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SUBJECT: Forwards non-proprietary response to RAI re TRs WCAP-14707 & WCAP-14708,Electricite de France repts D.5716/CTT/RB 97.6129 & D.5716/CTT/RS 94.6124 & proprietary W Science & Technology rept 94-7TE2-DAPER-R1.W/affidavit.Proprietary info withheld.

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February 23, 1998

PG&E Letter DCL-98-025

U.S. Nuclear Regulatory Commission
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Docket No. 50-275, OL-DPR-80
Docket No. 50-323, OL-DPR-82
Diablo Canyon Units 1 and 2
Response to NRC Request for Additional Information
WCAP-14707 and 14708

Dear Commissioners and Staff:

PG&E Letter DCL-96-206, dated October 4, 1996, transmitted to the NRC Westinghouse technical reports WCAP-14707 (proprietary) and WCAP-14708 (nonproprietary), "Model 51 Steam Generator Limited Tube Support Plate Displacement Analysis for Dented or Packed Tube-to-Tube Support Plate Crevices."

In a letter to PG&E dated December 2, 1997, the NRC staff requested additional information that was required to complete their review of the technical reports. Based on discussions with the NRR Project Manager for Diablo Canyon, the due date for response to the NRC request was extended from January 9 to February 23, 1998. PG&E's response to the request for additional information is enclosed. The enclosure includes two attachments: Attachment 1 contains a supplement to the response to NRC Question 2; Attachment 2 contains a copy of References 2, 3, and 4 of WCAP-14707, as requested in NRC Question 1. It should be noted that References 2 and 3 were previously considered to be confidential. PG&E has received confirmation that these two documents may now be submitted without restriction and, therefore, no exemption in accordance with 10 CFR 2.790 is requested.

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Reference 4, "Westinghouse Science and Technology Report 94-7TE2-DAPER-R1, Characterization of Crevice Deposits in the Dampierre Unit 1 Steam Generator Tube Support Plate Assembly," contains proprietary information. Accordingly, Attachment 2 includes a Westinghouse Application for Withholding Proprietary Information from Public Disclosure, a Proprietary Information Notice, a Copyright Notice, and an accompanying Affidavit CAW-98-1211 signed by Westinghouse, the owner of the information. The affidavit sets forth the basis upon which the information may be withheld from public disclosure by the Commission, and it addresses with specificity the considerations listed in paragraph (b)(4) of 10 FR 2.790. PG&E requests that the Westinghouse proprietary information be withheld from public disclosure in accordance with 10 CFR 2.790.

Correspondence with respect to the proprietary aspects of the Westinghouse report listed above or the supporting information provided in Attachment 2 should reference Westinghouse Letter CAS-98-1211 and be addressed to Henry A. Sepp, Manager, Regulatory and Licensing Engineering, Westinghouse Electric Corporation, P.O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Sincerely,

Lawrence F. Womack

c: Steven D. Bloom
Ellis W. Merschoff (w/o Attach. 2)
Kenneth E. Perkins (w/o Attach. 2)
David L. Proulx (w/o Attach. 2)
Diablo Distribution (w/o Figures and Attach. 2)

Enclosure

RLJ/2057

ENCLOSURE

RESPONSE TO NRC REQUEST FOR ADDITIONAL INFORMATION WCAP-14707 AND WCAP-14708

Attachment 1 -- Supplement to the Response to NRC Question 2

Attachment 2 -- Copy of References 2, 3, and 4 of WCAP-14707

RESPONSE TO NRC REQUEST FOR ADDITIONAL INFORMATION WCAP-14707 and WCAP-14708

PG&E Letter DCL-96-206, dated October 4, 1996, transmitted to the NRC Westinghouse technical reports WCAP-14707 (proprietary) and WCAP-14708 (nonproprietary), "Model 51 Steam Generator Limited Tube Support Plate Displacement Analysis for Dented or Packed Tube-to-Tube Support Plate Crevices." On December 2, 1997, the NRC staff requested additional information relative to the technical reports. The NRC questions and PG&E's responses follow:

NRC QUESTION 1.

Provide References 1, 2, 3 and 4 for staff review.

PG&E Response

Reference 1 of WCAP-14707 was previously provided to the NRC. A more recent revision (Revision 2 of EPRI Report NP-7480-L, Volume 1) was also previously transmitted to the NRC (see Reference 1.1 of this response). References 2, 3, and 4 of WCAP-14707 are provided as Attachment 2 of this enclosure.

NRC QUESTION 2.

Provide the technical basis for concluding that the Dampierre-1 test results (i.e., pull force and leak rate testing, before and after chemical cleaning) are applicable to all TSP intersections in all Model 51 steam generators despite potential differences in the TSP crevice conditions given differences in TSP location, SG service life, secondary side water chemistry, chemical cleaning process, etc.

PG&E Response

It should be clarified that the report's conclusions are not dependent on the Dampierre test results being applicable to "all" tube support plate (TSP) intersections. The report's conclusions are based on the presence of a sufficient number of dented and/or packed crevices without tube deformation that have adequate pull force capability to prevent TSP displacement. The Dampierre test results demonstrate large pull force margins compared to the potential loads on the TSP from a postulated steam line break (SLB). Limitations on leakage are inherent to the crevice conditions causing corrosion. The occurrence of primary water stress corrosion cracking (PWSCC) requires some degree of denting to sufficiently ovalize or locally deform the tube and thus is associated with a hard packed crevice that would limit leakage to very low values.

Modeling the behavior of crevices between the tube and TSP has gained the attention of numerous researchers (Reference 2.1). The concepts and supporting laboratory

tests have shown that locally restricting the flow of secondary side water to the heat transfer surface of the tubing will result in higher tube wall temperatures. These higher temperatures drive the concentration of dissolved species to factors that are readily in excess of 20,000 (Reference 2.2). With this factor, a bulk water contaminant present at 1 ppm will exceed a concentration of 20,000 ppm in a 2 percent solution. Since the bulk water feeding the crevice also contains some small quantity of suspended solids, e.g., non-oxides, the combination of transported solids and solids precipitating from concentrated solutions result in a packed, occluded crevice region. If the concentrating bulk water contaminants contain aggressive species, such as sodium hydroxide, these species may interact with the tubing to produce stress corrosion cracking.

The distribution of outside diameter stress corrosion cracking (ODSCC) in steam generators (SGs) that are experiencing TSP corrosion is consistent with this model. The corrosion is very preferentially distributed to the lower TSP regions of the hot leg side that are capable of producing the highest available superheat for the concentration of contaminants. The free span surface of the tubing has more access to the bulk water and more efficient heat transfer which prevents the formation of high concentration factors. In SGs that have flow distribution baffles (not included in Model 51 SGs), the crevices benefit in a similar manner since the crevice gap of a flow distribution baffle is significantly greater than that of the tube-to-TSP crevice and such variations in dimensions affect local superheat conditions (Reference 2.3).

The presence of ODSCC at the tube-to-TSP crevice region is therefore a very good indication that the crevice region has been packed. Numerous tube pulls, including those in support of the Generic Letter (GL) 95-05 alternate repair criteria (ARC), have confirmed this conclusion by the observation of residual unique precipitates adhering to the tube in the TSP region (References 2.4 to 2.7). Thus, leakage will be limited by the crevice conditions provided it can be demonstrated that the TSPs will not displace in a SLB event. The applicability to chemically cleaned units applies to current cleaning processes that do not fully clean the crevices as shown by the results provided in WCAP-14707. If a future chemical cleaning process is shown to more completely clean the crevices, there would be an appropriate operating time before the crevices would be again packed to limit leakage. The applicability to all Model 51 SGs is based on the fact that these units have operated for sufficiently long periods of time to develop packed crevices and most units show the presence of at least some denting.

The following discussion summarizes the characteristics of packed crevices and the commonality of packed crevice conditions between dented and non-dented intersections and between different plants. A more detailed discussion of packed crevice conditions is provided as a supplement to this response in Attachment 1 of this enclosure. This discussion supports the applicability of sufficiently large pull forces to prevent TSP displacement and to limit leakage for packed crevices. The presence of a packed crevice can be demonstrated by nondestructive examination (NDE) as discussed in the response to Question 4.

The crevice condition has been the focus of several tube and tube support plate removal operations that have been followed by detailed destructive examination of the tube-to-TSP crevice. In this response, the data from two fairly recent examinations, Dampierre 1 and Ringhals 3, and one historic examination, Turkey Point 4 (1976 removal), are discussed. The examinations show that the crevice deposits originate from the transport of secondary side materials into the crevice, the precipitation of "mineral" compounds that cement the matrix closest to the tube into an adherent composite and iron oxides formed from corrosion of the carbon steel TSP surface. Chemical analyses and crystallographic evaluations have identified that iron oxides and mineral formulations of silicates, aluminates, and/or phosphates are present in the locations expected based on models of crevice behavior (as discussed above) under SG heat transfer conditions. The porosity and hardness of the deposits are consistent with the models and the compounds produced. The examination of the field samples demonstrates that even deposits with significant "steam chimney" structure have the mechanical integrity to produce tube deformation without collapse of the deposits.

The driving force for the formation of crevice deposits such as those in the plant specimens evaluated is an inherent long-term result of SG operation. Operational conditions produce the superheat required for local boiling, which in combination with the flow restrictive properties of a narrow cylindrical crevice, results in the ability to develop solutions with boiling point elevations reaching the saturation levels for the formation of mineral deposits. Since the materials of plant construction dictate that all SGs will have a ferrous solute present, and the practicalities of water chemistry ensure that the silicate precursors are present, the formation of adherent crevice deposits is inevitable. The only question is the rate at which such crevice deposits will form, and this is dependent on the plant-specific concentration of the crevice packing materials.

The physical properties of the crevice composites and the physical conditions of the crevice-forming materials dictate the behavior of the assembly under different conditions of operation. The deposits are formed and the crevice is packed during plant operation, at elevated temperature, and with a positive primary-to-secondary side pressure differential. Upon plant shutdown, the temperatures are reduced and the primary-to-secondary pressure differential is removed. As a result, during the shutdown condition the composite would be under radial tension across the crevice and it would be expected to experience random fracture. Note that it is in this fractured condition that the composite displays high resistance to significant axial motion. This occurs by moving the tube relative to the TSP and developing interference that places the composite into compression, a condition under which it demonstrates high strength, as has been shown by plant operation leading to denting. The shear surfaces of the TSP crevice deposit generally form away from the mineral-magnetite composite (since deposits are generally observed adhering to the tube surface in the TSP crevice region of tube pull evaluations). Since the separation of crevice deposits, on a tube pull for example, occurs generally away from the tube surface, the magnetite component of the crevice is thus concluded to have sufficient integrity to resist axial movement. From

this it follows that even if the crevice had very little mineral deposit, there would still be resistance to axial movement from the transported and locally produced iron oxide packing.

Operational conditions, since they do not produce the fracture patterns that occur upon shutdown and depressurization, enhance crevice deposit integrity and would result in greater resistance to axial displacement. In addition, the increased primary-to-secondary side pressure differential of a SLB would induce additional compression loads that would further increase the resistance to axial displacement.

In a practical sense, confirmation of crevice deposit formation can be verified and/or deduced to be present by different techniques, namely tube pulls, eddy current NDE, visual inspection, and the observation of tubing corrosion in the TSP crevice region. Tube pulls have demonstrated that the crevices have holding power by measurement of the tube pull phenomenon of breakaway forces. In addition, numerous tube pulls have provided the opportunity to study deposits on the tube side of the crevice. These crevice deposits strongly adhere to the tube and are consistent with the expected chemical composition. Eddy current NDE techniques can provide information on magnetite packing of the crevice, the presence of denting, and also the presence of tube support plate corrosion in the absence of denting. Visual inspection has shown in many cases that the crevices are packed at the edges. Outside diameter (OD) SG tubing corrosion within the TSP is also a verification that the crevices are packed since concentration of dilute bulk water corrodants requires a deposit matrix to support the concentration process.

It is concluded that widespread crevice packing is the expected hot leg crevice condition for SGs experiencing TSP region tubing corrosion in SGs with the drilled hole TSP crevice design. The physical-chemical conditions of operation and chemistry dictate the general composition of the crevice composite, which has been demonstrated to provide restraint to significant axial movement. Attachment 1 of this enclosure provides a more detailed discussion of drilled hole TSP crevice conditions.

NRC Question 3.

Provide the technical basis for concluding the presence of "some denting" indicates all TSP intersections have packed crevices developing high forces resisting SLB displacement and resulting in negligible leakage (p. 2-1).

PG&E Response

The report states that "some denting in the SG can be used as the basis for the TSP corrosion necessary for packed crevices...." The report analyses and conclusions are not based on "all" TSP intersections having packed crevices even though this is the expected condition. A modest number of packed crevices is sufficient to limit TSP displacement as shown in Section 11 of the report. The presence of denting demonstrates support plate corrosion is present and TSP corrosion can be expected, to some extent, at all intersections, particularly hot leg intersections. However, as discussed in the Question 2 response, the crevice conditions of packed crevices are very similar to those for dented crevices and also very similar for all plants examined. Packed crevices resisting TSP displacement and limiting leakage are expected for all Model 51 SGs with or without denting. The presence of denting provides direct confirmation of TSP corrosion to further support the packed crevice conditions. The presence of a packed crevice can be determined by NDE as discussed in the response to Question 4 below.

NRC Question 4.

Discuss how one can directly verify, on a site-specific basis, that the TSP crevice conditions can be relied upon to ensure limited TSP displacement.

PG&E Response

Section 9.4 of WCAP-14707 identifies the distribution across the TSP of the SLB force per tube acting to displace the TSP. These forces vary from a few pounds per tube up to a maximum of 60 pounds. The Dampierre pull force test results demonstrate large margins compared to the less than 60-pound force per tube. For the most limiting tubes and the limiting SLB upstream of the flow restrictor, Section 11.2 provides an example assessment of the number of tubes required to prevent TSP displacement for the most limiting TSP sectors based on application of the Dampierre pull force test results. Given the small force per sector (tube group in dynamic structural analysis model) of the TSP required to limit displacements, it is adequate to demonstrate the presence of about one dented tube per sector or a few tubes with packed crevices. The number of tubes with packed crevices required to limit the displacement is a function of the force per tube required to displace the TSP for the given crevice condition. Therefore, the approach to demonstrate that the crevice conditions can be relied upon to ensure limited TSP displacement is to map the locations of dented tubes and tubes confirmed to have crevices packed with magnetite.

Bobbin coil NDE can be used to detect TSP corrosion and magnetite in the crevice region. This analysis methodology has been used historically to identify "locked" tube-to-TSP crevices at the top TSP in support of the corrective action evaluations in response to NRC Bulletin 88-02 relative to U-bend tube rupture. Figure 4-1 shows the

typical bobbin response as a figure 8 lissajous from a TSP with an open crevice and no TSP corrosion. Figure 4-2 shows distortion of the TSP lissajous obtained from a TSP with a 20-mil deep, 1/4-inch wide, 360 degree circumferential groove machined in the center of the TSP. This signal response is typical of TSP corrosion signals that preceded development of dents in operating plants. The accumulation of high density magnetite in the crevice causes an interference or distortion in the TSP signal. Figure 4-3 shows the same TSP simulant as Figure 4-2, but the groove was filled with magnetite. The "spike"-like signals represent the iron oxide influence and provide insight to characterize a TSP intersection.

An example of the application of the above bobbin NDE techniques to characterize and map TSP corrosion has been documented in Section 5.3 of Reference 4.1, which has been previously transmitted to the NRC as part of the submittals supporting the alternate repair criteria for ODSCC at TSP intersections. These results show that NDE can identify TSP corrosion and magnetite in about 80 to 100 percent of the hot leg crevices. Since it can be expected that all crevices are packed, the 80-percent NDE detection of packed crevices represents the probability of detection of the packed crevice condition.

Upon NRC approval of WCAP-14707, updated procedures for identifying denting, TSP corrosion, and magnetite in the crevice would be qualified using EPRI Appendix H methodology against laboratory specimens. Plants planning to apply WCAP-14707 as the basis for limited TSP displacement would then develop maps of TSP intersections dented or with the presence of TSP corrosion/deposits. These maps, together with tube/TSP breakaway pull forces for dented and for packed crevices, would be used to demonstrate that the crevice conditions provide significant margins against the SLB loads on the TSP such that TSP displacement is prevented. While NDE can identify crevice conditions rather than tube-to-TSP contact forces, the large margins between the load carrying capability of a packed or dented crevice and the SLB loads indicate that additional direct measurements of the crevice resistance to pull force loads are not required.

NRC Question 5.

Discuss the methods used to ensure that all relevant worldwide data have been obtained.

PG&E Response

To ensure that all relevant worldwide data have been obtained, a request was made by EPRI to the French, Belgian, Swedish, and Japanese requesting any available data on pull forces and leak rates measured for tube/TSP intersections. This inquiry did not identify any other new data beyond a single data point from Ringhals 3 that was published (discussed below) since the preparation of WCAP-14707.

Reference 2.7 discusses crevice morphology for two tube/TSP intersections that were removed from Ringhals 3 as described in the response to Question 2. The crevice morphology is very similar to that reported in WCAP-14707 for the Dampierre TSP intersection. The breakaway force to displace the tube relative to the TSP was measured for one TSP intersection with a measured force of 2,397 pounds. This result is in good agreement with the Dampierre data provided in WCAP-14707.

Following preparation of WCAP-14707, an in situ leak test was performed on an indication (Plant A-1, 13.7 bobbin coil volt ODSCC) that was found, after tube removal and destructive examination, to have a 0.42-inch throughwall crack. The indication was in situ tested at normal operating pressure differential and no leakage was obtained. The TSP crevice was packed but there was no dent deformation at the associated TSP intersection. This result provides additional support that packed crevices significantly restrict leakage potential.

No domestic utilities have removed intact tube/TSP intersections and measured tube/TSP breakaway forces or leakage under packed crevice conditions. Tube/TSP intersections have been removed from McGuire-1 under an NRC program but, at this time, breakaway force measurements have not been performed or are not known to be planned.

NRC Question 6.

In accordance with the staff's approach to risk informed regulation, changes in licensing basis are to be accompanied by an assessment of the associated potential for changes in risk. In view of future proposed changes to the design basis, address the implications for tube integrity under severe accident conditions. Specifically, address the effect due to defects left in service.

PG&E Response

Background and Introduction:

Based on an ARC addressing axial PWSCC indications at dented TSP intersections with a qualified NDE technique for sizing of indications, axially oriented flaws could be left in service with depths exceeding the current Technical Specification repair limit. Current plans are to apply the limited TSP displacement analysis of WCAP-14707 to an ARC for axial PWSCC indications within the bounds of the TSP. A later, separate submittal addressing axial PWSCC extending outside of the TSP appears technically supportable. The potential for a change in risk is expected to be reduced or similar to the potential change in risk associated with application of GL 95-05 alternate repair limits for axial ODSCC, previously evaluated by the NRC. The limited TSP displacement condition for the SGs is expected to reduce the severe accident risk for both corrosion mechanisms compared to the open crevice condition of the SGs. This

response is directed toward identifying the assessments that would be made to confirm an acceptably low risk to support ARC for axial PWSCC located within dented TSP intersections.

An engineering assessment would be made to evaluate the crack exposure outside the TSP under severe accident conditions with the goal of demonstrating that the limited tube-to-TSP displacement would not result in a large increase in burst probability or gross leakage. Most likely, restraint at dented intersections will remain, and burst and leakage probabilities will be greatly reduced compared to open crevice conditions. A preliminary assessment of the tube integrity evaluation is described below as well as the impact of the ARC on SG tube rupture probability.

In addition, to gain added insight into the implications for tube integrity under severe accident conditions, PG&E is participating in an EPRI pilot program (Reference 6.1) to develop the methodology to determine the frequency of SG thermal challenge following a severe accident. The methodology being developed is expected to demonstrate acceptably low thermal challenge frequencies at Diablo Canyon Power Plant following a postulated severe accident.

<u>Potential Impact to Inferred Spontaneous Steam Generator Tube Rupture Probability</u>

The application of the ARC for Axial PWSCC at dented TSP intersections is expected to result in a condition such that the associated risk is not expected to change significantly and would be bounded by the risk due to application of the GL 95-05 ARC for axial ODSCC at TSP intersections. The staff has concluded (Reference 6.2) that the application of GL 95-05 will not increase the spontaneous tube rupture frequency due to (1) the deterministic requirements inherent to the criteria that are intended to prevent ruptures, and (2) the TSP constraint prevents ruptures during normal operating conditions.

In the dented TSP ARC, it has been established that the axial constraint provided by the denting condition will preclude TSP displacement relative to the tube during the blowdown phase of a postulated SLB event. Since the SLB is the limiting event for TSP displacement, TSP displacement is also precluded at normal operating conditions and other design basis accident conditions. Therefore, the conditional burst probability at end-of-cycle conditions following application of the criteria will be several orders of magnitude less than the assumed conditional burst probability of 1×10^{-2} associated with the application of GL 95-05. The NRC staff has concluded (References 6.2, 6.3) that with an assumed conditional burst probability of 10^{-2} and given a rapid depressurization of the secondary side, that core damage frequency contribution is acceptably low. In addition, the NRC staff concluded (Reference 6.3) that SG tube performance would not be significantly impacted as a result of axially oriented ODSCC at TSP elevations and, therefore, high pressure severe accident analyses would not be affected. The core damage frequency due to application of the dented TSP ARC will

therefore be significantly below the level currently implied by the 10^{-2} burst probability for application of the ARC for ODSCC at TSP intersections.

Furthermore, consistent with NRC positions presented to the ACRS, primary-to-secondary leakage under design basis accident conditions is expected to be within the NRC-approved allowable leakage limit and well less than the normal charging capacity. It is concluded that application of the PWSCC ARC will not increase the overall core damage frequency.

Tube Integrity Considerations for Postulated Severe Accident Scenarios

Axial PWSCC indications within the TSP are not expected to result in a significant tube burst probability or leakage, even in the event that core uncovery occurs. In this scenario, the hot leg is expected to fail by a creep rupture phenomena, thereby eliminating the thermal challenge to the SG tubes.

Even if the hot leg is assumed to remain intact and increased thermal conditions are postulated for the SG tubes, the restraint forces (which prevent TSP displacement during a SLB event) from the dented TSP intersections would be expected to remain at most TSP intersections. This results in the TSP providing similar constraint to that during normal operating and design basis accident conditions. These constraint effects would therefore similarly greatly reduce the potential for an increase in burst probability and leak rate. At such postulated thermal conditions, the reduced material properties of the TSPs and stayrods would be expected to result in tube/TSP contact forces causing large TSP/stayrod deflections. The load applied to the TSPs and stayrods by the tubes due to thermal growth would significantly exceed the resisting force due to the out of plane stiffness of the TSPs. Therefore, residual burst and leakage constraint would be expected to be provided even under postulated severe accident thermal conditions for all TSP elevations. The TSP proximity during these conditions would act to prevent burst and greatly reduce leakage potential by preventing opening of the crack face. Upon approval of WCAP-14707 and submittal of an ARC, this expected behavior under the severe accident thermal conditions can be analyzed with the detailed structural model used for the WCAP-14707 TSP displacement analyses.

The tubes in the immediate vicinity of the wedges are the only tubes that may represent a potential for flaw extension beyond the TSP due to tube thermal growth and the increased stiffness of the TSP in the wedge regions. Large axial loads are expected to be applied to the TSP stayrods during the event due to tube thermal growth mismatch with the stayrods. It is expected that the dynamics of this configuration would result in the TSPs moving with the tubes, even in the stayrod regions, and therefore providing the proximity restraint that essentially precludes burst and greatly reduces leak rates. The majority of dented TSP axial PWSCC indications are concentrated at the first three TSPs. Under postulated severe accident temperature conditions and assuming the TSP restraint from dented TSP intersections is lost near wedges, tube axial growth

relative to the lower TSPs due to the thermal conditions is expected to result in substantial TSP proximal constraint applied to crack indications originally located within the TSP. This constraint effect acts to "shorten" the effective length of exposed axial flaws due to crack tip restraint within the TSP.

In conclusion, the displacement restraint characteristics of the packed/dented intersections are expected to remain during plant response to a severe accident, and the proximity constraint provided by the TSP during normal operating conditions will also be present during the event. The TSP constraint greatly reduces the burst potential of indications left in service by application of the ARC, and similarly reduces the potential for significant primary-to-secondary leakage.

REFERENCES

1.1 "Industry Database for Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates (Project No. 689), Letter R. C. Callaway, Nuclear Energy Institute, to Document Control Desk, U.S. Nuclear Regulatory Commission, November 20, 1997

2.1 "The ASME Handbook on Water Technology for Thermal Power Systems," Paul Cohen, Editor-in-Chief, The American Society of Mechanical Engineers, New York, NY, 1989, pp 279-340

2.2 Ibid., pages 302-303

2.3 Ibid., page 301, Figure 6-36

2.4 Gupta, K. K., et al., "Diablo Canyon Unit 1 Steam Generator Tube Examination," Westinghouse STC 96-5TC5-SGDCN-R1, July 16, 1996, Figures 2-1a to 2-7d

2.5 Albertin, L., et al., "Characterization of Crevice Deposits in the Dampierre Unit 1 Steam Generator Tube Support Plate Assembly," Westinghouse STC 94-7TE2-DAPER-R1, November 30, 1994

2.6 Morgan, E. P., et al., "Examination of Denting and Characterization of Associated Materials in the Plate-Tube Intersections of Westinghouse Nuclear Steam Generators," Westinghouse STC 76-7D2-SGEXM-P1, September 27, 1976

2.7 Lancha, A. M., et al., "Characterization of Ringhals 3 TSP Crevice and Tube Deposits," Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 10-14, 1997

4.1 WCAP-12871, "J. M. Farley Units 1 and 2 SG Tube Plugging Criteria for ODSCC at Tube Support Plates," February 1991, Westinghouse Electric Corporation

6.1 Fuller, E. L., et al., "Assessment of Risks from Thermal Challenge to Steam Generator Tubes During Hypothetical Severe Accidents: Diablo Canyon as an Example Plant," Draft Report, September 1997, EPRI Project S550-18

6.2 Official Transcript of Proceedings, Nuclear Regulatory Commission Advisory Committee on Reactor Safeguards, Materials and Metallurgy Subcommittee, Presentation of Mr. Long, August 3, 1994

6.3 NRC Memorandum to Brian Sheron from Themis P. Speis, "Office of Research Concurrence on Generic Letter (GL) 95-XX Voltage Based Repair Criteria for Westinghouse Steam Generator Tubes Affected by Outside Diameter Stress Corrosion Cracking," Attachment 3, Section 3.2, May 3, 1995

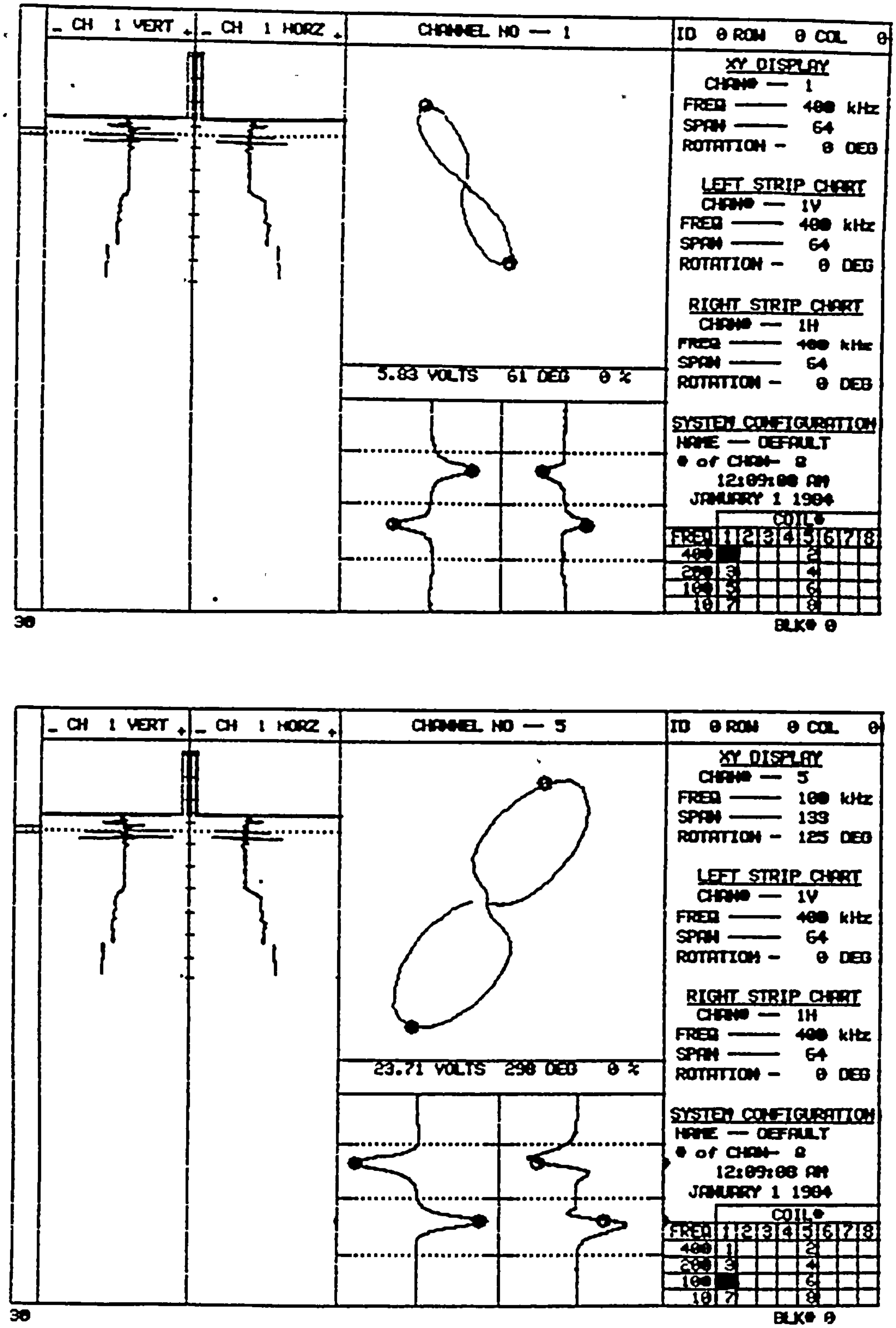
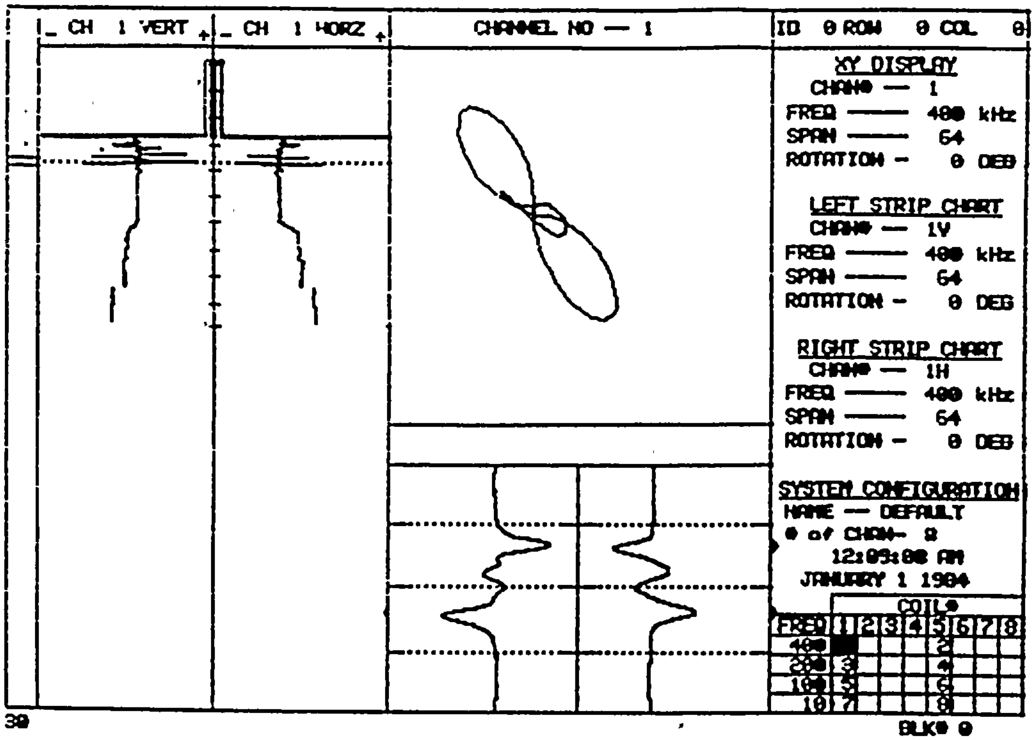


Figure 4-1. Bobbin Coil Lissajous Signal for TSP with No Degradation or Magnetite



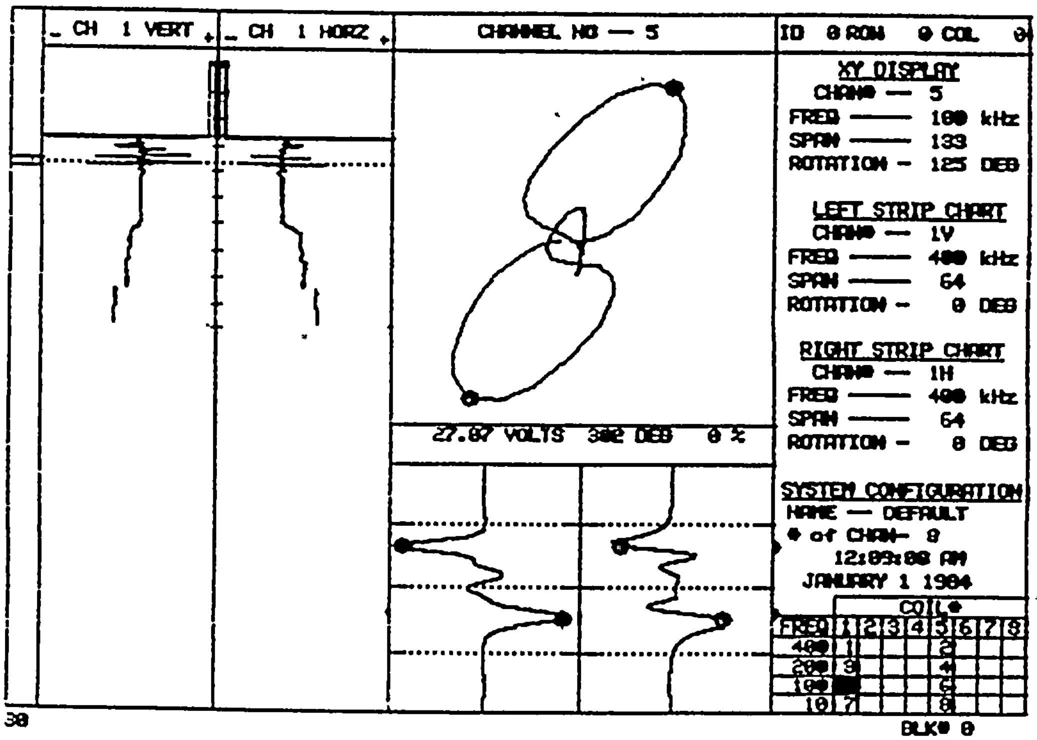


Figure 4-2. Bobbin Coil Lissajous Signal for a TSP with a 20 mil Deep, 0.25" Wide, 360 Degree Groove in Center of TSP

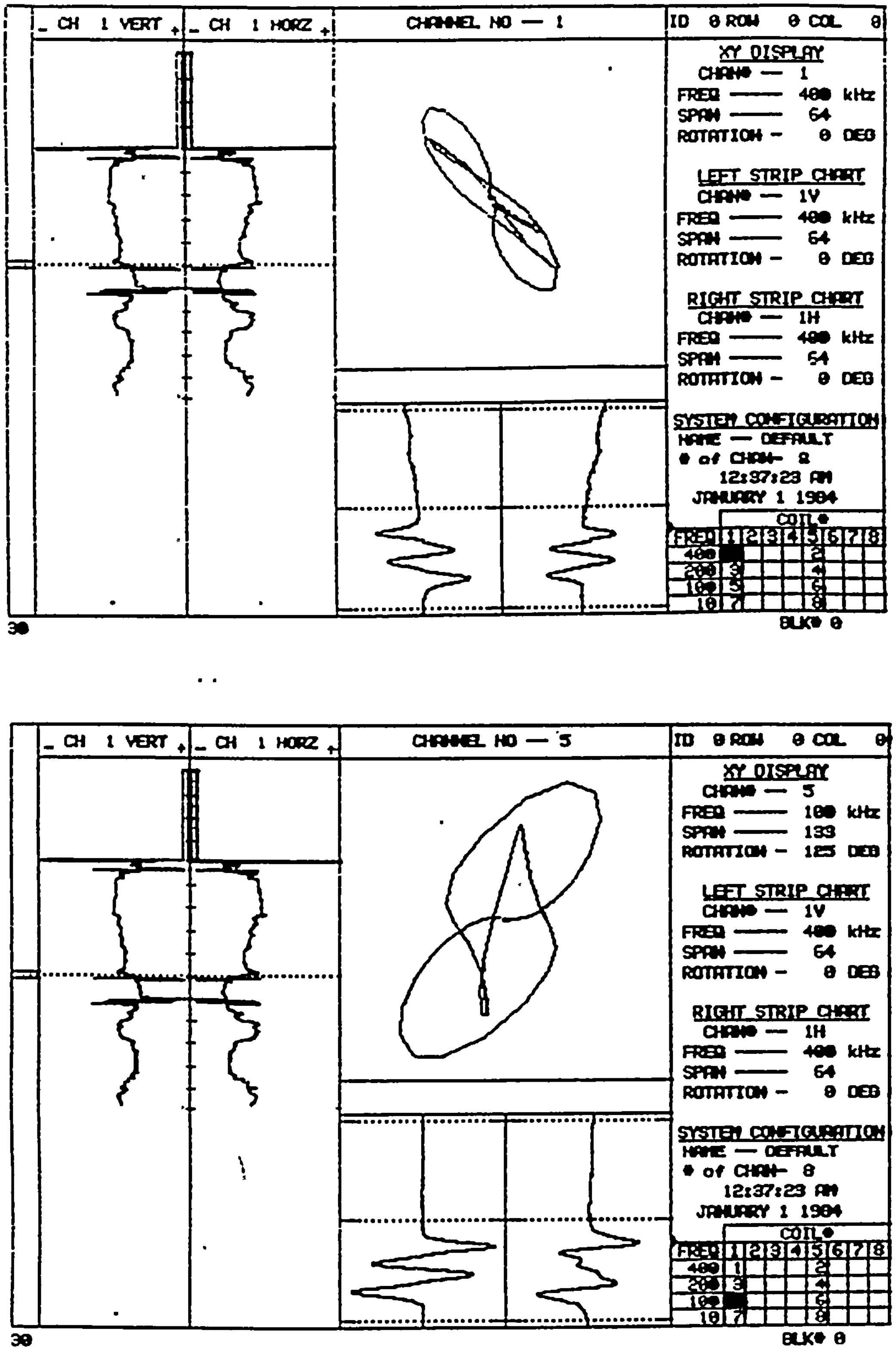


Figure 4-3. Bobbin Coil Lissajous Signal for TSP of Figure 4-2 with Magnetite Added to the Crevice Region

SUPPLEMENT TO THE RESPONSE TO NRC QUESTION 2

Drilled TSP Hole Crevice Conditions

The technical basis for concluding that the tube support plate (TSP) crevice condition for drilled hole steam generators (SGs) is represented by a crevice with deposits that provide significant resistance to axial displacement is grounded in field and laboratory data and the physical principles of crevice behavior in a heat transfer environment. This supplement to the response to NRC Question 2 develops the following topics:

- What does an operational crevice contain?
- Why are water chemistry variations between plants not expected to be a major variable?
- What is the influence of chemical cleaning?
- What differences in crevice morphology and resistance to axial displacement would be expected between shutdown, operational, and steam line break conditions?

What does an operational crevice contain?

Several opportunities to study the tube-to-TSP crevice have been provided by the removal of intact sections from either operational or retired SGs. One such opportunity arose from the retired SGs of the Dampierre 1 plant in France. These SGs were generally of the Westinghouse design and manufactured under license by Framatome. They were designated as Model 51M SGs. Although there were some non-Westinghouse design modifications to the SGs, the tube-to-TSP crevice geometry is essentially unchanged from the Westinghouse design and the results described below are considered representative of the class of similar SGs.

Figure 1 shows, on the right side of the figure, a photographic reproduction of the metallographic, axial cut, cross.section of a crevice from the Dampierre 1 retired SG as it was examined at the tube examination facilities of Westinghouse Electric Company. This intersection was not dented. The photograph shows just the edge of the outside diameter (OD) of the Alloy 600 MA tubing on the left, the adjacent crevice deposit, and on the far right, a portion of the carbon steel of the TSP. The eighteen spectra portrayed in six rows of three are from the energy dispersive X-ray (EDS) spectroscopic examination of the crevice deposits immediately adjacent to the tube (left column), in the central region (middle column), and adjacent to the TSP (right column). The approximate corresponding axial position of each row is designated by a reference arrow to the metallographic cross section. The data provided show that the elemental distribution within the crevice favors the concentration of silicon, phosphorous, zinc, aluminum, magnesium, iron, and oxygen containing deposits in the layer adjacent to the tube and across the width of the crevice at both the upper and lower openings. Other species such as copper and sulfur are also reported. The central region of the

crevice, both axially and radially, is predominantly filled with compounds formed from iron and oxygen. Supporting data in the form of electron probe microanalysis provide an area map of the elements and shows regions, for example, with common elements occupying the same area, supporting their presence there as compounds. In addition, X-ray diffraction analysis was performed to determine crystal structure, with the report of crevice compounds such as magnetite (Fe_3O_4), hematite (Fe_2O_3), silicon dioxide (SiO_2), manganese oxide (Mn_2O_3), willemite (Zn_2SiO_4), calcium phosphate hydrate ($Ca_3(PO_4)_2nH_2O$), xonotlite ($Ca_6Si_6O_{17}(OH)_2$), goethite ($FeO(OH)$), and others.

The combined data show that this crevice contains a mineral matrix composite including iron oxides adjacent to the tube, with a gradual radial transition to predominantly iron oxides adjacent to the TSP.

Another section of the same TSP location on the opposite side of the tube (300 degree versus 120 degree angular position) is shown in Figure 2. Although only a few areas are shown for this position, it can be seen that the results are the same. In addition, the photographs of the respective deposits reveal the interlaced composite formation adjacent to the tube and the transition to predominantly iron oxides adjacent to the TSP.

The porosity of the deposits adjacent to the tube and the TSP is low, i.e., in the range of 1 to 10 percent void. The central region of the 120 degree section has a higher porosity, ranging to 50 percent void (see Figure 1). The corresponding region of the 300 degree section has no corresponding void space (see Figure 2). This variation in porosity may represent the operational crevice condition or it may be an artifact of sample preparation. There is a possibility, for example, that the cutting and polishing operations resulted in some crevice material dropouts that contributed to this apparent porosity. This is partly supported by examination of the micrographs, which show regions were the deposit forms bridges across the crevice with adjacent and irregular void patterns suggestive of material that dropped out. Figure 3 shows this in an enlargement of a portion of the 120 degree section.

Another possibility is that steam chimneys formed in a portion of the crevice and contributed to the porosity. An example of such porosity was observed in a TSP section removed from Turkey Point 4, Steam Generator C, in 1976 while the plant was still operational, as shown in Figure 4. The particular TSP intersection shown was cut axially for one sample and then the remainder was polished in the direction of the face of the TSP to provide the metallographic sample illustrated in Figure 4. Denting magnetite has formed over the entire circumference of the crevice boundary, and the tube was uniformly dented, in the radial direction, by the forces exerted by this corrosion product. A region of exceptional morphology exists, just to the right of the 180 degree location, on the sample at the top of the figure. This area is enlarged in the cutaway and shows a porosity that is believed to exist as a result of a "steam chimney" in the crevice that allowed refreshment of secondary side contaminants to concentrate

in this region and resulted in a higher corrosion rate. This corrosion rate is reflected in the greater recession of the carbon steel surface of the TSP, as well as the additional deformation that forms an indentation on the already dented profile of the tube, as shown in Figure 5. Incidentally, this also shows that porosity is not synonymous with compressibility, at least not at the levels required to deform SG tubing.

Although the microanalytical techniques of the late 1970s were not quite as sophisticated as those available for tube examinations today, the EDAX (energy dispersive analysis by X-ray) technology of Figure 6 shows that the elemental distribution in the crevice placed mineral forming compounds adjacent to the tube wall, with iron oxide on the TSP side of the crevice.

A more recent characterization of a tube and TSP crevice intersection was performed on a drilled hole crevice of the Ringhals 3 plant. This Model D3 preheat SG has essentially the same tube-to-TSP crevice configuration as the Model 51 series (see Figure 7). That report provides a view of the crevice that is packed with deposits to greater than 90 to 99 percent density for most of the crevice regions, with a few locations, particularly on the 0 degree section, ranging to about 50 percent porosity. Radial distribution of species such as zinc, manganese, and silicon were preferentially high in the crevice region adjacent to the tube. These decreased in quantity as the TSP surface was approached and as the concentration of iron oxide compounds increased. Magnetite, a chromium substituted oxide, and zinc silicate were reported based on the X-ray diffraction examination of crevice deposits. The tube-to-TSP breakaway force was measured in the laboratory and determined to be essentially the same as that measured for Dampierre 1.

Both of these evaluations support the common theme of crevice deposit composition as being a mineral rich composite formation in the vicinity of the tube with a higher composition of iron oxides adjacent to the TSP. This occurs because the heat transfer conditions at the tube surface provide an available superheat over the saturation temperature of the bulk water. If a clean crevice were assumed to be the starting condition, the flow of water into the crevice would carry with it a proportion of the suspended solids circulating in the SG and also some soluble material in the form of additives and contaminants. Since the crevice conditions are confined and the surface of the TSP provides an additional surface for deposition of particulate material, the deposits soon build up in a manner similar to that on the free tube surface. The deposits are porous at the beginning and provide a matrix for water to work its way to the tube and for steam, with its greater volume per unit mass, to move from the crevice through steam chimneys. Since most common SG solutes, such as sodium, chloride, sulfates, silicates, and phosphates have a lower solubility in the steam phase than in the liquid phase, the concentration of solutes increases in small liquid pockets that form in the matrix of porous deposits. These liquid pockets exist because of boiling point elevation that occurs due to the vapor pressure lowering from the increasing concentration of solute. For most SG solutes, the solution will become saturated in

mineral content and the solution will begin to precipitate whatever phases can no longer be held in solution. (Sodium hydroxide, if present among these components, will remain in solution and contribute to corrosion.) The continued ingress of many of the SG solutes, however, would tend to mitigate against the continued long-term stability of substantial quantities of sodium hydroxide by providing a buffer for the crevice. As these deposits form, the species that are more volatile, e.g., organic acids and mineral acids such as HCl, are carried out of the crevice with the steam. The steam channels would provide a mechanism to carry low concentrations of mild carbon steel corrodants to the surface of the carbon steel TSP in the crevice. This would further contribute to a low level of carbon steel corrosion and the production of iron oxides. (In cases where the concentration of HCl is excessive, the carbon steel may corrode at an accelerated rate and produce denting.) The mass transport, concentration, and precipitation cycle continues as the crevice loses porosity and the ability to freely communicate with the bulk water is reduced. In the case of the Dampierre 1 crevice, it would seem that the crevice essentially becomes sealed with an encrustation of precipitated mineral deposits that form across the openings of the crevice.

Since these principles of mass transport and heat transfer are common to all similar drilled hole crevices operating on the hot leg of the SG, all such crevices would be expected to behave in a similar fashion.

Why are water chemistry variations between plants not expected to be a major variable?

Although the rate of crevice packing and the exact nature of the mineral deposit will, of course, vary somewhat with plant-specific water chemistry, the ultimate crevice conditions will end up being similar. One common feature will be iron oxides coming from both the feedwater system and internal SG sources. Silica is a ubiquitous component of secondary-side water and is found in all plants. Silicon compounds will accordingly be commonly found in crevices. Manganese most likely has origin in the corrosion of the steel and is also generally observed. These species alone are sufficient to form a strong crevice matrix adjacent to the tube.

The iron of the carbon steel TSP also oxidizes, and in situ iron oxide growths from the carbon steel TSP will necessarily be formed and contribute to crevice packing.

Plants with ODSCC corrosion occurring in the TSP crevice region have, by definition, produced concentrated aggressive contaminants capable of initiating that corrosion. These aggressive species cannot simply separate themselves from other dissolved and suspended species and concentrate in the absence of other components. The mineral species described earlier are also undergoing concentration in the same time frame in a manner consistent with their concentration and the thermal and hydraulic characteristics of the crevice. The continued precipitation of mineral species adjacent to the tube surface and the reduction in porosity, with its associated reduction in mass

transfer rates, eventually results in chemical buffering and a "fully packed" crevice with little ability to allow mass flow in or out.

Observations to extend this plant documented crevice packing condition to other crevice locations are amply provided in the many tube examinations that have been performed over the past years. If the crevices universally contain a relatively adherent mineral precipitate adjacent to the tube, then the residual of these deposits should be observed at the TSP regions, even after all of the rigors of a tube pull. Typically most tubes are removed by being pulled through the 21 inches of a relatively close-fitting tubesheet hole, as well as other TSP crevice locations. This process would be expected to dislodge all but the most adherent of deposits. The TSP crevice region, however, is generally easily recognized visually because of its unique banded appearance and/or the presence of residual deposits. These deposits have been analyzed on many occasions and are completely consistent with the crevice formation deposit model described herein. One recent tube pull examination for Diablo Canyon Unit 1, Steam Generator 2, showed tube adherent TSP 1 and 2 deposits containing calcium, magnesium, silicon, aluminum, manganese, and zinc. Specific crevice compounds identified by X-ray diffraction were magnetite, copper, aluminum silicate hydroxide, and possibly magnesium and iron silicate hydroxide phases.

Furthermore, deposits located at the uppermost or lowest TSP crevice of the hot leg have generally similar characteristics with respect to the mineral deposits and chemical composition. The Turkey Point 4 TSP crevice examination and the Dampierre 1 crevice examination occurred with upper level TSP crevices. Most of the completely consistent tube pull deposit information of interest occur from lower TSP locations, since these are typically subject to more ODSCC due to the higher temperature and higher available superheat at the lower TSP crevice regions.

The major difference that would be expected to occur as a result of water chemistry on the formation of packed TSP crevices is the rate of deposit buildup that would allow the initial concentration processes to occur. This would be a strong function of the corrosion transport processes in the overall plant. If a plant operated with extremely low dissolved and particulate transport iron, the rate of tube deposit formation would be extremely slow. Correspondingly, the rate of crevice packing would also be slow. Conversely, such a plant would not be expected to be experiencing any significant amount of tubing corrosion at the TSP, since a concentration mechanism is not operative. In this sense the actual operational time of a SG is not the sole determining factor in the crevice packing condition. Some SGs have dented in the first cycle of operation and others (a very small population) have operated for many cycles with low deposit inventories and no signs of the concentration processes, e.g., hideout return, that are suggestive of packed crevices.

What is the influence of chemical cleaning?

Westinghouse Electric Company, among other organizations, has carried out extensive development work on chemical cleaning of prototypical crevices for decades. Many different solvent variations have been tried along with unique methods of application, such as pressure pulse chemical cleaning and depressurization boiling with chemical cleaning solvents present. All of this has established that laboratory dented crevices and crevices obtained from operating SGs are both very difficult to clean. Figure 8 shows the post-chemical cleaning examination of a crevice from the Dampierre 1 plant following laboratory chemical cleaning using pressure pulse application. Although the crevice appeared to be clean based on observation of the edges after the cleaning operation, the metallographic examination revealed that the plant-formed deposits were barely touched. This is probably due to the fact that the EDTA chemical formulations that are the compositional basis of the EPRI cleaning process do not dissolve silicates and similar mineral species.

This difficulty in removing crevice deposits by chemical cleaning was confirmed at the Doel plant where tube pulls following chemical cleaning verified that the TSP crevices were not clean.

Some researchers, however, have reported recently that similar Dampierre 1 crevices have been cleaned under laboratory "steam generator conditions" that were not specified in detail. Similarly, and in contrast to the extensive Westinghouse experimentation, other researchers have also reported the cleaning of laboratory-produced dented crevices, again under conditions that were not specified in detail.

Considering these reports and the fact that chemical cleaning is intended to remove SG deposits, which it does with good efficiency from the free tube surfaces, it should be considered possible, albeit unlikely, that substantial crevice deposits would be removed during a chemical cleaning. (Note that this is very unlikely for dented TSP locations.) With this in mind, crevices should be evaluated following chemical cleaning by a review of the visual and eddy current crevice magnetite condition. In the event that a substantial number of crevices are reported to be relatively free of deposits, these evaluation techniques could be used in subsequent years to determine when crevices have become packed again.

What differences in crevice morphology and holding capability would be expected between shutdown, operational, and steam line break conditions?

General Discussion - Of necessity, tube pulls and other operations on tubes, such as leak testing, occur under conditions of plant shutdown. It is thus pertinent to consider what physical changes could occur to an operationally packed crevice under plant shutdown conditions. It has been established that packed crevices contain mineral species, such as silicates, phosphates, aluminates, and iron oxides. These materials form an adherent composite material that fills the crevice to high density. In fact, it is a tribute to the mechanical integrity of these crevice fillers that they can withstand the rigors of the cutting and polishing operations that allow them to be metallographically examined. They are mineral species, however, and as such they do not have high tensile strength properties. In contrast, minerals are quite capable of sustaining large forces when they are in compression, as demonstrated by the load carrying capabilities of stone structures, for example.

The mineral packing of the crevice occurs during plant operation with the tube hot and pressurized and the deposits forming to a low porosity. As a result of this origin, the condition of the crevice under various conditions of plant operation are proposed as follows:

Shutdown Conditions - When the temperatures are reduced, and the primary side pressure differential is removed, the tube contracts slightly. This serves to increase the crevice gap. The mineral deposits of the crevice filling are not elastic, however, and they cannot expand to accommodate this additional space. Separation must therefore occur and a gap is created within the crevice. The characteristics of this fracture process are key to the shutdown condition axial displacements that the tube can experience. Consider three general conditions that the crevice packing can experience to accommodate this larger crevice. These three general conditions are:

- the crevice packing has no room temperature bonding strength to the tube and the tube breaks free of the deposits cleanly and uniformly; or

- the crevice packing has no bonding strength to the TSP and breaks away cleanly and uniformly at the TSP surface, or

- the crevice packing randomly fractures in three dimensions, along the surfaces least able to sustain the tensile forces of tube contraction.

The situations described in case 1 and 2 clearly do not happen. The mineral deposits that have precipitated on the tube have been established as being well bonded to the surface of the tube based on the observations from numerous tube pulls. Similarly, the in situ-grown iron oxides extend back to the TSP and, in one way or another, are molecularly bonded to the carbon steel of the TSP.

Logically, the mineral composite known as crevice packing deposits would be expected to fracture in the same manner as their larger scale counterparts experiencing expansion and contraction in nature, i.e., along the complex three-dimensional surfaces least able to sustain the tensile forces. Fortunately there are some examples of these fracture paths that can be observed in the crevice examinations. Three of the four micrographs in Figure 9 (a slight modification of Figure 2) show fracture paths or probable fracture paths. A more complex example is shown in Figure 10, where the fracture paths, through the magnetite formed during the denting process, are decorated with nickel and silicon species. The result of these fracture patterns is that some slight motion would be accommodated upon the application of an axial force. It would be expected that the fracture surfaces would move slightly with respect to one another and the nonplanar interfaces would begin to act on one another like a series of intertwined wedges. As more and more force is applied, particularly applied dynamically as in a tube pull, the compressive loads developed by the randomly inclined fracture surfaces increase in magnitude. The deposits resist substantial displacement until finally the leading surfaces begin to crumble, starting the chain reaction deposit failure that allows the tube to break free of the crevice. On the other hand, sustained static loads, such as those that may develop as a result of tube deformation in a repair process, are most likely relieved over the long term. This is accommodated with the lubricating effect of water and the ability of the particulate materials along the fracture faces to be displaced and move slightly with respect to one another, while the plant is in the shutdown condition.

Returning to Power Operation - As the crevice, with its fractured surfaces, now perhaps slightly displaced with respect to one another or with a foreign particle lodged in place, is repressurized and returned to service, it closes the gaps that were produced during shutdown. This accommodation may not be completely straightforward if the surfaces have interference particles present. These particles may be incorporated into the composite if there is space available, thereby reducing the apparent porosity. In contrast, the particles may be crushed and distributed along a fracture surface, leaving gaps that form a flow path for the migration of steam or water that contributes to the mass transport properties of the crevice. Or, in the case of a dented plant, the inability of the crevice to return to its original configuration may result in some additional tube deformation.

In any event, it is difficult to imagine that the crevice packing would be in any configuration other than the original tight but not compressed packing configuration or a slightly compressively loaded variation of the original configuration.

Steam Line Break Conditions - As previously discussed, the general crevice condition during normal operation is concluded to be tight. The crevice deposits have demonstrated good cohesiveness, not only as a crevice packing, but also as bonding agents to the tube and TSP. They are well protected from mechanical disturbance in the long and narrow confines of an operating crevice and cannot be readily dislodged.

With this general set of conditions, which is well supported by numerous tube pulls and examinations, the only plausible scenario is that the increasing primary-to-secondary side pressure differential will further compress the crevice packing. This increased compression would further lock the TSP in position and should result in tighter bonding than would be displayed for the shutdown condition of the tube pull.

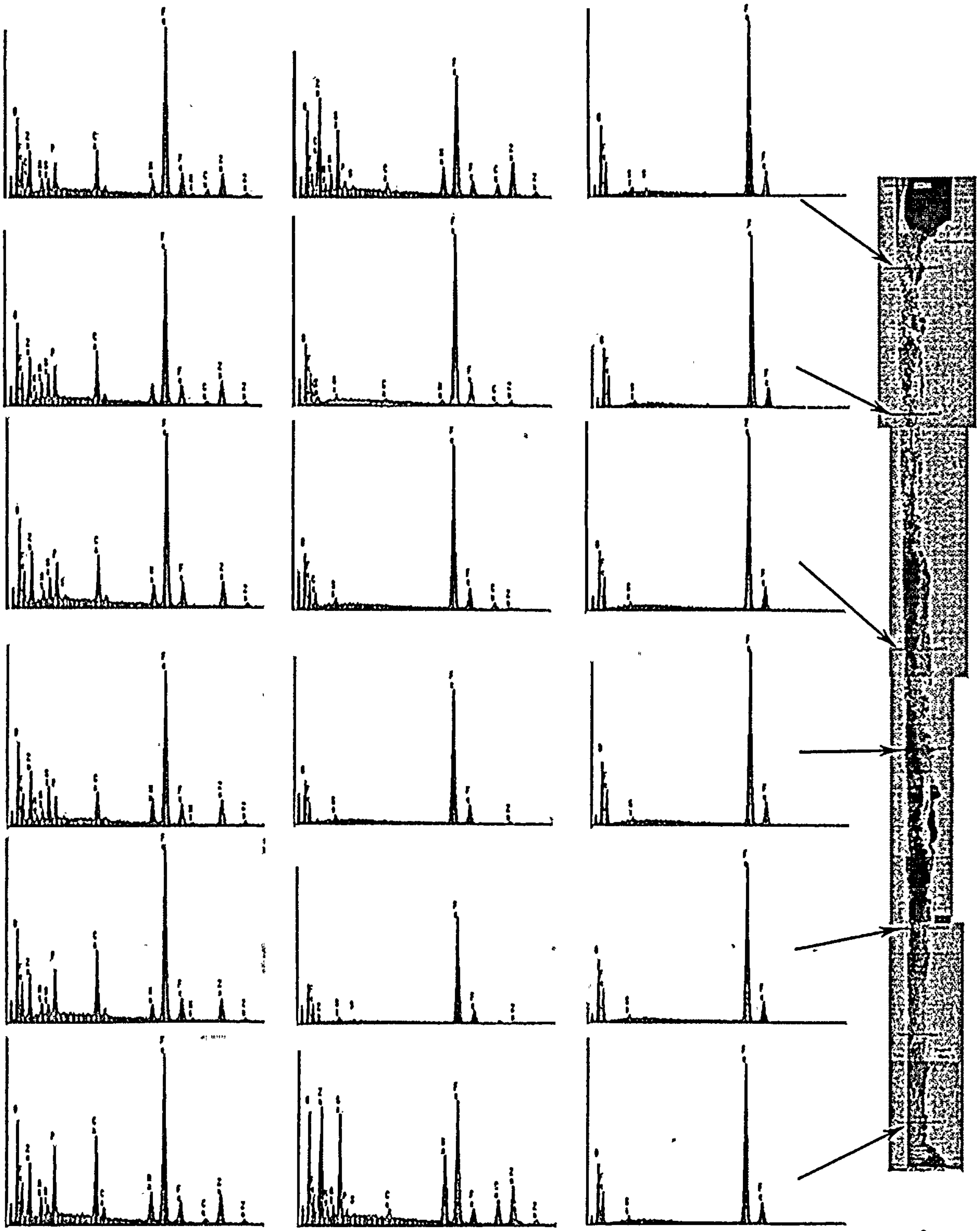


Figure 1. Elemental Composition Profile of 120 Degree Sector Dampierre Tube Support Plate Crevice

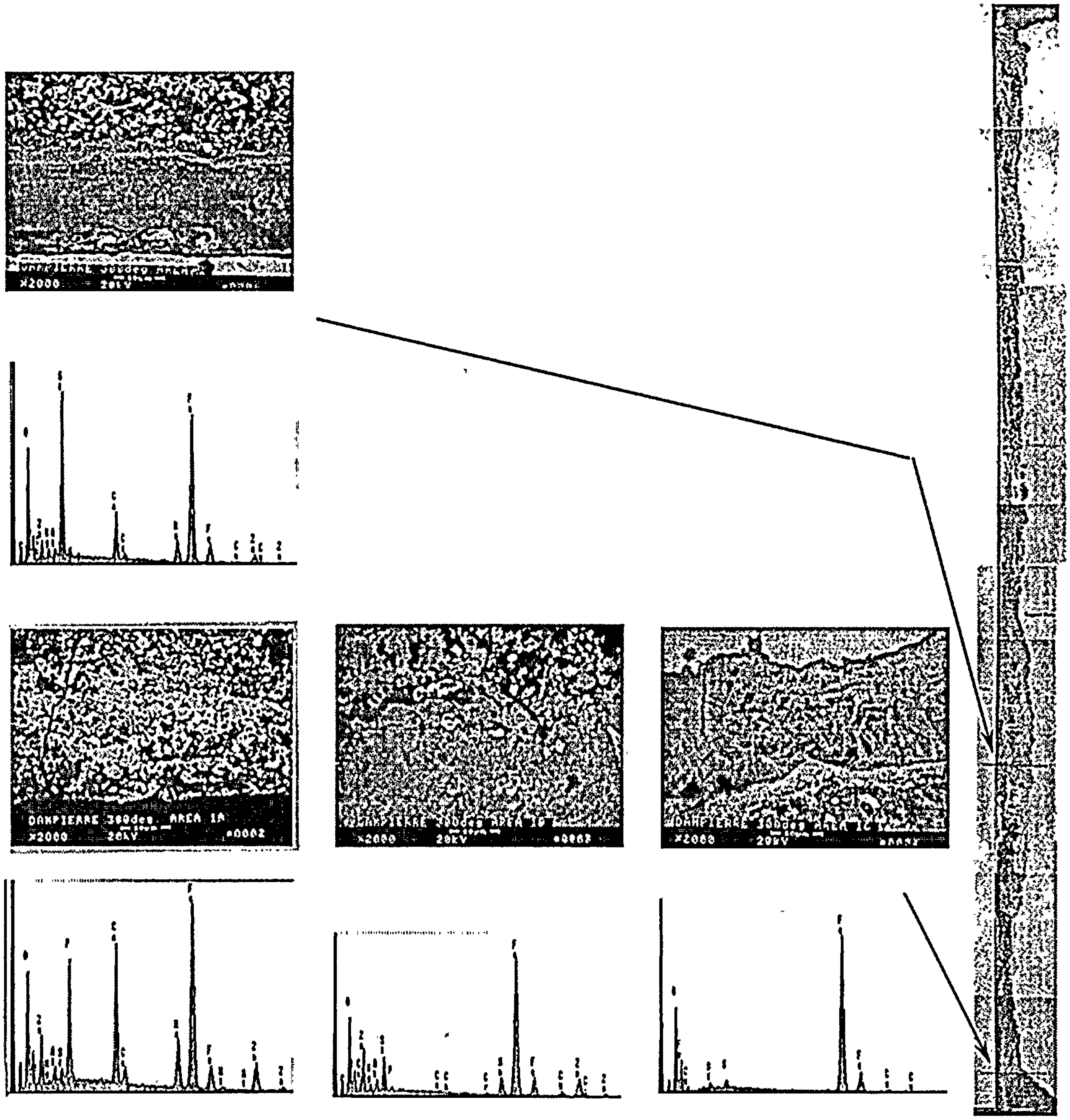
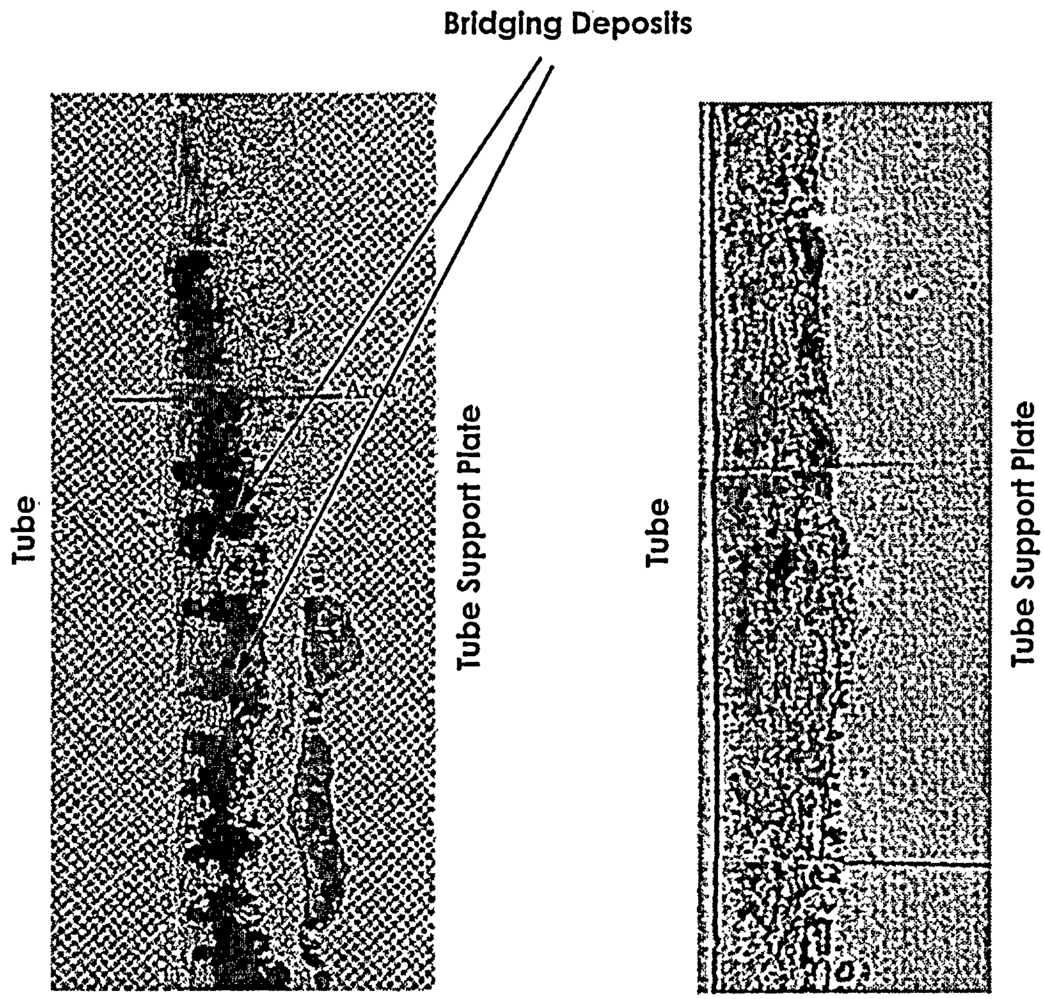


Figure 2. Elemental Composition Profile of 300 Degree Sector Dampierre Tube Support Plate Crevice



(A) 120 Degree Section **(B) 300 Degree Section**

Figure 3. Section of Dampierre 1 TSP Crevice at 120 Degrees Showing Deposit Formations Bridging the Central Crevice Region in Some Areas (A). The 300 Degree Section Reveals More Uniform Deposits (B).

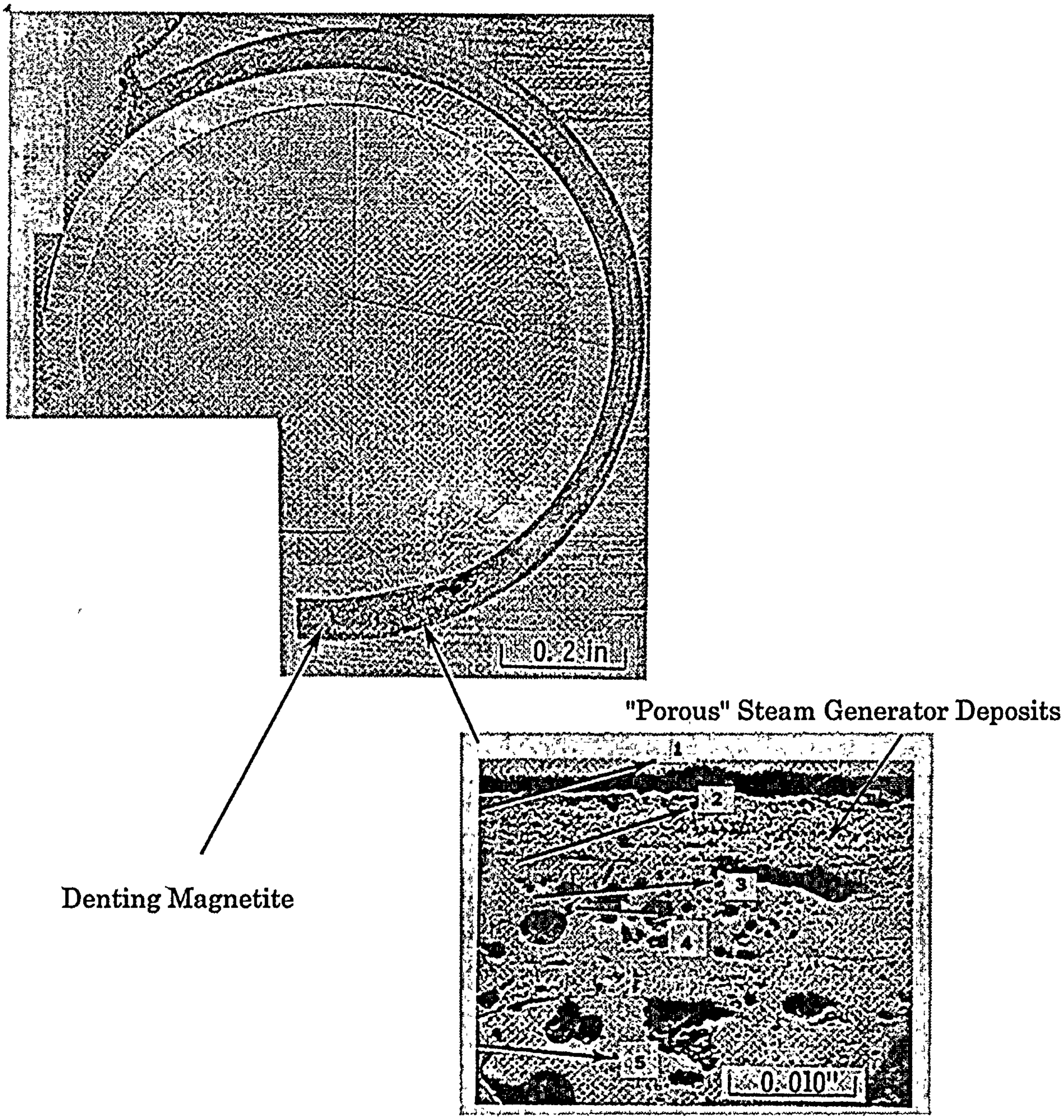


Figure 4. Crevice From Dented Steam Generator Establishes That "Porous" Steam Generator Deposits Sustain Denting Forces

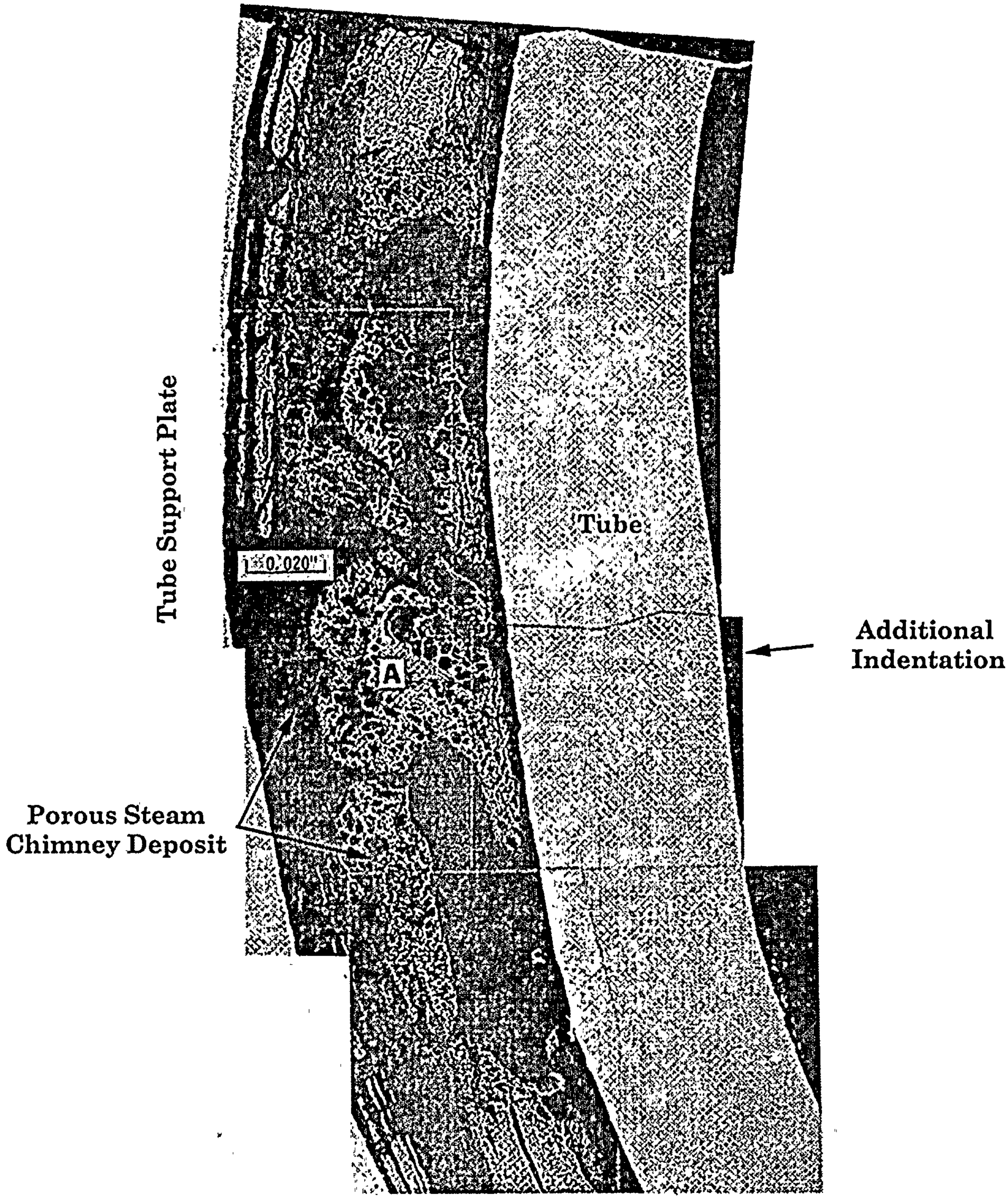


Figure 5. Turkey Point 4 Dented TSP Section Shows Additional Deformation of Tubing in Porous "Steam Chimney" Region.

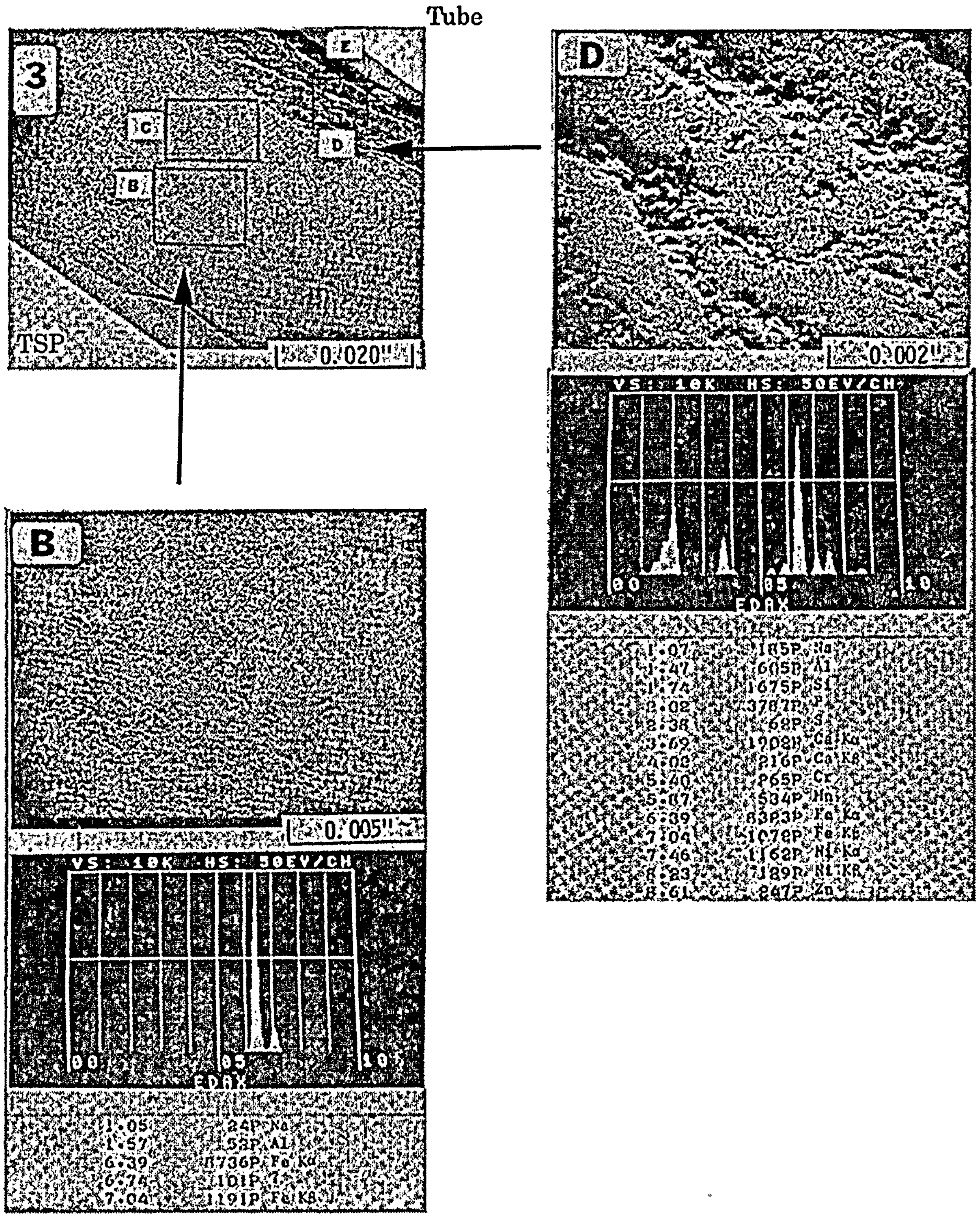


Figure 6. Micrographs and Energy Dispersive X-ray Analysis Shows Mineral Forming Elements in the Crevice Region Near the Tube and Iron Oxide Composition in the Denting Region Closer to the TSP.
(Turkey Point 4 Dented Tube Support Plate Examination)

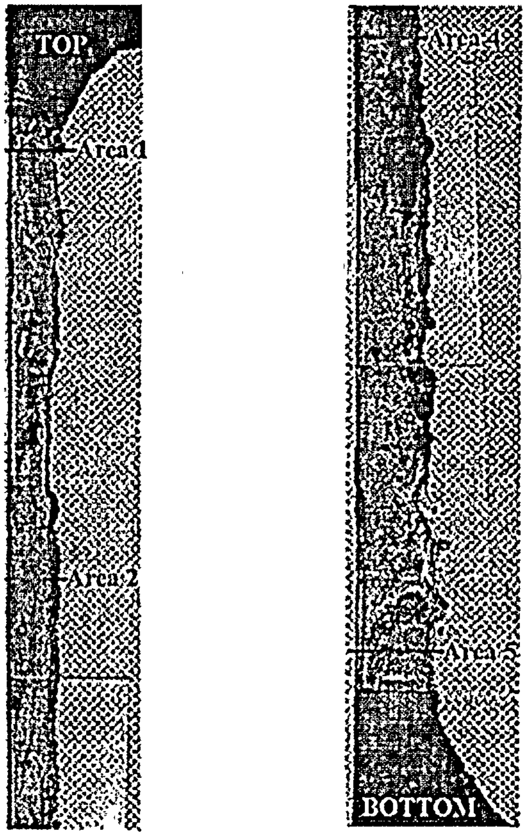


Figure 7. Metallographic Cross Section of Ringhals 3 TSP Sample Displays the Same General Features as the Dampierre 1 Crevice Examination.

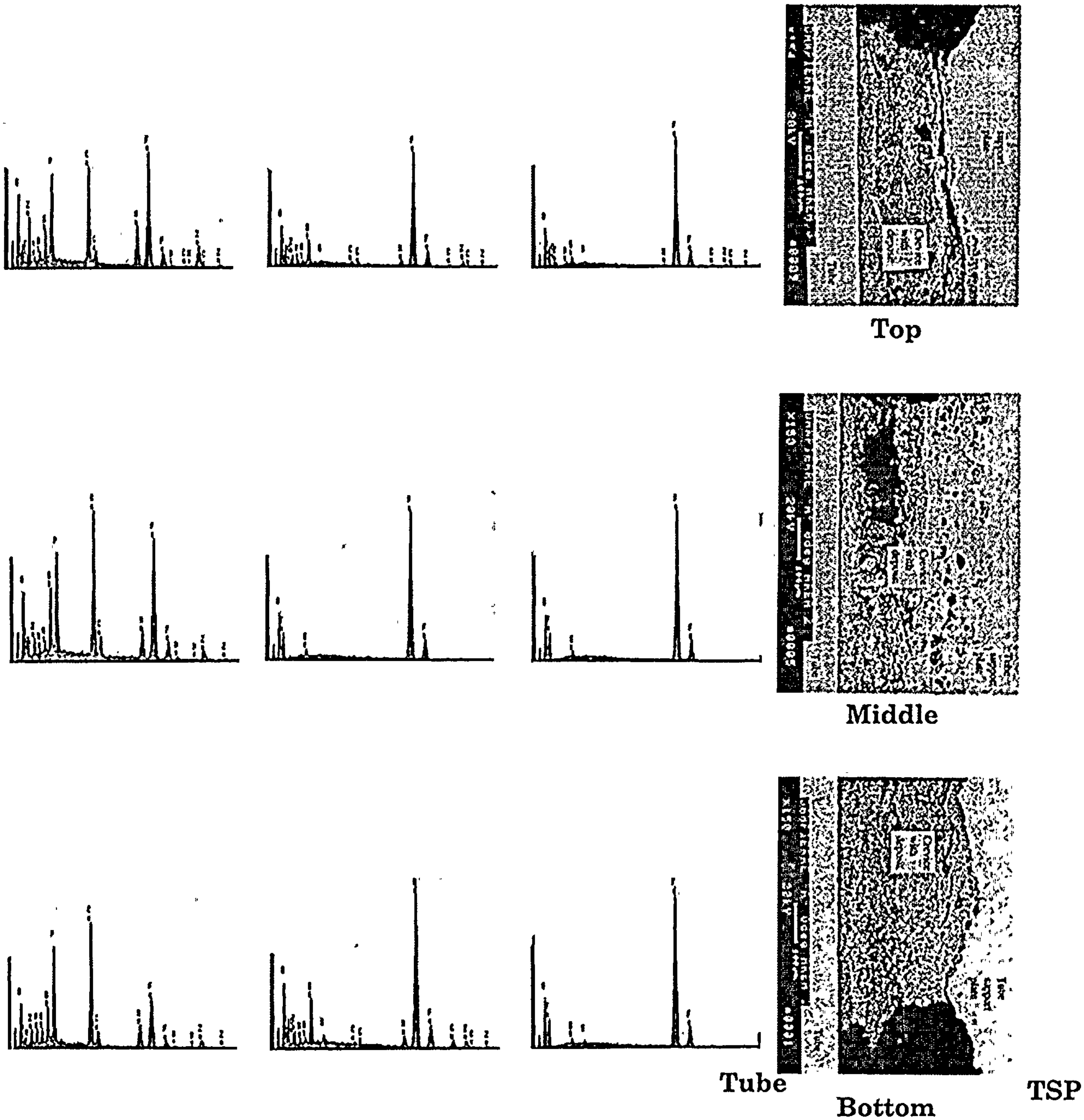


Figure 8. Cross Section Crevice Examination of
Dampierre 1 Tube Support Plate Specimen
Following Chemical Cleaning Test

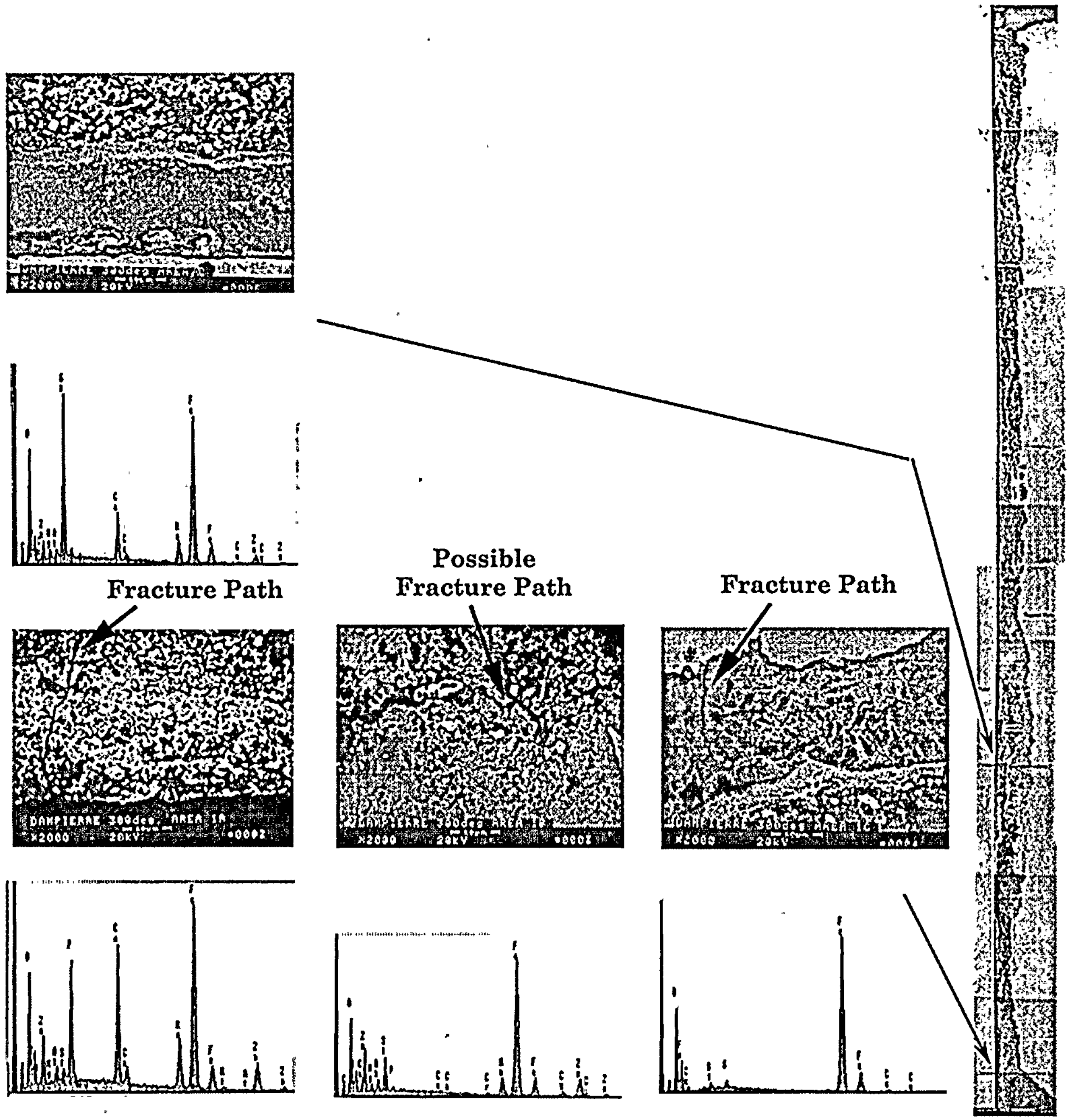


Figure 9. The 300 Degree Sector Dampierre 1 TSP Crevice Shows Indications of the Expected Fracture Lines in the Crevice Deposit.

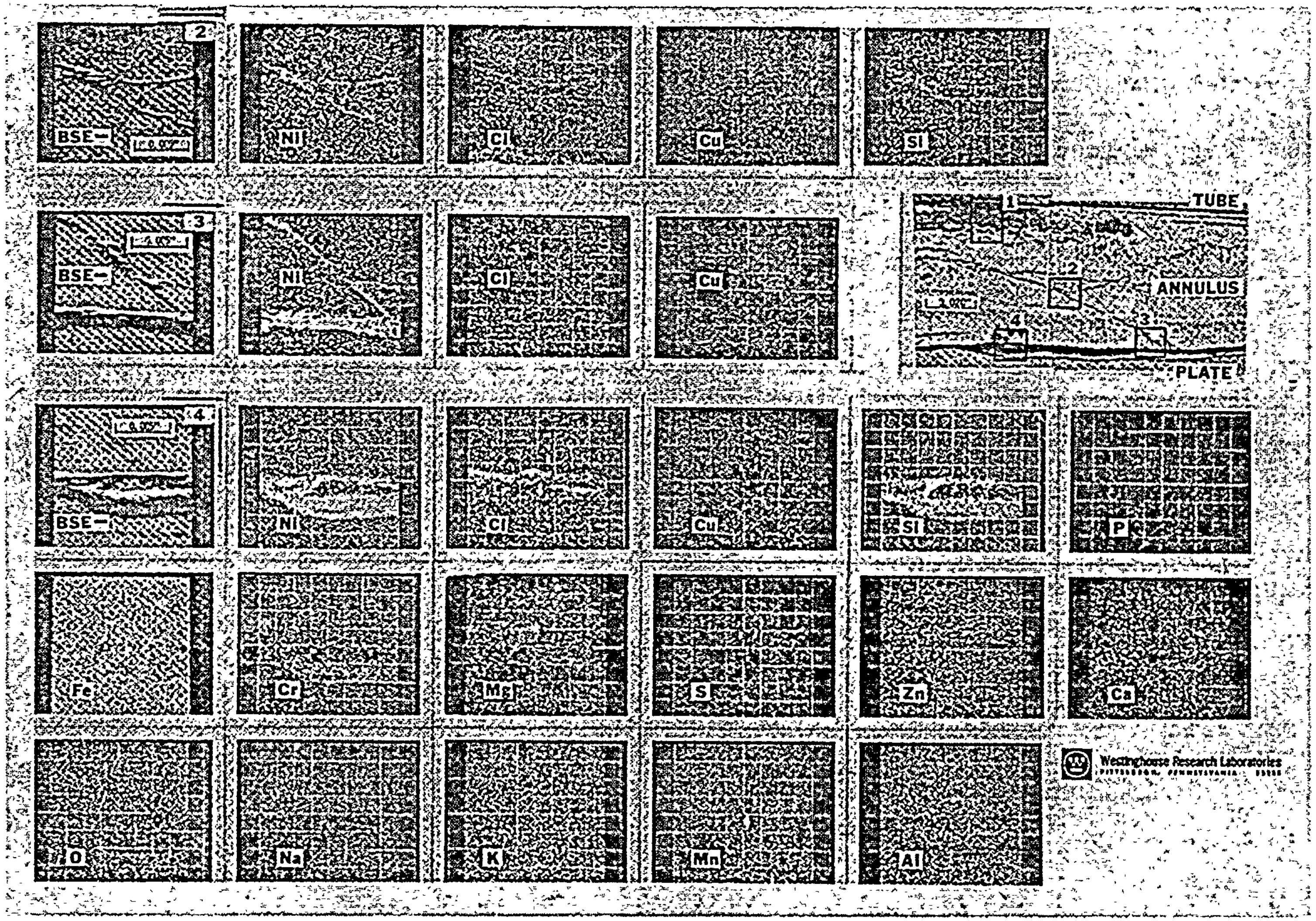


Figure 10. Fracture Paths in the Turkey Point 4 Dented Crevice Sample Are Decorated with Contaminant Species Such as Ni, Si, Cr, Cl and Cu.

References 2, 3, and 4 of WCAP-14707, "Model 51 Steam Generator Limited Tube Support Plate Displacement Analysis for Dented or Packed Tube-to-Tube Support Plate Crevices"

Reference 2

Electricité de France Report D.5716/CTT/RB 94.6129, "Pressurized Water Plants, Steam Generator, Some Applications of Leak Flow Rate and Burst Tests Performed on Pulled Tubes in Evaluation of the Operating Safety and Reliability of the Tube Bundle," dated July 8, 1994

Reference 3

Electricité de France Report D.5716/CTT/RS 94.6124, "Pressurized Water Plants, Steam Generator, Results of Leak and Burst Tests Performed on Pulled Tubes," dated August 10, 1994

Reference 4

Westinghouse Electric Corporation Application for Withholding Proprietary Information from Public Disclosure (Henry A. Sepp to Document Control Desk), CAW-98-1211, dated February 23, 1998.

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Affidavit CAW-98-1211 of Henry A. Sepp, Manager, Regulatory and Licensing Engineering, Nuclear Services Division, Westinghouse Electric Corporation, dated February 23, 1998.

Westinghouse Science and Technology Report 94-7TE2-DAPER-R1, "Characterization of Crevice Deposits in the Dampierre Unit 1 Steam Generator Tube Support Plate Assembly," dated November 30, 1994 (PROPRIETARY)