February 7, 2001

MEMORANDUM TO: William H. Bateman, Chief
Materials and Chemical Engineering Branch
Division of Engineering
Office of Nuclear Reactor Regulation

Nilesh C. Chokshi, Chief
Materials Engineering Branch
Division of Engineering Technology
Office of Nuclear Regulatory Research

FROM: Emmett L. Murphy ***/ra/***
Materials and Chemical Engineering Branch
Division of Engineering
Office of Nuclear Reactor Regulation

Joseph Muscara ***/ra/***
Materials Engineering Branch
Division of Engineering Technology
Office of Nuclear Regulatory Research

SUBJECT: FOREIGN TRIP REPORT - INTERNATIONAL STEAM GENERATOR TUBE INTEGRITY PROGRAM - 2, TECHNICAL COORDINATION GROUP MEETING IN MISSISSAUGA, ONTARIO ON OCTOBER 31 - NOVEMBER 2, 2000

On October 31 to November 2, 2000, we attended the Technical Coordination Group meeting for the International Steam Generator Tube Integrity Program - 2 (ISG-TIP-2). This meeting was conducted at the Sheridan Science and Technology Park Facilities of Atomic Energy of Canada, Ltd. (AECL) in Mississauga, Ontario. Our trip report is attached.

Attachment: As stated

CONTACT: E. L. Murphy, EMCB/De
415-2710

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Distribution: ESullivan JRStrosnider BWSheron RZimmerman SCollins
E. Hackett MMayfield AThadani JDunn-Lee MCullingford
EMCB RF

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NAME	ELMurphy:elm		EJSullivan:ejs		JMuscara:jm	
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ISG-TIP-2 Technical Coordination Group Meeting
Mississauga, ON
October 31 - November 2, 2000
Trip Report

The fall 2000, meeting of the International Steam Generator Tube Integrity Program-2 (ISG-TIP-2) was held on October 31-November 2, 2000, at the Sheridan Science and Technology Park Facilities of Atomic Energy of Canada, Ltd. (AECL) in Mississauga, ON. A meeting agenda and list of attendees are attached. Printed copies of all the presentation materials were provided to the attendees at the meeting, and a CD-ROM containing all of these materials in electronic form is being prepared for distribution to the attendees. This trip report summarizes some of the more important discussions at the meeting.

The meeting was opened by introductory remarks by Bob Tapping of AECL-Chalk River, followed by a welcome from Basma Shalaby, Chief Engineer for AECL. Joe Muscara (USNRC) then gave a brief overview of the NRC Steam Generator Tube Integrity Program, and Bob Tapping followed with an overview of the steam generator activities on the part of AECL and the CANDU Owner's Group (COG).

P. V. Balakrishnan of AECL then gave the first detailed technical presentation of the day on the topic "Steam Generator Crevice Chemistry." During this presentation, Roger Staehle asked Balakrishnan if he had chemically analyzed the crevice deposits after his autoclave experiments and whether crevice boiling was observed. Balakrishnan responded that they had not performed a complete analysis, but the had observed, for example, that the magnetite had transformed to hematite. He also stated that crevice boiling was observed, and the crevice environment was observed to be acidic. Balakrishnan added that the results of his experiments led him to conclude that molar ratio control was not a desirable way to ameliorate the aggressive crevice environments.

Mike Wright (AECL) then followed with a presentation on Alloy 800 corrosion, with particular emphasis on Pb-induced cracking. In a discussion of Wright's results, Roger Staehle noted that dissolved Pb in very small concentrations can induce SCC in almost all steam generator tube alloys over a wide range of pH, water chemistry, and temperature conditions. Since ample Pb appears to be present in most reactor systems, Staehle wondered why Pb-induced cracking is not more widely observed than it is. In answer to his own question, Staehle speculated that certain impurities naturally present in the crevices may prevent Pb-induced cracking by chemically combining with and precipitating the Pb out of solution, thereby reducing the Pb chemical activity. Lead silicate, for example, is a stable compound in equilibrium with aqueous solutions over the entire range of pH values at room temperature (see discussion of Pb Cracking Seminar at the end of this summary). He further noted that Sb and As may well have the same effect as Pb, but they have not been as widely investigated.

Sean Sullivan of AECL presented work on Recent Advances in AECL Eddy Current Inspection Technology. During the discussions, Joe Muscara inquired about the status of the qualification of the X Probe. Gary Elder (Westinghouse) noted that the Palo Verde station used the X Probe as a part of its most recent inspection, and further use of the probe at other facilities is planned.

Attachment

A general discussion of the capabilities of the X Probe relative to array probes and the bobbin coil then followed. Jim Benson (EPRI) asked whether the X Probe was used to measure the magnetite film thickness on the outside of the tubes. Sullivan responded that it was not, though the probe had been used to some extent in an attempt to evaluate the effectiveness of sludge lancing. Elder added that data similar to that provided by the X Probe had been used to estimate magnetite thicknesses on tubes in a few U.S. plants. The presentation also addressed recent investigations at AECL on advanced data analysis methods. Preliminary results were presented on sizing of flaws in a tube standard with C6 probe and reconstruction of volumetric flaw profiles from bobbin coil data. Sasan Bakhtiari (ANL) inquired as to what type of algorithm was used to create the flaw images shown in Sullivan's presentation. According to Sullivan, the bobbin coil inversion technique is based on the skin depth equation and uses multiple-frequency information along with the signal shape to determine the flaw depth and extent.

Terry Harasym (OPG) followed with a presentation on nuclear steam generator tube inspection capabilities at OPG. He noted the difficulties in getting probes through tight-radius U-bends, particularly in the smaller-diameter CANDU steam generator tubes. Where the probes get through, they typically have very short lives. The use of ceramic wear-resistant shoes appears to provide at least some improvement in probe life. Roger Staehle noted that Peter Scott of Framatome has recently conducted a study in which he found that certain heats of Alloy 600 used in Framatome steam generators were clearly more susceptible to SCC than other heats. He asked whether OPG could identify which heat of material was used for a given tube in their reactors. Harasym stated that, in general, they could, though no systematic study of the susceptibility of particular heats had been conducted. In response to anther question, Harasym stated that UT had been used for detailed examinations of a limited number of tubes to look for specific types of degradation, e.g., fretting at the U-bend supports.

Mike Kozluk (OPG) described experimental work by OPG on the integrity and pressure testing of steam generator tubes. Difference in the safety factors on tube rupture and permissible tube leakage between the U.S. and Canada were discussed. Joe Muscara asked whether the design of the Canadian pressure testing facility avoided the problem of pressurized water flashing to steam upstream of the test specimen, which would result in flow measurements being made under two-phase flow conditions, thereby potentially invalidating the test results. Kozluk stated that the facility was being rebuilt to minimize upstream flow-related friction. The facility would then be checked out by measuring the flow rate through standard orifices, noting that, based on work at ANL, they were quite comfortable with the standard orifice correlation formula.

Dave Kupperman (ANL) then gave a review of the progress on the ANL steam generator tube mockup and NDE round robin. Jim Benson and Gary Elder discussed the use of the ANL multivariate analysis to determine the "true state" of the tubes in the mockup. They expressed the need for an NDE Task Group meeting to consider this matter further. Joe Muscara felt that there was probably insufficient time for such a meeting before a topical report from ANL on the round robin work was due at the NRC. He suggested that it would be better to hold such a meeting sometime early in 2001, after the report was submitted. He noted that the topical report was an interim analysis in any case. Benson asked whether a multivariate analysis was being performed at tube locations where the independent expert, Cheryl Gortemiller, had called an indication but where ANL had not intentionally placed a flawed tube. Sasan Bakhtiari said

that such locations would be analyzed after all of the known flaws had been characterized. Muscara added that such tubes were likely candidates for destructive examination. Finally, the uncertainty limits on the POD determined by the round robin exercise were discussed.

Sasan Bakhtiari (ANL) presented the status of his work on the research on inservice inspection technology. Recent investigations on multiparameter analysis of rotating probe data were discussed, including NDE profiles from various collections of laboratory-degraded and machined specimens. The presentation also included results from a separate study aimed at quantifying the influence of OD support structures and deposits on detection and sizing by using a set of tubes fitted with simulated collars. Joe Muscara and Jim Benson asked about the possible use of smaller-diameter coils to obtain improved resolution. Bakhtiari responded that smaller coils would indeed give better resolution, but these smaller coils generally operate at higher frequencies, resulting in decreased sensitivity to OD flaws in particular. Muscara asked what part of the multivariate analysis algorithm needed to be changed to better accommodate smaller coils. Bakhtiari responded that the rule-based part would most likely require some modifications. He added that efforts are currently being made to minimize the effect of coil geometry and operating frequency by adding more flexibility to that part of the algorithm.

When the meeting resumed on Wednesday morning, Dwight Diercks (ANL) presented work performed by Jang-Yul Park (ANL) on the production and characterization of laboratory-degraded tubes. Comparisons between crack profiles determined by the ANL multivariate analysis of EC data and actual destructive analysis results evoked considerable interest. Roger Staehle asked whether these results have yet been published in the open literature (they have not), and he suggested a forthcoming EAC meeting as a possible place for publication. Jim Benson asked the approximate time required to perform the destructive analyses, and Diercks noted that it was rather variable, but that the heat tinting operation; SEM and macroscopic examinations; and data gathering, reduction, and digitizing were rather time consuming. After further discussions, Diercks agreed that times of about one week per tube were of the right order of magnitude.

Saurin Majumdar (ANL) then presented ligament rupture data and analysis of specimens with two part-throughwall axial notches that are either collinear or offset circumferentially. Ligament widths of 0.010, 0.05, and 0.1 in. were tested. Test showed that ligament rupture pressure for 2-EDM notches is not different from that of 2 similar laser cut notches for ligament widths $\leq$ 0.01 in. Critical ligament widths for 2- 0.25 in. and 2- 0.5 in. long part-throughwall notches (i.e., beyond which the ligament rupture pressure is the same as that of two single independent notches) are dependent primarily on the notch depths. For 70 and 80% deep notches, the critical ligament widths are ~0.2 and 0.35 in., respectively. The notch tip ligament rupture pressures for both types of notches could be predicted by the equivalent rectangular crack method reasonably well. Critical ligament width for 2- 0.25 in. and 2- 0.5 in. long throughwall notches (i.e., below which the ligament does not add to the burst strength of a single notch of the same total length) is ~0.05 in. Critical ligament widths for 2- 0.25 in. and 2- 0.5 in. long throughwall notches (i.e., beyond which the burst pressure is the same as that of two single independent notches) are ~0.125 and 0.25 in., respectively. Critical ligament widths for 2- 0.25 in. and 2- 0.5 in. long throughwall notches (i.e., beyond which the burst pressure is the same as that of two single independent notches) are ~0.125 and 0.25 in., respectively.

Roger Staehle presented his ongoing work on modeling of SCC in mill-annealed Alloy 600 on the secondary side of steam generators. The model will emphasize cracking at TTS and TSP crevices, with lesser emphasis on cracking in the freespan, at least in the initial stages of the modeling effort. Staehle noted that, while a model based on atomistic first principles may be desirable, it is not attainable at the present stage of understanding. He instead proposed a multiple-step approach that includes quantifying the cracking submodes with respect to their dependencies on the principal variables, quantifying the environments with respect to their inputs to the principal variables, selecting and modeling the relevant submodes and environments, and finally statistically modifying and optimizing these models. The overall structure and methodology of the proposed model was described, and Staehle presented proposed mathematical formulations for dealing with the major variables. There was some discussion by meeting participants of the modeling approach and of specifics such as the definition of crack initiation and the uncertainties in the various model parameters.

Jim Benson then presented the present status of the EPRI Heated Crevice Program on behalf of Nikki Torigoe, who could not attend the meeting. Several meeting participants asked whether the chemistry of the blowdown is really representative of the crevice chemistry, and it was suggested that an instrumented model boiler might be a better means for measuring the parameters of interest. Roger Staehle noted that he will be obtaining access to the chemical analyses of numerous “crevice collars,” which are rings of corrosion products and impurity deposits that were dislodged from tube sheet and TSP crevices during steam generator sludge lancing and subsequently collected. These collars should therefore be representative of the crevice chemistry. Staehle also suggested using cubic zirconia rather than diamond for the Raman system window, since carbon is somewhat unstable in the operating environment. After some discussion, there was a general consensus that the Jesse Lumsden’s experiments at the Ohi reactor should provide a reasonable picture of the crevice chemistry.

Dwight Diercks then presented work on the leak and pressure testing of Korean archive tubes on behalf of Seong Sik Hwang of KAERI, who could not attend the meeting. He also distributed copies of the KAERI semiannual progress report to the participants. Jim Benson asked whether the tests should have been conducted on tubes in the RTZ mechanical condition, since this is where the cracking is being observed in the Ulchin reactor in Korea. However, Gary Elder noted that the cracking is actually occurring in the “kiss roll” region above the RTZ. He added that such kiss roll cracking is fairly common in FTI steam generators, even in Alloy 600 TT tubing. Roger Staehle suggested that the Koreans might want to contact Peter Scott of FTI about his recent work on identifying susceptible heats of Alloy 600.

Myung Ho Song (KINS) gave presentations on the interactions of parallel axial cracks in SG tubing and on numerical modeling and neural network analyses of eddy current results. In the first presentation, it was concluded that an initial analysis that assumed failure to occur upon contact of the plastic zones associated with the two cracks was too conservative and that further studies were needed to define an appropriate failure criterion. In the second presentation, the classification and sizing capabilities of hybrid neural networks were described. Geometric features of EC Lissajous patterns from various axisymmetric simulated flaws were

used to train the networks. In addition, the feasibility of remote field eddy current (RFEC) testing of steam generator tubes was discussed. Numerical simulations were carried out to optimize various coil parameters, such as exciter-to-sensor spacing and operating frequency. Although the feasibility of RFEC testing for the inspection of the non-ferromagnetic SG tubing has been confirmed by theoretical analysis, further evaluations are necessary to experimentally verify these findings.

In the final presentation of the meeting, Bob Keating (Westinghouse) described the results of analyses of the effect of ramp rate on the burst pressure of SG tubes. Based on both experimental results, analytical studies, and a review of literature data, it was concluded that a rate effect was observed in the results from testing of Type 14 specimens and that the potential exists for a rate effect for deep ($\geq$90% TW) planar axial cracks. This effect was not considered to affect industry burst correlations, but industry guidance for in situ burst testing is being issued. Saurin Majumdar argues that in the absence of data the claim that rate effects occur only for planar cracks but not for SCC does not seem supportable. Majumdar pointed out that we observe time-dependent leakage in the blowdown facility, which suggests the presence of ligaments that might lead to an apparent rate effect. Keating agrees that a possible way to resolve this might be to test at various rates specimens with 2 deep axial notches that are offset in the circumferential direction by short ligaments. Joe Muscara requested that ANL determine if they are still in possession of the tube material on which the PNNL burst tests were conducted so that elevated-temperature tensile properties could be obtained for this material.

Joe Muscara concluded the meeting with a number of procedural items. He first noted that he needed updated ISG-TIP-2 proposals from EPRI and Westinghouse as soon as possible. He also stated that he was not receiving the required semiannual progress reports from most of the participants. He suggested that the delinquent participants could catch up by preparing a single progress report covering work to date, followed by the required reports at 6-month intervals. Muscara than then noted that the present program ended in 2001, and he inquired about participant interest in a follow-on program. If there were such interest, what sorts of work should be emphasized in the new program. Gary Elder suggested that such a follow-on program include more emphasis on Alloy 600 TT and Alloy 690 TT tubing. Muscara suggested that a half-day session at the next ISG-TIP-2 meeting be devoted to the question of the follow-on program and how the cooperative efforts can be made more effective. The next meeting is to be held in Korea in the Spring of 2001. Muscara noted that an International Crack Growth—Environmentally Assisted Cracking (ICG-EAC) group meeting was to be held in Seoul on April 22-27, and he suggested that the ISG-TIP-2 meeting be scheduled in proximity with this meeting, perhaps on the following week. Muscara further suggested that the meeting might be held in Taejon, since that was where the principle facilities of KINS and KAERI were located.

Lead-Cracking Seminar

During the tour of the Babcock & Wilcox—Canada manufacturing facilities on the afternoon of Wednesday, November 1, Roger Staehle and several other meeting attendees remained behind at Sheridan Park to conduct an informal seminar on the effects of lead on SCC in steam generators. The seminar was held in Room B of AECL offices at Sheridan Park from noon until 17:00. Participants in the seminar were Roger Staehle, Mike Wright (AECL), Mavash Mirzai (OPG), Sandra Pagan (OPG), Carmina Maruska (OPG), P. V. Balakrishnan (AECL).

Mike Wright presented data from AECL work, and Roger Staehle presented data from the work of numerous investigators based on a set of notes that he prepared and distributed to the attendees. Other participants contributed from laboratory and plant experience. Important observations by the group, as reported by Roger Staehle, are the following:

1. The SCC observed in both laboratory and operating plants is related to an effect of lead in some soluble ionic form and is not a form of liquid metal embrittlement. This is based on the observations that PbSCC (SCC due to lead) occurs in oxygenated water as well as deoxygenated water. These environments include a potential range from the Pb/PbO equilibrium to potentials probably at least 500 mV more positive and are removed from potentials for which there was any possibility that metallic lead could exist.

2. PbSCC has been observed in a wide range of alloys, including Monel 400, Type 304 stainless steel, Alloy 800, Alloy 600, Alloy 690, and 17-4 PH. This range of alloys in which PbSCC is observed is among the widest of any environmental effect.

3. PbSCC is observed over the full range of pH values from concentrated alkaline, through neutral, to mildly acidic (at least proved to be true for Alloy 600). No other single species produces SCC over such a wide range of pH.

4. Pb can produce SCC at concentrations as low as 0.1 ppm in homogeneous aqueous solutions in the neutral range when the Pb is introduced as PbO (the case for Alloy 600).

5. PbSCC is observed to produce both transgranular and intergranular SCC in various materials. The generality that the occurrence of TGSCC is indicative of Pb is not correct. IGSCC can be produced by Pb (this has already been proven both by experiment and in the Bruce A SGs); further, chloride by itself produces TGSCC of Alloy 600. Thus, the path of SCC cannot be uniquely ascribed to the presence or absence of Pb.

6. PbSCC is observed at stresses as low as 20% of the YS and probably occurs at lower stresses. This is similar to the pattern for ClSCC.

7. PbSCC has been observed at temperatures as low as the 270-280°C range. No SCC work seems to have been conducted at lower temperatures. However, as with ClSCC,

PbSCC at much lower temperatures should be considered reasonable (the solubility of Pb at lower T's will become the issue).

8. In analyzing Pb with surface methods, it is sometimes missed either because of the thinness of the Pb layer or because of the interference of the Pb lines with others.

9. Pb seems to exert its effect mainly by decreasing the stability of passive films. The effects of Pb on the polarization response have not been studied in alkaline, neutral, and mildly acidic environments. Pb consistently causes the active peak to increase and to broaden with increasing concentrations (proven to be the case for Alloy 600 and Alloy 800). However, at higher potentials, Pb seems to exert less if any effect. This decrease in stability of the passive film then produces a range prone to SCC which is in the classically defined location between the active peak and the passive range. Such a range was predicted in 1971 and has been consistently the most likely location for the occurrence of SCC.

10. Pb seems also to exert some inhibition at higher concentrations possibly greater than 500 to 1000 ppm, although any threshold for such an inhibitory effect is not well defined.

11. Probably the most important question relative to PbSCC is why there is not very extensive SCC, in view of the ubiquity of Pb in deposits of all plants in the 10's of ppm range and in view of the low concentrations at which PbSCC can occur. It seems that one reasonable explanation is related to the reactions with Pb with other species to lower its activity, and the need for high stresses/strains. Preliminary thermodynamic calculations were reviewed based on binary combinations in water for Pb with B, Si, S, N, C, Cr. Significant insolubilities are observed with S, Si, C, N, and Cr. However, only the S and Si seem at all relevant. Further, the Si compounds with Pb seem to dissolve with increasing temperature, being very insoluble at RT but extensively soluble at 300°C. It is quite likely that Pb is prevented from producing PbSCC by the reaction of lead to form insoluble compounds, i.e. the activity of lead is reduced when various Pb compounds are produced. However, it should be noted that if certain species might react preferentially, say with silica as for Ca, then the silica may not be available to react with Pb. Thus, the availability of Pb to produce SCC may depend on the presence of other species that form insoluble compounds; their absence or insufficiency may permit PbSCC.

AGENDA
ISG-TIP-2 Technical Coordination Group Meeting
Mississauga, ON, Canada
October 31-November 2, 2000

Date and Time	Topic	Presenter
Tuesday, October 31		
9:00 - 9:15	Opening Remarks	J. Muscara, NRC
9:15 – 9:30	Overview of AECL Activities on Steam Generators	R. Tapping, AECL
9:30-10:15	Steam Generator Crevice Chemistry	Balakrishnan, AECL
10:15 – 10:30	Break	
10:30 – 11:15	Alloy 800 Corrosion—Recent Results and Links to Previous work on Alloy 600	M. Wright, AECL
11:15 – 12:00	Recent Advancements in AECL Eddy Current Inspection Technology	S. Sullivan, AECL
12:00 - 1:00	Lunch	
1:00 – 1:30	Ontario Power Generation Nuclear Steam Generator NDE Capability	T. Harasym, OPG
1:30 – 2:15	OPG's Steam Generator Tube Testing Project	M. J. Kozluk, OPG
2:15 – 3:00	Progress Review for the Argonne SG Mock-up NDE Round Robin	D. S. Kupperman, ANL
3:00 – 3:15	Break	
3:15 – 4:30	Steam Generator Tube Integrity Program Task 2: Research on Inservice Inspection Technology	S. Bakhtiari, ANL
4:30 – 5:00	Production and Characterization of Laboratory-Degraded Tubes	D. R. Diercks, ANL
6:00	Dinner	
Wednesday, November 1		
9:00 – 10:15	Pressure and Leak-Rate Testing and Analysis of Test Results for Multiple Flaws	S. Majumdar, ANL
10:15 - 10:30	Break	
10:30 – 11:15	Modeling and Predicting Initiation of SCC in Mill-Annealed Alloy 600 on the Secondary Side of Steam Generators	R. W. Staehle, Consultant
11:15 - 12:00	Lunch	
12:00	Leave for Babcock & Wilcox Tour	
1:30 – 3:00	Technical Presentations by NRC and B&W	
3:00 – 5:00	Tour of Babcock & Wilcox Fabrication Facilities	

AGENDA (Cont'd.)
ISG-TIP-2 Technical Coordination Group Meeting

Date and Time	Topic	Presenter
Thursday, November 2		
9:00 – 9:30	Heated Crevice Program	J. Benson, EPRI
9:30 – 10:15	Leak/Pressure Testing of Korean Archive Tubes	S. S. Hwang, KAERI
10:15 – 10:30	Break	
10:30 – 11:30	Investigation on the Interaction Effect of Two Parallel Axial Through-wall Cracks in Steam Generator Tubes	M. H. Song, KINS
11:30 – 12:30	Numerical Modeling and Neural Network Analysis of Eddy Current and Remote Field Eddy Current Testing	M. H. Song, KINS
12:30 – 1:30	Lunch	
1:30 – 2:15	Effect of Ramp Rate on Burst Pressure	R. Keating, Westinghouse
2:15 – 3:00	Summary and Discussions	

LIST OF ATTENDEES

ISG-TIP-2 Technical Coordination Group Meeting
Mississauga, ON
October 31 - November 2, 2000

Name	Affiliation	Telephone/email
R. L. Tapping	Atomic Energy of Canada, Ltd.	(613) 584-8811, x3219 tappingr@aecl.ca
Mike Wright	Atomic Energy of Canada, Ltd.	(613) 584-8811, x6879 wrightmd@aecl.ca
Sean Sullivan	Atomic Energy of Canada, Ltd.	(613) 584-8811, x3436 sullivans@aecl.ca
P. V. (Bala) Balakrishnan	Atomic Energy of Canada, Ltd.	(613) 584-8811, x3264 balakrishnanb@aecl.ca
Colette Taylor	Atomic Energy of Canada, Ltd.	(613) 584-8811, x3779 tayloyc@aecl.ca
Marc Leger	Atomic Energy of Canada, Ltd.	(905) 823-9060, x3066 legerm@aecl.ca
Mahvash Mirzai	Ontario Power Generation	mahvesh.mirzai@ontariopowergeneration.com
Mike Kozluk	Ontario Power Generation	(416) 592-4567 mike.kozluk@ontariopowergeneration.com
Carl Daniel	Ontario Power Generation	(416) 592-4052 carl.daniel@ontariopowergeneration.com
Erik Carter	Ontario Power Generation	(416) 592-2587 erik.carter@ontariopowergeneration.com
Stan Buhay	Ontario Power Generation	(416) 592-6905 stan.buhay@ontariopowergeneration.com
Carmina Maruska	Ontario Power Generation	(416) 592-5668 c.maruska@ontariopowergeneration.com
Kay Brennenstuhl	Ontario Power Generation	(416) 592-5623 kay.brennenstuhl@ontariopowergeneration.com
Sandra Pagan	Ontario Power Generation	(416) 592-7525 (416) 592-4483 (FAX) sandra.pagan@ontariopowergeneration.com
Joseph P. Van Langen	Ontario Power Generation	(905) 839-1151, x2203 joseph.vanlangen@ontariopowergeneration.com

Name	Affiliation	Telephone/email
Terry Harasym	Ontario Power Generation	(905) 839-1151, x2357 terry.harasym@ontariopowergeneration.com
Don Martin	Ontario Power Generation	(905) 592-5658 (905) 592-4483 (FAX) don.martin@ontariopowergeneration.com
Charles Baker	CANDU Owner's Group	(416) 595-1888, x114 charles.baker@candu.org
Ahmed Ibrahim	CNSC	(613) 947-0624
Jovica Riznic	CNSC	(613) 943-0132 riznicj@cnsc-ccsn.gc.ca
Joe Muscara	USNRC/RES	(301) 415-5844 jxm8@nrc.gov
Emmett Murphy	USNRC/NRR	(301) 415-2710 elm@nrc.gov
Myung-Ho Song	KINS	82-42-868-0191 k084smh@kins.re.kr
Gary Elder	Westinghouse	(412) 374-4884 eldergg @westinghouse.com
Gary Keating	Westinghouse	(724) 722-5086 keatinrf@westinghouse.com
Jim Benson	EPRI	(650) 855-2146 jbenson@epri.com
Roger W. Staehle	Consultant	rwstaehle@rwstaehle.com
Saurin Majumdar	Argonne National Laboratory	(632) 252-5136 majumdar@anl.gov
Sasan Bakhtiari	Argonne National Laboratory	(632) 252-8982 bakhtiari@anl.gov
Dwight Diercks	Argonne National Laboratory	(632) 252-5032 bakhtiari@anl.gov
Dave Kupperman	Argonne National Laboratory	(632) 252-5108 dsk@anl.gov