 pm – 3:30 pm

Heated Crevice—Design, Experimental Methods, and Data Interpretation [Keynote Talk]	Jesse B. Lumsden [Rockwell Scientific] Keith Fruzzetti [EPRI]
Experimental Simulation of Crevice Chemistry Evolution	C. B. Bahn [Seoul National Univ.] S. H. Oh [Seoul National Univ.] I.S. Hwang [Seoul National Univ.]
Experience of heated crevice experiments at Studsvik	H.-P. Hermansson [Studsvik Nuclear AB] A. Molander [Studsvik Nuclear AB] P.-O. Andersson [Ringhals AB]

High Temperature pH Probes for Crevice/Crack Tip Solution Chemistry Applications—A Preliminary Study [Not attending paper included in proceedings]	R. Srinivasan [Tohoku University, Japan] Y. Takeda [Tohoku University, Japan] T. Shoji [Tohoku University, Japan]

Discussions : 3:30 pm – 5:30 pm

October 9 (Wednesday) 8:30 am – 5:30 pm Technical Session

Topic: Results from Experimental Studies Chairman: F. Vaillant

Presentations: 8:30 am - 10:30 pm

Limits to Crevice Concentration Processes [Keynote Talk]	Allen Baum [Bechtel Bettis, Inc.]
My Conclusions after 25 Years of Model Boiler Testing [Not attending paper; presented by A. Baum]	Jacques Daret [CEA]
Inferences Regarding PWR SG Crevices from Model Boiler Results [Keynote Talk]	Jeff A. Gorman [Dominion Engineering, Inc.]

Discussions: 10:30 am - 12:00 noon

Presentations: 1:00 pm – 3:30 pm

Laboratory Experiments on Steam Generator Crevice Chemistry	P. V. Balakrishnan [AECL] G. L. Strati [AECL]
The Hideout and Return in a Sludged Ringhals TSP Crevice	P.-O. Andersson [Ringhals AB] A. Molander [Studsvik Nuclear AB] J. Chen [Studsvik Nuclear AB] P. Gillen [Studsvik Nuclear AB]

Experimental Study of Concentrated Solutions Containing Sodium and Chloride Pollutants in SG Flow Restricted Areas	D. You [CEA-Saclay] S. Lefevre [CEA-Saclay] D. Feron [CEA-Saclay] F. Vaillant [Electricite de France]
Some Effects of Steam Generator Deposits on Crevice Chemistry	Chuck Marks [Dominion Engineering, Inc.]
Evaluation of the Effect of Startup Oxidants on the ECP of a Crevice Filled with Deposits	Jesse B. Lumsden [Rockwell Scientific] Al McIlree [EPRI]

Discussion : 3:30 pm – 5:30 pm

October 10 (Thursday) 8:30 am – 5:30 pm Technical Session

Topic: Modeling **Chairman: Peter King**

Presentations: 8:30 am – 10:30 pm

Mechanisms for Concentrating Impurities at Line Contact Tube Support Crevices in PWR SG's [Keynote Talk]	Peter Millett [iSagacity] Dennis Hussey [iSagacity]
Hideout and Hideout Return in PWR Steam Generators: Predictions of Crevice Chemistry [Keynote Talk]	Steve Sawochka [NWT Corporation]

Discussions: 10:30 am - 12:00 noon

Presentations: 1:00 pm – 3:30 pm

Status of EPRI Software Tools for Evaluating Crevice Chemistry	Tina Gaudreau [EPRI]
Modeling and Analysis Supporting Argonne Model Boiler Facility Development	Kenneth E. Kasza et. al. [Argonne National Lab]
Numerical Modeling of Steam Generator Crevice Thermal-Hydraulics	Stephen Bajorek [USNRC] Donald Helton [USNRC]

Application of Chemical Equilibrium Model to the Evaluation of Magnetite-Packed Crevice Chemistry	C. B. Bahn [Seoul National University] I. H. Rhee [Soonchunhyang University] I. S. Hwang [Seoul National University]
The Conditions Known to Produce Crevice Corrosion by the *IR* Mechanism and Those Yet to Be Investigated [Not attending paper included in proceedings]	Howard W. Pickering [Univ. of Pennsylvania]

Discussion: 3:30 pm – 5:30 pm

October 11 (Friday) 8:30 am – 12:00 noon Technical Session

Panel Discussion **Chairman: Roger Staehle**

Panel : Session Chairmen, Keynote Speakers, and Others

Topic:

Integrated View of Prediction of Properties of Line Contact Crevices

Needed Research to Develop Predictive Methodologies for Heated Crevices and the Related Phenomena

What Useful Analyses should be Performed for Field Crevice Samples from SGs and How?

Summary and Integration, Conclusion and Future Direction

LIST OF PARTICIPANTS

Per-Olof	Andersson	Ringhals AB
Chi Bum	Bahn	Seoul National University
Stephen M.	Bajorek	U.S. Nuclear Regulatory Commission
Poyilath (Bala)	Balakrishnan	Atomic Energy of Canada Limited
Allen J.	Baum	Bechtel Bettis, Inc.
Stephen P.	Chambers	U.S. Department of Energy
Jiaxin	Chen	Studsvik Nuclear AB
James A.	Davis	U.S. Nuclear Regulatory Commission
Dwight	Diercks	Argonne National Laboratory
Dan	Duncan	Lockheed-Martin/KAPL
Richard W.	Eaker	Duke Energy
Damien	Feron	CEA-Saclay
Keith P.	Fruzzetti	EPRI
Tina	Gaudreau	EPRIsolutions
Jeffrey A.	Gorman	Dominion Engineering, Inc.
Donald M.	Helton	U.S. Nuclear Regulatory Commission
Hans-Peter	Hermansson	Studsvik Nuclear AB
Forrest D.	Hundley	Southern Nuclear Operating Company
Ken	Kasza	Argonne National Laboratory
Peter J.	King	Babcock & Wilcox Canada Ltd.
David S.	Kupperman	Argonne National Laboratory
William T.	Lindsay, Jr.	Lindsay and Associates
Jesse B.	Lumsden	Rockwell Scientific
Saurin	Majumdar	Argonne National Laboratory
Charles R.	Marks	Dominion Engineering, Inc.
Allan R.	McIlree	EPRI
Peter	Millett	iSagacity
Anders	Molander	Studsvik Nuclear AB
Denise	Moores	Argonne National Laboratory
Joseph	Muscara	U.S. Nuclear Regulatory Commission
Ken	Natesen	Argonne National Laboratory
Suat	Odar	Framatome-ANP GmbH
John J.	Oras, Jr.	Argonne National Laboratory
Krzysztof I.	Parczewski	U.S. Nuclear Regulatory Commission
Jangyul	Park	Argonne National Laboratory
Jeffrey M.	Sarver	McDermott Technology, Inc.
Stephen G.	Sawochka	NWT Corporation
Peter	Scott	Framatome-ANP
William J.	Shack	Argonne National Laboratory
Roger W.	Staehle	Staehle Consulting
Gina L.	Strati	Atomic Energy of Canada Limited
Michael A.	Switzer	U.S. Nuclear Regulatory Commission
Francois J.	Vaillant	Electricite de France
Glenn A.	White	Dominion Engineering, Inc.
Zhongquan	Zhou	Argonne National Laboratory

Location of Seminar:
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439 U.S.A.

Minutes from Heated Crevice Seminar by D. R. Diercks

Tuesday, Oct.8

Roger Poeppel (ANL): Welcomed attendees and gave a brief review of ANL involvement in nuclear energy and LWR work in particular.

Keith Fruzzetti (EPRI): Briefly reviewed goals and objectives of seminar and described seminar format and structure.

Joe Muscara (NRC): Reviewed NRC-sponsored programs on SG tube integrity. Noted that two previous programs did not consider mechanistic aspects of SCC in SG tubes. Stated that this is a goal of the present SGTIP-3, and we must therefore understand crevice conditions (both chemical and physical) in SGs. The principal objective of the current SGTIP-3 is to understand past problems in Alloy 600 and provide the knowledge base needed to avoid these problems in Alloy 690. Thanked ANL and EPRI for organizing seminar.

Roger Staehle (U. Minn.) Discussed structure and format of seminar. He noted that first crevice corrosion seminar was held in 1996 at Studsvik in Sweden, and a follow-on seminar was held there in 1998. Proceedings exist for both seminars but they have limited availability. Peter Millett (then of EPRI) had committed to organizing the next seminar in this series. At the same time, ANL was expanding its research work in this area. Therefore ANL and EPRI combined to organize the present meeting. Staehle felt that the ultimate objective of the present meeting is to outline the process for developing the bases needed to predict the corrosion performance of heated crevices, such as those in nuclear SGs.

Jangyul Park (ANL): Reviewed the meeting mechanics and, in particular, the use of the question and answer sheets,

Session 1: "Corrosion in Crevice Geometries" [W. J. Shack (ANL), Chair]

"An Overview of Recent French Studies of Possible Secondary Side Crevice Environments Causing IGA/IGSCC of Mill Annealed Alloy 600 PWR Steam Generator Tubes," by P. M. Scott F. Vaillant (Framatome-ANP) and F. Vaillant (EdF—R&D)

The first half of the paper was presented by Vaillant and the second half by Scott. [Note that Vaillant used several overheads that were not included in the handout. These overheads appear to be from May 8, 2002 SG Conf. in Canada.]

Following the Vaillant and Scott paper, there was a general discussion of the likelihood of "dry" crevices and the consequences of such crevices. Some questioned the ability of H to concentrate in such a crevice, in view of its high diffusivity. Note however, that the diffusion distance to the crevice is much shorter from the primary water than to the secondary water . It was argued that H must be produced at a very high rate in the crevice in order to maintain a meaningful H inventory there. Scott noted that, in view of the extremely fine porosity (1-2 nm) and smallness of the crack openings (≈100 nm), flow of liquid phase with impurities in and out of crevices and the associated cracks would appear highly unlikely. Scott asserted that detailed experimental studies are needed to define the nature of the crevice phase.

Bill Lindsay raised a point about Scott's use of the Kelvin equation correlating the vapor pressure of liquid droplets with droplet size. Lindsay stated that his recollection of this correlation was that the vapor pressure increases with increasing curvature for convex surfaces (as in a liquid droplet) but decreases with increasing curvature for concave surfaces (as for the meniscus of a liquid phase in a pore). [Lindsay later added that checking Adamson's text ("Physical Chemistry of Surfaces, Wiley, NY, 1997, pp. 53-54), the recollection is correct, but experimental evidence for the effect in capillaries is mixed. It is possible that surface tension itself may be affected for thin films in very small diameter capillaries.]

Scott closed the discussion by stating that there is a critical need for model boiler tests in which the H concentration in the vapor phase is measured particularly in plugged crevices, i.e., the potential is determined.

"Approach to Predicting Corrosion of SG Tubes Based on Quantifying Submodes of SCC in a Statistical Framework," by Roger Staehle

In the question and answer period, Joe Muscara asked what Roger's timeframe was for completing his predictive model for SCC in heated crevices. Staehle responded that he hoped to have the basic quantitative features of the model completed by the end of calendar year 2003.

Dan Duncan (KAPL) asked if the model would become more complicated if the various submodes of corrosion turned out to be not completely independent. Staehle responded that he believed the submodes to be independent, but if they were not, the model would have to deal with this complexity.

Bill Shack asked the effect on the model if the crevices are filled with steam rather than liquid phase, as most have assumed in the past. Staehle responded that that would mean that much of the existing laboratory data, most of which were obtained in liquid phase, may not be applicable. However, he had to use the data available in formulating the structure of the model. Ultimately, the model and its various components would have to be validated using the real field data, rather than simply fitting the existing laboratory aqueous data.

Jesse Lumsden (Rockwell) asked what the crack propagation mechanism was in the steam plus impurities phase. Staehle answered that this was uncertain and was a subject for ongoing research.

Bill Lindsay noted that if corrosion is assumed to be an electrochemical phenomenon, then ionic mobility was required. This would appear to require the presence of at least some liquid phase in the crevice. Staehle added that the electrochemical potential also appeared to be important in the corrosion process, and this again implied the presence of some liquid phase. However, Scott noted that SCC can occur by non-electrochemical processes, e.g., H cracking or in situ grain boundary oxidation.

Peter King (BWC) asked if we can determine whether the crevice phase was liquid or vapor by conducting laboratory experiments under both conditions and determining which results most closely reproduce reality.

After lunch, the discussion continued on the nature of the corrosive environment at the crevice and the evolution of that environment with time. Allen Baum (Bettis) stated that important processes with respect to corrosion are those that occur while the crevice is plugging. This, for example, is when Pb and other low soluble corrosive species are apparently introduced. Lindsay noted that in a model boiler test, the crevices are generally filled with sludge before the test is started.

Ken Natesan (ANL) noted that the Staehle modeling approach breaks the SCC process into various submodes. He asked if there was a hierarchy of submodes and whether beta in the Weibull statistical description varied with submode. Jeff Gorman (Dominion Engineering) stated that beta was typically 3 to 4 for field data, but could be higher for some specialized situations. Staehle responded that the value of beta varied somewhat with how you analyzed the data, and variations in beta were possible. He felt that the central problem was developing an understanding of the initiation process, what the dominant submode(s) were in complex environments, and the effect of sulfides and Pb, for example.

Baum asked that, assuming the local environment at the tube surface is superheated steam, how is that environment modified with time? Gorman responded that, based on the fact that cracks occur over long lengths of tube sheet and TSP crevices in plants, the introduction of impurity species appears to contaminate the entire crevice, and all the steam becomes doped steam, with cracking occurring more-or-less uniformly along the crevice length. Lindsay wondered whether impurity species might migrate into the crevice and replace the pure steam.

Peter Millett (iSagacity) stated that another critical point was whether the boiling point can be elevated sufficiently that steam can be present in equilibrium with liquid phase containing the concentrated corrosive species. King noted that even if the crevice is filled with steam, it is not necessarily dry steam, since it is probably in equilibrium with liquid phase whose boiling point has been raised by high levels of dissolved impurities. Scott was not sure this was true, since extremely high levels of dissolved impurities were required to raise the boiling point sufficiently.

Baum then proposed that, in general, the crevice probably contains superheated steam at the center of the crevice, steam in equilibrium with liquid near the edges, and liquid phase outside the crevice. The relative sizes of the various zones varies with the steam generator design and operating conditions.

Scott suggested that in situ oxidation generally precedes actual cracking. This process can occur without other impurities, but cracking is generally greatly accelerated by impurities.

<u>Session 2: "Experimental Methods" [K. Fruzzetti (EPRI), Chair]</u>

"Heated Crevice—Design, Experimental Methods, and Data Interpretation," Jesse Lumsden (Rockwell Scientific)

In question and answer period, Jiaxing Chen (Studsvik) asked how the dissolved OH^- species was identified in the Raman spectrum. Lumsden responded that it was the only reasonable possibility, since there were no other impurities in the feedwater.

Lindsay asked whether Lumsden's experiments were at sufficiently high temperatures that NaOH and water were completely miscible. Lumsden responded that he was not sure. [Lindsay later added that NaOH and water are completely miscible at temperatures at and above the melting point of pure NaOH, 318.4 C (605.1 F).]

"Experimental Simulation of Crevice Chemistry Evolution," Chi Bum Bahn, Seoul National University

There were a few questions of clarification.

"Experience of Heated Crevice Experiments at Studsvik," H-P Hermansson (Studsvik) and A, Molander (Ringhals AB)

In response to a question from Ken Kasza (ANL), Molander stated that the heat flux at the crevice was ≈40% of full power, or <20 watts/m^2. He also stated that the crevices were concentric.

In the second half of the talk presented by Hermansson, Baum asked if all the results presented were electrical heat input. Hermansson responded that they were, both for the unfilled and filled crevices.

Gorman proposed that, in a heated crevice, we would like to be able to predict the pH and potential relative to the H stability line and whether the crevice is dry or wet. Baum agreed, but noted that the crevice is, in his opinion, generally a two-phase environment. It can be difficult to characterize this environment in terms of a singe parameter with respect to pH and potential.

In the following general discussion, Staehle observed that the magnetite packing used in heated crevice experiments appears to be different from that in the plants. Lumsden agreed, noting that the packing in experiments is particles while the magnetite in the plant is a monolithic "brick." However, he noted that packed particles in his experiments typically turns into a brick over the course of the experiment.

Staehle asked whether we should therefore reformulate the magnetite in these experiments, perhaps adding silica, for example. He asked how fast the porosity in the packed magnetite is filled up, since this relates to how fast the porosity is closed off.

Forrest Hundley (Southern Nuclear) observed that, in operating plants, consolidation of the deposit does occur, as evidenced by the loss of thermal performance. Staehle asked whether this would then imply that cracking should slow down and stop with time. Baum responded that this was not necessarily so, since the hostile environment in the crevice was sealed in by the non-porous deposits at the ends. Staehle then asked if the pH would be buffered by the magnetite, thereby again inhibiting cracking. Steve Sawochka (NWT) thought this would not be expected.

On the subject of deposit consolidation, Andersson observed that porosity data from Dampierre indicated deposit porosity in the range of ≈5-30% or more, depending upon location. Tube pulling forces were very high, indicating a solidified deposit.

King noted that the tubes in Lumsden's experiments cracked in times much shorter than those in observed in the field, even though the test conditions were ostensibly prototypic. Rich Eaker (Duke) responded that the conditions were not necessarily prototypic. Sawochka concurred and stated that field conditions were too variable to permit extrapolation of laboratory results like Lumsdens's with respect to the rate at which cracking would be expected to occur.

Staehle asked whether Lumsden should be considering more experiments in the mid-pH range and under more complex impurity conditions. Lumsden responded that he felt that the logical next step was to use more complex chemistries, but to add the impurity species one at a time to maintain a well-controlled experiment.

Shack suggested that the point of Lumsden's experiments was to get results for simple chemistries that agree with the models. The logical next step was to try somewhat more complex chemistries and see whether the results are still predictable. King agreed, observing that there was no need to go to line-contact experiments right away, for example.

Staehle expressed doubt that crevice chemistry was the same for line contact as for a drilled hole geometry. He noted that French work indicated that the hideout returns for drilled holes were significantly different than for line contact geometries. King again urged that the variables should be changed one at a time, and the line contact could be considered after more complex chemistries have been explored.

Allan McIlree (EPRI) inquired about correlating crack growth rates with electrochemical noise. Lumsden said that he had some limited success in doing this. Staehle then asked about correlating crack growth rates in plants with chemistry. Gorman stated that this had been tried to some extent, with little success, and Sawochka observed that, in general, crack growth rate data could not be obtained from operating plants. King felt that this was something that needed to be done.

With the objective of successfully predicting cracking behavior Staehle summarized by stating that the consensus of the group was that we should (1) look at mid-range pH conditions while slowly varying the chemistry to more complex environments, (2) defer the consideration of line-contact geometries to later, and that (3) we need crack growth rate data, especially for the mid-range pH situations.

The first-day's proceedings were adjourned.

Wednesday, October 9: Session 3: "Results from Experimental Studies" [F. Vaillant (EdF), Chair]

"Limits to Crevice Concentration Processes," A. Baum (Bettis)

"My Conclusions after 25 Years of Model Boiler Testing," Jacques Daret (CEA) [presented by A. Baum]

In the question and answer period, Staehle noted that in a number of experiments, Pb tended to end up at the metal-oxide interface. He asked where it ended up in the CEA AJAX tests that Baum described. The answer was that it was not clear, though it tended to not to be in the crevices.

"Inferences Regarding PWR SG Crevices from Plant Operating Experience," J. A. Gorman (Dominion Engineering)

Suat Odar (Framatome-ANP) corrected a point in Gorman's presentation, noting that, including four replacement steam generators and the Angra station, there are 22 PWRs with steam generators having Alloy 800 NG tubes, not 17 as stated by Gorman. He added that a total of two tubes in all of these steam generators had experienced damage. One of these tubes experienced IGA/IGSCC plus pitting and the second had pitting alone.

Steve Chambers (DOE-NR) asked whether the use of phosphate chemistry in the early operation of Japanese plants had any influence on subsequent cracking experience. Gorman responded that there was no obvious effect, but Baum observed that some of these plants experienced subsequent TSP corrosion, apparently associated with increased impurity ingress into the cleaner crevices resulting from the early phosphate water chemistry. (See the response by Gorman to Chamber's written question)

Gorman noted that the overall point of his first presentation was that a large plant experience data base exists that can and should be used to calibrate models developed for crevice corrosion.

"Inferences Regarding PWR Steam Generator Crevices from Model Boiler Results," J. A. Gorman (Dominion Engineering)

In the question and answer period, Baum observed that in tests with 2 ppm sulfates and 1 ppm Pb, for example, throughwall cracking was observed in ≈4 years. However, tests conducted with these levels of hydroxide to produced throughwall cracking in days. He noted that, as a practical matter, resins seem much less able to lead to cracking than caustic.

Kasza asked whether there was a quantitative process for determining whether a concentration process in the crevice was hydraulically or thermally driven. Baum responded that there was not; this must be determined from the details of the experiment. Millett added that there can be a transition from one mode to the other over time in a given crevice.

Kasza then asked for a clarification of Baum's statement that crevices are thermally driven. Baum responded that this statement applied to drilled holes on the hot side.

Chambers expressed surprise over an earlier statement by Baum that Pb was not responsible for much crevice ODSCC. Gorman stated that he did not put much faith in conclusions regarding the role of Pb, since laboratory techniques for detecting Pb have not been sufficiently sensitive until rather recently.

Staehle observed that Alloy 600 MA material usually cracks intergranularly, so the "fingerprint" for Pb-assisted SCC is not transgranular, as some have suggested. He noted that Pb typically ends up next to the metal at the OD interface with the oxide, and the oxide must be stripped away to see it. He added that Pb is seems to concentrate at the crack tip as $PbO_x^{=}$ in the alkaline state and as Pb^{+2} in acidic environments, in agreement with theory. The extent of Pb-induced cracking is very pH dependent, and it is most aggressive in the alkaline region. He asserted that, in the extreme case, virtually all cracking could, in principle, be associated at least in part with Pb. The reality is that Pb effects are not well understood, and more research is needed. No dedicated facilities for Pb-cracking studies exist, since no one is willing to contaminate their system with Pb.

Hundley noted that plant operators all know that Pb is bad and they work to keep it out of the plant. Why do research to confirm what plant operators already know? Staehle responded that the biggest question is why Pb is not causing everything to crack in the short term. We need to understand how it is tied up and thereby disabled by other impurities and under what circumstances it can be re-released.

Damien Feron (CEA) agreed that Pb must be reduced as much as possible. However, Millett noted that it will always be present at the ppt level in the bulk coolant, because it is introduced into the system as a tramp impurity in the other materials of fabrication. It cannot be reduced below this level as a practical matter.

Staehle then observed that chemical cleaning may be a potential problem in that one cannot be sure if it is removing Pb or instead removing the impurities that are tying the Pb up. However, Odar observed that chemical cleaning has been observed to remove the sources of Pb and to result in reduced levels of SCC in the tubes. His opinion is that chemical cleaning is beneficial in that it removes the sources of Pb.

"Laboratory Experiments on Steam Generator Crevice Chemistry," by P. V. Balakrishnan and G. L. Strati

In the question and answer period, Baum asked how the sludge is held in place in the AECL apparatus and what the crevice dimensions are. Strati responded that the sludge is held with a SS frit at the bottom and that the crevice dimensions are variable. In answer to a question from Sawochka, she stated that the Na/Cl ratio in the crevice was near unity. Sawochka wondered why $Mg(OH)_2$ was identified as a precipitate in AECL run no. 177, since the reported Na/Cl ratio suggests that the crevice is acidic.

"The Hideout and Return in a Sludged Ringhals TSP Crevice," by P.-O. Andersson (Ringhals) et al.

In the question and answer period, Andersson responded to a question from Gorman by stating that the Na^{24} tracer used was in the form of a carbonate. The pressure in the tubes was ≈200 bars. Feron noted that the French had reported similar results from the CLARINETTE loop at the Breckenridge Conference.

"Experimental Study of Concentrated Solutions Containing Sodium and Chloride Pollutants in SG Flow Restricted Areas," by D. Feron et al.

In the question and answer period, Gorman asked for a clarification of Feron's statement that " hideout return is not the opposite of hideout." Feron answered that the hideout/hideout return process is not completely reversible. Lindsay commented on this by noting that he had always been suspicious of attempts to calculate what was in the crevice by running MULTEQ backwards.

"Some Effects of Steam Generator Deposits on Crevice Chemistry," by C. R. Marks (Dominion Engineering)

"Evaluation of the Effect of Startup Oxidants on the ECP of a Crevice Filled with Deposits," by J. Lumsden (Rockwell Scientific)

Staehle asked whether Lumsden had considered the reduction of sulfates by hydrazine. Lumsden said that he was looking into that, but there was no evidence of reduction in the crevice so far.

Zhongquan Zhou (ANL) asked whether the ECP was stable at pH = 10 in deaerated water. Lumsden responded that it was stable.

In the general discussion of the papers from the afternoon session, Staehle reiterated that the biggest issue with Pb was immobilizing it. He said that we have identified many of the appropriate species, but we don't understand how they work or under what conditions the Pb is released. Gorman added that Pb levels in the deposits were typically in the range of 100-1000 ppm in the crevice, while the bulk water Pb level required to cause IGA/SCC is ≈0.1 ppm.

McIlree stated that the destructive examination of tubes from the Farley 1 SG may have characterized the crevice deposits with respect to Pb, but he was not sure of the details offhand. Marks stated that the Farley 1 results were included in the Dominion Engineering analysis, but he had no numbers for Pb. McIlree then added that Pb had also been found in the Thane 1 crevice samples in Belgium, and the researchers at Laborelec were very surprised.

Staehle noted that if Cu is added to a Pb-containing environment, cracking is enhanced according to some data. This appears to be an ECP effect, but it has not been well characterized. He also wondered why Pb usually ends up at the metal-oxide interface. Eaker noted that Duke had detected Pb at this interface in samples from Oconee through the use of EDF high resolution XRD analysis, since this technique penetrated the oxide film to the interface. Staehle noted that this segregation to the interface had been seen in several French plants as well as at Oconee.

Jeff Sarver (McDermott) noted that Pb appears to be reactive with Cr, based on C-ring tests. Staehle added that Pb also appears to be extremely aggressive in the steam phase over caustic solutions thereby producing severe SCC even in Alloy 690 TT in laboratory tests. It is not clear why, although we know that Pb has strong effect in breaking down the passive film.

McIlree noted EPRI-sponsored work by Lumsden on attempts to crack Alloy 600 with Pb additions. They found that 1.5 molal sodium sulfate solutions with silica, alumina, and magnetite additions and 50 ppm Pb did not crack Alloy 600. This may be because this Pb level is in balance with the sulfate additions. The next experiment will be to add excess Pb in an attempt to produce cracking.

Staehle noted that C. Laire at Laborelec has shown that phosphate ions can immobilize Pb very effectively. The important point is that Pb is one of the few species that can readily crack Alloy 690 TT. We need to understand why.

Gorman than brought up the effects of S species and their possible influence on cracking. He wondered whether we are wise or unwise in pushing for high hydrazine, since hydrazine appears to react with S species (i.e., it reduces sulfates). Vaillant agreed and noted that the French program was looking at the question of optimum hydrazine levels. Staehle added that in cracking involving Pb, sulfides are also commonly found in the cracks.

Andersson asked what is meant by high and low hydrazine. Gorman responded that anything above 100 ppb was high and 25 ppb or less was low. Andersson noted that these levels won't affect the potential, and Eaker agreed.

Eaker then asked which S specie or species should be tested. Staehle responded that several S species have similar deleterious effects, but those with +2.5, 2.0 and -2 valences appear to be the most aggressive. Species with the +4 and +6 valences are more benign. Eaker than asked about the relative volatilities of these species, and Staehle responded that he was not sure.

The second day's session adjourned.

Thursday, Oct. 10: Session 4: "Modeling" [P. King (BWC), Chair]

"Hideout and Hideout Return in PWR Steam Generators: Predictions of Crevice Chemistry," by S. Sawochka (NWT)

Following Sawochka's presentation, there was a general discussion of the uncertainties and limitations associated with the hideout return methodology.

Tina Gaudreau (EPRI Solutions) asked about the use of chloride additions (molar ratio control) to change crevice chemistry and pH. Sawochka responded that these additions are effective and have been used at Farley, for example, to achieve near-neutral pH values in the crevices, based on hideout return data.

Baum contended that we should not place too much importance on molar ratio control, since he is somewhat leery of the of hideout return data for predicting the chemistry in the hottest crevices in the steam generator. Sawochka responded that the industry believes in hideout return as a basis for determining crevice chemistry. Baum wondered whether it might introduce a false sense of security. Hundley stated that the utilities were not suffering from any false sense of security, since steam generators were so expensive and SG problems were so pervasive. The utilities feel that a sound basis exists for the hideout return methodology.

"Mechanisms for Concentrating Impurities at Line Contact Tube Support Plate Crevices in PWR SG's," by P. Millett (iSagacity)

Chen asked whether the parameters in equation for crevice chemistry can be verified from hideout data. Millett responded that the diffusion coefficients from hideout data are of the right order of magnitude, but they tend to be averaged values.

In the ensuing general discussion on the modeling of crevices, Duncan observed that one can successfully model the individual features of crevices, but it is very difficult to link them together in an overall model. On the other hand, one can validate the overall results of a model, but it is difficult to validate the individual components. For the case of the sludge deposits, one has the problem that in trying to accelerate the process of sludge buildup in an experiment, the deposits built up are typically not prototypic.

King stated that the utilities are asking what the applicability and practical significance of these models are to their situation, i.e., how can they be used at the operating plant? Sawochka concurred and added that, from the utility point of view, the primary objective is to keep the SGs operating. How does modeling help? Is it the most cost-effective approach, particularly in view of the difficulty in getting the required fundamental data? Hundley further commented that the utilities need to make the SGs last and keep them operating at 100% power. The utilities don't want to repeat the mistakes that have destroyed SGs in the past. If modeling is to be relevant, it must help toward these objectives.

Millett felt that the evolution of the crevice chemistry is a very important consideration in modeling, and Feron added that, to accomplish this, one must couple chemistry, hydraulics, and heat transfer. There was general agreement that deposits, particularly at the point of line contact, are very important, and the deposition process is very difficult to model.

"Status of EPRI Software Tools for Evaluating Crevice Chemistry," by Tina Gaudreau

Zhou asked what the advantage of MULTEQ was over competing softwares for determining water chemistry. Lindsay responded that MULTEQ is overseen and accredited by a distinguished committee of experts on water chemistry. The code is very widely used and has been shown to be quite stable. In a related question, Chen asked how useful MULTEQ was in a practical sense. Gaudreau responded that MULTEQ is built extensively on past experience and incorporates ongoing developments in the area of water chemistry,

Staehle asked whether MULTEQ considers the mixed Fe-Cr and Fe-Ni oxides in its analysis. Gaudreau replied that it does not at present. Lindsay added that MULTEQ does not treat solid phases of variable compositions, which would include the mixed oxides. He stated that the standard MULTEQ consists of three basic parts: (1) a data base, (2) a chemical equilibrium calculator, and (3) simulation programs. Staehle then asked how many Pb compounds were accounted for in MULTEQ and Gaudreau answered that ≈7-9 such compounds were included.

“Modeling and Analysis Supporting Argonne Model Boiler Facility Development,” by K. E. Kasza (ANL)

Lindsay suggested that a downcomer on the secondary side of the model boiler might be useful to define the circulation pattern in the boiler, but Kasza replied that it was not felt to be needed. Baum expressed further concern about adequate coolant mixing on the secondary side.

Staehle then asked whether the holes in the crevice simulators were to be broached or drilled, and Kasza replied drilled. Staehle then observed that the flow velocity on the secondary side has an important effect on the formation of deposits in the crevice region.

In response to a question from Molander, Kasza stated that model boiler incorporated features to permit control of ammonia and hydrazine levels on the secondary side. A number of questions were asked regarding the measurement of temperature, pH, potential, and chemistry in the crevice region.

With respect to the ANL modeling of the crevice heat transfer process, Sawochka and Duncan stated that in an actual SG crevice, one has multiple nucleation sites for bubbles in the crevice deposit. They wondered how relevant it was to model an idealized single-site nucleation process. Duncan added that under high-pressure, one gets very tiny bubbles with frequent departures. In addition, local temperature fluctuations are large and have a high cyclic frequency.

“Numerical Modeling of Steam Generator Crevice Thermal-Hydraulics,” by S. Bajorek (NRC)

Duncan observed that the CFD codes required to perform the desired modeling will require a very great amount of effort and time to adapt to this analysis. Baum added that the problem being solved was intellectually interesting, but the industry is much more interested in flow in a packed crevice. Eaker added that an eccentric crevice was of more interest than the concentric crevice being considered here. Bajorek responded that his approach was to start with a simplified and more tractable problem and then eventually extend it to more prototypic situations.

“Application of Chemical Equilibrium Model to the Evaluation of Magnetite-Packed Crevice Chemistry,” by C.-B. Bahn

Lindsay expressed reservations about using the HSC Chemistry Code for the analysis described. He suggested redoing the analysis with MULTEQ and comparing the results. Zhou added that her experience with HSC Chemistry Code has not been particularly good, and she recommended that the results be checked experimentally, if possible.

Feron questioned how applicable the modeling was, since the system described did not appear to be at thermodynamic equilibrium. Chen added that the mass transport in and out of the system also appeared to indicate non-equilibrium conditions. However, Lindsay stated that he felt that a code like MULTEQ could be used here, since the system appeared to be at ionic equilibrium. Complete thermodynamic equilibrium is not essential.

Odar stated that it was not possible to transform magnetite to hematite in the solid state, as the model had assumed, since the two phases have different crystallographic structures. One must instead dissolve the magnetite and then precipitate hematite. Finally, King observed that the results of the analysis do not appear to be consistent with the Pourbaix diagram for the system, and he expressed further doubts about the adequacy of the HSC Chemistry Code.

In the ensuing general discussion on the Modeling Session, Staehle began by asking just what problem we are trying to model. He stated that we should be primarily interested in the formation of the deposit and its properties. He suggested that there were two types of approaches, namely the heat-transfer, fluid dynamics approach and the morphological deposition approach. In view of our limited resources, and, in particular, the limited availability of model boilers, he questioned what our priorities are.

Baum broke the crevice attack problem down into three phases: (1) the buildup of the deposit, which is a thermal-hydraulic problem, (2) the development of the chemical environment in the pores of the crevice, which is a chemical problem, and (3) the impact of the local environment on the corrosion process, which is a metallurgical problem. He suggested that a multi-disciplinary approach was needed to attack the problem effectively.

Sawochka suggested that we think about what was achievable in a realistic time frame, since the industry needs guidance in the relatively near term. Their biggest question is how long they can operate before they form deposits at line contact point crevices. He stated that there was no interest in the drilled-hole geometry. He felt that we had a reasonable understanding of deposit formation, and he felt that we know how to perform the appropriate heated-crevice experiments. However, we must know more precisely what the corrosion people need to analyze or model the corrosion problem. He felt that the model boiler design proposed by ANL was not amenable to looking at the crevice deposition problem.

Lindsay stated that in past model boiler experiments, the deposition step was typically omitted by pre-packing the crevice with deposits. He didn't feel that line-contact crevices were all that different from drilled holes—we still expect to get deposits in either case.

Staehle observed that we see great variability in the cracking behavior of drilled-hole SGs in terms of time to cracking. For a line-contact crevice, which appears to be less constrained, he speculated that we might see even more variability. Lindsay speculated that perhaps there would be less variability, since the crevice has more exposure to the bulk water.

Staehle predicted that we would begin to see increased cracking of Alloy 690 TT tubes in the field in the future, and he felt that we must be more proactive in anticipating and dealing with these failures before they become a major problem.

King wondered about the critical depth of deposits required to lead to cracking and how long it takes to get to this depth. He felt that this was the critical question. Baum added that he felt that model boiler tests, as opposed to isothermal tests, are essential to obtaining a detailed understanding of the cracking problem.

Hundley stated that, from the utility's point of view, they need to know when and how often they should perform chemical cleanings to stay out of trouble. Millett added that the industry needs engineering solutions rather than rigorous scientific analyses, and the level of precision required by industry might well be attainable through modeling.

Baum suggested that Byron and Braidwood Units 1 versus Units 2 might be the ultimate model boiler experiment for quantifying the benefit of thermally treated tubing, since the tubes cracked in Units 1 while those in Units 2 did not under presumably similar operating environments.

Gorman suggested that it might be useful to consider the Alloy 800 operating experience. Many of these tubes have operated for more than 20 years. These crevices have surely built up substantial deposits by now, and yet cracking is virtually unknown. Why? Baum then suggested that we should compile the most relevant data from operating plants. Staehle added that we should look the deposits in operating SGs.

Muscara noted that the NRC was supporting modeling work to predict the onset of tube cracking. He suggested that operational assessment was the next step. We know that we cannot completely avoid cracking, so we must learn to minimize it and live with it. He asked how we could optimize the ANL model boiler.

Hundley wondered how one extrapolates model boiler results back to the conditions in an operating SG. He felt that the model boiler results were likely to be either far too conservative or much too optimistic. The past experience of the utilities in attempting to use model boiler data, e.g., on the use of inhibitors, has not been particularly successful.

The session adjourned.

Friday, Oct. 11: Panel Discussion (R. W. Staehle and A. Baum, Co-chairs)

Roger Staehle began by stating that the principal objective of the panel discussion was to "bring things back into focus." He then handed out a proposed agenda for the discussions.

Alllen Baum then opened the first portion of the discussion with a short presentation.

Gorman began the discussion by inquiring about the nature of the cracking seen in the Alloy 600 TT tubes at Seabrook. McIlree replied that the cracks were short and separated by ligaments. He said that even if they were 99+% throughwall, they would not threaten the pressure integrity of the SGs.

McIlree then noted that if Alloy 600 or 690 TT tubes were properly processed at the mill, in principle there should be no residual stresses present to drive cracking. At Seabrook, however, they found that the tubes were re-straightened after the TT heat treatment, thereby introducing residual stresses. It seems likely that other TT tubing is out in the field with similar residual stresses. He wondered if we could develop NDE techniques to detect residual stresses in tubes in the field or to determine if the TSP lands were becoming active crevices.

Jim Davis (NRC) then commented that the Seabrook tubes appeared to have a MA metallurgical microstructure rather than a TT microstructure. McIlree observed that there is a great variation in TT microstructures, and some in fact resemble the MA microstructure. He stated that one cannot judge SCC resistance from the microstructure. The response of the microstructure to the heat treatment appeared to depend upon the C level. Gorman added that EDF experiments indicate that ≤ 0.033 wt. % C was needed to obtain the expected microstructural response to the TT heat treatment.

Davis noted that cracking had also been seen in Alloy 600 TT at a Korean plant, and Baum and Diercks (ANL) said that this was the Kori 2 plant. McIlree added that again the microstructure did not have the appearance normally associated with the TT heat treatment. McIlree said that we must assume that there are other "poor" TT microstructures in the field, and we must control residual stresses and environment in these plants to avoid cracking. He felt that most, but probably not all, of the plants with Alloy 600 TT tubes have low residual stresses.

Staehle observed that the highest stresses in SG tubes are typically at the top of the tube sheet. He suggested that perhaps our focus on chemistry at the line contact region of the tube sheets might therefore be somewhat misplaced. If we could somehow reduce the residual stresses from tube manufacture and SG fabrication, we might not have to worry so much about the operating environment. However, this does not seem likely. He agreed with McIlree that perhaps the use of NDE techniques to detect residual stresses in tubes in the field should be looked into further.

Duncan suggested that we should determine if there is a small population of high stress tubes in service that need to be followed more closely. Baum said that his earlier model boiler work focused on tube sheet joints, where the residual stresses were highest. Nevertheless, that one incident of ODSCC in Alloy 600 TT tubing was in a TSP crevice rather than a TS crevice.

Staehle then suggested that another important consideration is to figure out how to lengthen the time between inspections. He also noted that, in laboratory tests, both Alloy 600 TT and 690 TT can be cracked in environments not greatly different from those in service. He wondered why they are not cracking in service in significant numbers. Finally, he stated that we must be proactive in anticipating failures in Alloy 690 TT. We need to do the research now so that we are in a position to prevent failures in the field. As a part of this, we need to do research to enable us to conduct credible operational assessments.

Duncan stated that in addition to lengthening the time between inspections, we must make decisions about appropriate inspection intervals in the case where we have an existing crack. We therefore need crack growth rate data under the relevant conditions.

Muscara said that regulators must take the position that undetected cracks exist in the field, and these cracks must be properly dealt with. He also noted that should not totally shift our emphasis away from the TSP region, since conditions for mild denting exist there and even this mild denting can lead to cracking.

Gorman agreed that crack growth rate data are essential for doing a proper operational assessment. He also noted that the subject of mild denting at the top of the tube sheet was considered at a secondary side workshop in 1995. He expects to see more such denting in the future, leading to tube cracking.

Muscara noted that in terms of crack evolution and operational assessments, we must consider when to use ligament correlations for existing cracks and when to use a planar crack correlation.

Baum then offered one last comment on the Seabrook cracking, noting that while the greatest concern is on the mechanical aspects (i.e., residual stresses), there is also a chemical aspect to the problem. He noted that Seabrook had low silica (5-10 ppb) in the bulk water chemistry compared to other plants, and he wondered if this was significant.

Peter King then briefly reviewed ongoing SG research in Canada (Denise is typing up his handwritten overheads).

King noted that the precursors for cracking do not appear to form in Alloy 690 like they do in Alloy 600, at least not in reasonable times. He felt that the major questions to be answered were the time to critical crevice deposits and how to interpret and use the extensive available field data and relate it to our expectations for Alloy 690 TT.

Chambers then made several points. He first noted that residual stresses from manufacture are unavoidable. In addition, one would expect operating stresses in tubes from temperature cycling. He also suggested that *in situ* monitoring of autoclave and heated crevice test (e.g., Raman spectroscopy) could be very enlightening. Finally, he wondered how crevice chemistry might change under zero-power hot conditions.

King responded by first noting the work of Lumsden and others on monitoring crevice chemistry. With respect to the effect of zero-power hot conditions on crevice chemistry, he noted that people are working on this problem. He added that it is very difficult to get crack growth rate data under field conditions. He also agreed that we must assume that tubes, in general, have residual stresses from manufacture, and we must also assume that operations will produce aggressive environments somewhere in the SG. Therefore we must have the most crack resistant tube material possible, and this is why the industry is going with Alloy 690 TT at present. He stated that BWC is still interested in model boiler testing and crevice monitoring, but these tests are very expensive. He expressed the hope that future work at ANL can address these areas.

Per-Olaf Andersson then briefly reviewed ongoing SG research in Sweden. He noted that Sweden has only three PWRs, namely Ringhals 2, 3, and 4. Units 2 and 3 have replacement SGs, and there have been no problems with these. Unit 4 still has the original Westinghouse Model D-3 SG with Alloy 600 MA tubes from 1984, and this unit has experienced very little tube cracking.

Odar supplemented Andersson's presentation by showing results obtained from Na-24 hideout studies conducted in the Ringhals 3 plant simulator before SG replacement. Significant Na hideout was observed. The new KWU SG with grid tube supports showed virtually no hideout. Tests conducted three years later showed some hideout, indicating sludge buildup. The hydrazine concentration ratio in the SG feedwater for plants with higher Fe (1-2 ppb) decreased with time. For lower Fe (<1 ppb), the decrease was less rapid, thus suggesting increased sludge loading.

François Vaillant then summarized ongoing SG research in France. He reviewed work on life prediction and frequency of NDE inspections as well as on hydrazine requirements and SCC under plant shutdown and startup conditions.

Keith Fruzzetti reviewed EPRI-sponsored work on SGs.

Staehle then continued the discussion by noting that in order to predict cracking in a specific environment, we must have sufficient relevant data. However, almost no relevant data exist on cracking associated with reduced S species. With respect to silica effects, he cited a 1985 paper by Berman, who found a specific region in the silica-alumina system where cracking occurs in Alloy 690 MA. He felt that acid SCC had been pretty well characterized, as had alkaline SCC, though both remain issues. Cracking in complex environments has not been well defined, but relevant work is being conducted in France. Overall, he felt that there was much room for serious work to determine the dependencies for several of these submodes. He added that we cannot predict the behavior if we do not know the dependencies.

Gorman stated that, with respect to sulfate chemistry and complex environments, he has difficulty in understanding the process for attack since the species involved are not liquid at the superheats present in drilled hole crevices. He felt that further testing and/or modeling was needed.

Lindsay made an impromptu presentation on the subject of predicting the performance of line-contact crevice deposits, noting that, on the molecular scale, the tube surfaces and the TSP lands look flat. We must consider things on this scale. When things are considered on this scale, it is clear that chemical reactions in solution within the various types of crevices are not different from each other or from reactions that can take place in bulk water. The differences among crevice types are most likely due to their differing susceptibility to fouling. Lindsay added that he was not aware of any significant engineering science relating to crevice fouling under boiling heat transfer conditions. Good engineering science research is needed in this area. Staehle concluded that the important question is what remains to be done in this area and what resources are available to do it.

On the subject of critical experiments in model boilers, Staehle noted that there are only one or two model boilers available at present. How do we best use them and what alternative experimental techniques do we have? Duncan agreed that model boiler tests are needed, since codes and modeling cannot answer all of the questions that must be addressed. He said that model boiler experiments should emphasize multiple variable validation experiments. He felt that a different model boiler design from that being developed at ANL was needed to understand the fouling process at the crevices. Muscara noted that the ANL model boiler was not designed for such studies, but rather to study the evolution of crevice chemistry and how it leads to crack initiation.

Baum added that MULTEQ is a useful tool. But model boiler experiments were nonetheless needed to determine crevice chemistries with confidence. Duncan contended that model boiler results cannot reliably predict absolute cracking rates—they can only provide relative rates.

Staehle then stated that he felt that items 6-8 on the panel discussion agenda had already been thoroughly considered in the previous sessions, and, in view of the short time, they would not be further discussed here.

Muscara observed that, with respect to the data base, a tremendous amount of work was still needed. He suggested that perhaps an international group should be constituted to coordinate this work, and he suggested that perhaps the NRC and EPRI could pull this together.

Staehle suggested that discussions be ended on that note, and he thanked all of the participants.

Introductory Comments

Keith Fruzzetti

Electric Power Research Institute

It is my pleasure to welcome you all here to the Heated Crevice Seminar co-sponsored by the Electric Power Research Institute (EPRI), Argonne National Laboratory (ANL) and the U.S. Nuclear Regulatory Commission (NRC). As most of you are aware, both EPRI ANL, and the NRC were each planning a workshop to bring together international experts in the field of steam generator thermodynamics and chemistry in order to facilitate a technical exchange and discussion in this area. However, upon learning of each other's plans, we decided to combine forces in the spirit of partnership and cooperation. The result of this effort has come to fruition today and in the next few days with an exciting agenda of presentations and discussion topics.

We have a full agenda and many interesting presentations to hear. The purpose of the meeting, as I see it, is to present the work that is on-going with respect to crevice chemistry in order to develop an understanding of where we are as a community and then to identify those areas requiring further work. Hopefully, by the end of the seminar on Friday, we will have come to some consensus on the direction and areas requiring the most attention in the near term and in the long term going forward.

As you can tell from the agenda, there is plenty of time built into the seminar for discussion. Therefore, I encourage everyone to participate in open and frank dialogue as each presentation is given. The seminar has been divided into four sessions, each with a corresponding session chair, to focus the information presented and encourage technical exchange in a systematic manner. In addition, a panel discussion will take place following the fourth session, allowing for additional discussion.

So, I welcome you all to what I anticipate to be a very informative and fruitful seminar, and thank each of you for your support.

Introductory Comments

Joseph Muscara
US Nuclear Regulatory Commission

As many of you know, the NRC has completed two major Steam Generator tube Integrity research programs over the last two decades. We are now in the first year of another five-year program on SGTI. The first two programs concentrated on quantifying and improving in-service inspection reliability and on development of methods for predicting the failure pressures and leak rates of degraded steam generator tubes under normal operating, accident and severe accident conditions. Relatively little work was conducted in the previous two programs on developing an understanding of degradation mechanisms.

The new program will continue and complete work on improved inspection techniques and modeling of steam generator tube integrity. Much more attention will be placed in the new program in gaining a better understanding of degradation in steam generator tubes, particularly on the secondary side of the generator. We need this better understanding to be able to predict the future degradation of SG tubes in operating plants, including the behavior of Alloy 690 tubes. Key to understanding degradation on the secondary side is a better understanding of crevice chemical and physical conditions.

With knowledge of these conditions we can conduct realistic corrosion tests to develop correlations of crack initiation times and growth rates. I want to stress that we need a good understanding of both the chemical and physical conditions of crevices. Therefore understanding the thermal hydraulics and heat transfer across the crevices is also very important. Because conditions vary from location-to-location in a given generator and between generators, because crevices are not symmetric and there is a presence of line contact, it is important to know the crevice conditions axially and radially around the tube. Thus many varied situations are of interest, and we need to develop models to predict crevice physical and chemical conditions as a function of the surrounding conditions.

We intend to develop and evaluate such models. In addition to modeling efforts, we will be measuring physical and chemical conditions experimentally in a model boiler.

Information from the model boiler will be used to conduct corrosion tests of interest and to validate the crevice predictive models. Corrosion test results for both Alloys 600 and 690 will be used to develop correlations for crack initiation and growth. By coupling the laboratory behavior of 600 and 690, to the field experience of Alloy 600, we hope to develop a predictive capability for the behavior of 690 in the field. Gaining a good understanding of crevice conditions will be crucial to developing a predictive methodology for the behavior of steam generator tubing in operating plants, and hopefully we could avoid repeating the poor operating experience with Alloy 600 tubing.

From this seminar, we hope to gain a good understanding of the state-of-the-art of crevice conditions and of crevice corrosion. I look forward to obtaining your input and recommendations that will help us to effectively meet our objectives of developing a capability for predicting steam generator tube degradation under field operating conditions. I want to thank ANL and EPRI for organizing this seminar and you, the world experts, who are participating in the seminar.

Introduction

Roger W. Staehle
University of Minnesota

This meeting is the third in a series to consider in detail the properties of heated crevices in PWR steam generators. Such heated crevices include those associated with various support structures, deposits and top of tube sheet geometries.

The first two meetings were held in Studsvik, Sweden in 1996 and 1998 and were organized by Bo Rosberg and Andres Mollander and their colleagues. These were informal meetings and the proceedings were not intended for distribution but rather as records of the discussions. The present meeting resulted from two sources: one was a commitment by Peter Millett, who attended the Studsvik meetings, for EPRI to sponsor a third such a meeting in the US; the other was a strong interest at ANL to address critical problems in corrosion with the heat transfer crevice being the focus.

As a result of these prior commitments, EPRI and ANL agreed to sponsor jointly this meeting. Accordingly, Paul Frattini of EPRI and Jangyul Park of ANL organized the meeting.

I would like to thank all of you for attending and I would like to thank Roger Poppel, Division Director at ANL, for supporting the meeting at ANL.

The primary purpose of the considerations in this meeting is to develop a means for predicting the corrosion of steam generator tubes with respect to the secondary side of steam generators. Such a prediction requires specifically that the environment to which the tubes are exposed be specifically characterized. Prediction of any corrosion is not possible without a detailed characterization of the local environment that occurs specifically on surfaces. This meeting considers mainly environments that occur in heat transfer crevices. By this is meant those conditions were superheat occurs and where this superheat leads to the concentration of chemicals in the secondary water. Such geometries occur at tube suuports, antivibration bars, sludge piles, and top of tubesheet crevices. Concentration of chemicals also occurs on free spans and importantly on free spans in the upper bundle of OTSGs. These need to be considered.

This meeting has been organized to bring the world's experts together from the important disciplines that can contribute significantly to the discussion. To facilitate the interaction and synergy of these experts, extensive time has been allocated for discussions.

In order to facilitate preparing a record of the meeting, Dwight Diercks has agreed to prepare minutes of the meeting. Also, questions and answers from the audience will be included in the final proceedings. The operation of the meeting itself is being facilitated by Denise Moore and Zhou Zhongquan of ANL.

We hope that this meeting will: define the present state of understanding, define priorities for future work, and develop improved understandings through interactive discussions.

I would like to thank Paul Frattini and Jangyul Park especially for their extensive work in organizing this meeting. The quality of meetings is always proportional to the amount of work ahead of time.