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WCAP-12791 SG-90-12-024

Kewaunee Steam Generator

Mid-Cycle Report

December, 1990

Prepared for Wisconsin Public Service

WESTINGHOUSE ELECTRIC CORPORATION
NUCLEAR SERVICE DIVISION
P. O. BOX 355
PITTSBURGH, PA 15230

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1. INTRODUCTION

This report provides an update of the April 1990 Return to Power Report (Reference 1) for the Kewaunee Nuclear Power Plant based on evaluation of pulled tube examination results. Two tubes (R4C81, R11C9) from steam generator B were pulled in March 1990 to assess eddy current indications on the tubes in the tubesheet crevice region and in the sludge region within the first few inches above the top of the tubesheet. Both tubes had been identified as tubes to be plugged and removed from service. Leak rate tests were performed on simulated dents at the top of the tubesheet to determine the expected leakage from a crevice restricted by a dent at the top of the tubesheet. The results from the tube examinations and leak rate tests are used in this report to perform an evaluation of tube integrity and associated radiological consequences to show that continued operation provides adequate safety margins. An evaluation using the guidance of NSAC-125 demonstrates that an unreviewed safety question does not exist.

1.1 Background

During the 1990 Kewaunee refueling outage, the bobbin coil eddy current inspection was supplemented by increased application of rotating pancake coil (RPC) inspections including the tubesheet crevice region and a few inches above the top of the tubesheet on the hot leg side. There are two areas of interest that are evaluated in this report. One is the axial indications in the tubesheet crevice region and the other is the distorted indications just above the top of the tubesheet.

The bobbin coil inspection revealed a number of tubes which exhibited signals from the 400/100 kHz differential mix channel. Subsequent rotating pancake coil (RPC) eddy current inspection of the tubesheet crevices of the tubes exhibiting such signals revealed the presence of single or multiple, axially oriented indications. These indications, although not accurately sizeable by RPC, were classified as axial cracks. In general, the bobbin coil differential mix response from these indications was of large enough volume that the data analysts had no difficulty in detecting and reporting them.

One tube, however, exhibited a bobbin coil differential signal from within the crevice region barely above the noise level. This tube also exhibited axial indications from the RPC inspection in the tubesheet crevice region. To provide an assessment of the potential number of such indications the RPC program was expanded in the crevice region. More than 300 tubes were inspected by RPC in the tubesheet crevice region. Approximately 20% of these more than 300 additional tubes inspected by RPC revealed the presence of axially oriented indications which could not be identified in the bobbin coil differential mix when that data was evaluated. These indications were generally located five inches or more below the top of the tubesheet. Fourteen tubes contained indications which were judged to be less severe by WPS and were left in service to track the growth or change in indication at the next inspection. Additionally, it was projected by WPS that similar indications exist in unsleeved tubes which were not inspected by RPC.

Tube R11C9 was pulled to further evaluate the RPC indications found in the tubesheet crevice. In Reference 1, an analysis was performed to show that potential leakage from the tubesheet crevice indications left in service was less than the maximum acceptable leakage during a postulated steam line break. This analysis was based, in part, upon the fact that through wall tube cracks within the tubesheet crevice cannot burst and that crevice flow restrictions due to deposited material in the tubesheet crevice limits the leakage rate from assumed through wall cracks.

The bobbin coil inspection also revealed indications just above the top of the tubesheet. Some of these indications were distorted due to top of tubesheet dents and tube deposits such that degradation depths could not be assigned. The indications were further evaluated by RPC inspection. The distorted tubesheet indications were classified as potential cracks, pitting or thinning based on geometric representation of C-scan. Prior Kewaunee inspection experience has shown low growth rates for top of the tubesheet indications, these indications were judged to be pitting or thinning indications. Consequently, 24 tubes with volumetric types of indications, for which depths could not be assigned, were left in service for further monitoring at the next inspection. Tube R4C81, which exhibited both axial and volumetric (pit-like) indications at the top of the tubesheet and had been identified to be plugged, was pulled to further characterize this degradation.

In Reference 1, it was stated that the pulled tube examination results would be reviewed in comparison with the safety analyses of the reference report. This report provides the committed assessment.

1.2 Evaluation Approach and Results

The pulled tube examination results are described in Section 2 of this report. Difficulty was encountered in pulling both of these tubes such that considerable tube elongation occurred. As a consequence, the presence of tubesheet crevice deposits could not be confirmed by either deposits on the tube or by optical examination of the tubesheet hole following the tube pull. As noted above, the Reference 1 safety evaluation was based in part on restricted leakage resulting from crevice deposits. The presence of the crevice deposits could not be firmly established by the tube pulls or by eddy current evaluation. To further supplement the Reference 1 safety assessment for restricted flow from the tubesheet crevice, the flow restriction due to top of tubesheet denting, as confirmed by eddy current review (Section 3), is evaluated in this report.

Tests were performed to measure leak rates from through wall tube holes with simulated tubesheet crevices and top of tubesheet denting as described in Section 5. Analytical models were confirmed against these test results and used to calculate leak rates from through wall cracks (Section 6) to update the safety assessment of Reference 1. In the lab evaluation Tube R11C9 was found to have a relatively long, axial crack network below the top of the tubesheet with a maximum depth up to 74%. This result is generally consistent with the field RPC axial crack indication. The lab evaluation of Tube R4C81 also found a long axial crack network within the tubesheet crevice with a maximum depth of about 40%. This indication was not identified by field RPC.

The lab evaluation of tube R4C81 identified multiple axial cracks between the top of the tubesheet and an elevation of about 0.8 inch above the tubesheet. The maximum depth of these axial crack networks was found by destructive examination to be 76% within a group of short axial cracks and up to 68% within the principal crack network extending up to 0.6 inch above the tubesheet. No volumetric pit or thinning indications were found in the tube examination. The lab review of field bobbin coil data found an indication depth of about 80% with the RPC indicating both axial crack and volumetric classes of indications. It is therefore possible that the RPC indications classified as volumetric indications may be associated with closely spaced, axial crack networks. The 24 tubes with indications classified by the field RPC at the top of the tubesheet as volumetric were therefore revaluated in this report assuming they are axial crack networks. The eddy current data were reviewed as described in Section 3 and evaluated for tube integrity considerations as described in Section 4.

Section 7 of this report summarizes the radiological evaluations of the maximum acceptable primary to secondary leak rate during a postulated steam line break. Section 8 of this report summarizes the inspection plans for the 1991 outage. Section 9 integrates the evaluations of this report and the Reference 1 return to power report to provide a safety evaluation supporting continued operation of the Kewaunee Nuclear Plant to the planned 1991 outage.

2. PULLED TUBE EXAMINATION

2.1 Discussion of Examination Results

The hot leg tube segments, Tube R4C81 and Tube R11C9, were pulled from Steam Generator B of the Kewaunee Plant for destructive examination. Figures 2-1 and 2-2 show sketches of the crack network found on the two tubes. Tube R4C81 was found to have multiple axial stress corrosion cracking (SCC) at and above the tubesheet top location as well as less extensive (fewer and more shallow) circumferential SCC. The SCC had a strong propensity towards developing a three dimensional intergranular attack (IGA). In general, the corrosion at the top of the tubesheet occurred uniformly around the circumference with most of the corrosion confined from the tubesheet top to 1.0 inches above the top. Cracking greater than 40% through wall was confined to within 0.6 inches of the tubesheet top. All of these macrocracks, with one exception discussed in the next paragraph, were short (less than 1.0 inch long). The axial macrocracks were composed of numerous shorter (less than 0.1 inches long) axial microcracks which grew together by intergranular corrosion. The maximum depth of the axial cracking in this location was 76% through wall. The largest region with circumferential involvement was 0.24 inches long and up to 75% deep. It was actually a series of close axial cracks which grew together with their "IGA skirts" to form the circumferential opening. The circumferential opening had an IGA morphology. The deepest circumferential crack found by metallography was only 20% through wall. Less extensive and much more shallow axial SCC was observed up to 2.0 inches above the tubesheet top. It was estimated that the cracking was significantly less than 10% deep in the region from 1.0 to 2.0 inches above the tubesheet top.

A long axial intergranular SCC was also found in the tubesheet crevice region of R4C81 near 180°. (The 180° is the azimuthal location of the SCC with reference to axes defined in the report on the tube examination.) It extended to and above the tubesheet top where it was deepest. Unlike the other axial stress corrosion cracks at the tubesheet top in this tube, this crack was very long. It existed below an elevation of 7.4 inches above the tubesheet bottom and extended to 1.0 inch above the tubesheet top. It may have been continuous for 14.8 inches. Multiple nucleation sites were observed at intervals (typically less than 0.1 inches) on the crack fracture face and at locations where the tube was partially bent to open the crack for visual mapping.

The crack was, therefore, composed of many short axial cracks which nucleated in a very narrow axial band and which grew together by intergranular stress corrosion cracking at relatively shallow depths. This crack had some IGA characteristics, especially near the top of the axial crack. Within the crevice region, the crack was estimated to be between 20 to at least 40% deep. The maximum depth found by three transverse metallographic sections was 40%. It is assumed that the crack could be somewhat deeper at other locations along the long crack. From the tubesheet top to 0.6 inches above the top, the crack was 40 to 68% deep. No unusual surface features were observed at or near the long crack.

Parallel to the 180° crack, (near 175°) a number of shorter axial cracks were sporadically observed. The longest of these parallel cracks was approximately 1.0 inch long. Minor OD surface IGA (2% deep) was observed at all surface locations within the tubesheet crevice. At the tubesheet top, the uniform minor IGA was not present.

Tube R11C9 had a long axial crack within the tubesheet crevice region. The crack extended from 3.3 to approximately 20 inches above the tubesheet bottom at a circumferential position of 280°. The 16.7 inch long crack was continuously deeper than 40% from 3.5 to 14 inches above the tubesheet bottom and had a maximum depth of 74%. Unlike in the long crack in Tube R4C81, it was difficult to observe separate nucleation points in the crack on Tube R11C9. It is possible that the minor (2-3% deep) OD surface IGA, found at all tube surface locations within the tubesheet crevice, acted as nucleation points for cracks that grew together by intergranular corrosion at a depth of one to two grains below the surface. In general, the axial SCC in Tube R11C9 had minor IGA characteristics. However, when the crack approached mid-wall, the crack morphology changed to IGA, suggesting that the local stress state had decreased. A drop in the local stress state would also imply that the crack growth rate decreased.

An axial scratch was observed at 280° from 3.6 to approximately 18 inches above the tubesheet bottom. Surface deposits and surface oxides on the scratch indicate that the scratch predated plant operation. The scratch was deepest and widest at the bottom elevation and gradually became less deep and wide with increasing elevation. The crack ran along the right side of the axial scratch near bottom elevations and along a ridge adjacent to the scratch at higher elevations. The ridge was probably part of the axial scratch where the scratch became less visible. Similar scratches were observed at other circumferential locations on this tube and also on Tube R4C81. None of these other axial scratches had corrosion associated with them. The axial scratches were not located at regular intervals around the circumference as has been identified at other plants.

At the mechanical expansion transition, no primary water stress corrosion cracking (PWSCC) was observed on the ID surface of either tube.

On Tube R11C9 no corrosion was observed at the tubesheet top other than one minor (6% deep) area with intergranular penetrations. No IGA was present.

Characterization of both tubes showed that neither tube was sensitized and that both had typical hardness values (mechanical properties). The microstructures of both tubes had a less than semi-continuous grain boundary carbide distribution.

Table 2-1 summarizes the lab NDE data and Table 2-2 summarizes the destructive examination results obtained from this program. In general, the field eddy current inspection located corrosion greater than 40% deep found in the destructive exam. In the case of Tube R4C81, the location and extent of tubesheet top degradation was well described by the lab NDE. However, no tubesheet crevice indication was observed by NDE. The deepest region of cracking found by destructive examination within the crevice of Tube R4C81 was 40%. In the case of Tube R11C9, 9.5 inches of the tubesheet crevice cracking was observed by eddy current testing in the lab. The tubesheet crevice cracking was greater than 40% through wall for a distance of 10.3 inches. On Tube R11C4 the top 0.8 inches of the greater than 40% deep cracking was not observed in the lab eddy current. Laboratory UT examination of the pulled tubes accurately located the degradation in the sections of the tube which were examined. However, there were other indications observed where later destructive examination found no corrosion degradation. UT was apparently sensitive to surface conditions that provided false indication signals.

The residual stress state, which could have contributed to the long axial cracks observed in both tubes, is not understood. Observations of long axial cracking within the tubesheet crevice region are infrequent in the industry but are prevalent at Kewaunee. Isolated instances have been observed in exams done of pulled tubes from steam generators in other plants. In some cases, the cracking appeared to be associated with a circumferential spacing of 120°. With only a single crevice crack, it is not known if a 120° spacing for residual stresses existed within the Kewaunee tubes. The axial scratches were not located at 120° intervals. OD axial scratches have been observed at other plants in apparent association with the axial cracks but, this is not the case at least one other plant nor for one of the tubes in this examination.

A review of tube and steam generator manufacturing procedures did not provide a potential source for the postulated residual stresses. Westinghouse has conducted laboratory stress corrosion testing on tubes with axial scratches and found that surface scratches did not increase the propensity to crack initiation. Furthermore, long axial SCC has not been reproduced in the laboratory. In laboratory testing, axial surface scratches, 0.002 inches deep, were introduced into Alloy 600 tubing with a tool that plowed through the tube surface. These scratches appeared to be similar to those observed in the Kewaunee tube. Control specimens did not have these scratches. The specimens and controls were also given four polished surface conditions (as-received from normal tube manufacture, polished with a very fine grit 3M Scotch Brite with a medium abrasive force, polished with a very fine grit 3M Scotch Brite with a high abrasive force, and polished with a medium grit 3M Scotch Brite with a medium abrasive force). The tube specimens were internally pressurized (30 ksi hoop stress) and tested in a 10% NaOH environment at 650°F until through wall failure developed. While various times to failure were noted depending on the surface finish, no preferential cracking occurred within the axial scratches. The surface scratches had no apparent effect on corrosion development or initiation. Consequently, the cause of postulated residual stresses confined to a long narrow pattern remains unknown.

Field eddy current data suggests that the tubesheet crevice (Tube R11C9) and top of the tubesheet (Tube R4C81) corrosion had been present for at least one year with a slow growth rate between that period. This is further supported by the observation that the tubesheet crevice SCC morphology was modified to an IGA morphology when the cracking approached the tube mid-wall. The corrosion at the top of the tubesheet also had strong IGA characteristics.

Secondary side, Alloy 600, stress corrosion cracking can be caused by soluble ions (OH^- and H^+) that are no longer concentrated within crevices and sludge piles after plant shut down. Inferences regarding the chemical environment may be drawn from remaining insoluble compounds that reflect their origin. Unfortunately, the cracks in the Kewaunee steam generator tubes have been in existence for at least one year prior to tube removal, and any chemical analyses data gathered may reflect only the recent chemical environment.

Analyses of the secondary side deposit compositions and crack face oxide films were performed to identify the chemical environment which caused the cracking. Of these analyses, the most useful in determining the local chemical environment were x-ray diffraction of OD deposits, Electron Spectroscopy Chemical Analysis (ESCA) analyses of OD and fracture face deposits, and Auger Electron Spectroscopy (AES) analyses of fracture face oxide films.

A number of distinct observations were made from ESCA-AES and x-ray diffraction data which can be used to form judgements concerning the local chemical environment within the hot leg tubesheet crevice and sludge pile. These observations suggest that an alkaline environment had been recently present.

X-ray diffraction provided results which suggest the presence of an alkaline environment. Magnesium silicate hydroxides were found in tightly bound inner deposits on Tube R11C9. $Mg_3Si_2O_5$ minerals (the serpentines) are stable in neutral and alkaline aqueous environments to temperatures above 400°C, but they are slowly attacked by acid. $Mg_3Si_4O_{10}(OH)_2$ is stable well above 500°C in alkaline aqueous environments. Quartz (SiO_2) was found in the OD deposits of Tube R4C81. Quartz would not be expected to form in acidic or neutral environments since silicic acid is volatile and would be lost into the steam before concentrations permitting quartz precipitation would be reached (0.01 Molal is the solubility of quartz in pure water at 300°C.) Alkaline environments would favor the concentration of silica in crevices, and quartz can precipitate from aqueous sodium hydroxide environments at steam generator temperatures. The formation of quartz would not be expected if Ca, Mg, or other alkaline earth ions were responsible for the crevice alkalinity. Silicates are favored under such conditions. One possibility is that the quartz was formed in an alkaline crevice and that the alkalinity was caused by sodium hydroxide or another alkali metal hydroxide. Another possibility is that the quartz was not formed within the crevice, but was deposited there during shutdown or during handling.

ESCA-AES analyses of crack fracture faces, of fracture face oxide films, and of adjacent OD deposits provided numerous data which suggested the presence of an alkaline environment. A large fraction of the oxygen on the fracture faces was bound up as hydroxide. Some of the carbon was present as carbonate, and alkaline surfaces can react with atmospheric carbon dioxide to form carbonate. Sodium (also magnesium) was present on the crack fracture faces. The crack oxide films were depleted in Cr, also suggesting an alkaline environment. (Since the degree of Cr depletion was not large, it is suspected that the recent environment was somewhat alkaline as opposed to strongly alkaline.) And finally, magnesium silicates were also found by ESCA analyses as they were by x-ray diffraction.

OD surface pH measurements obtained with moistened wide-range pH paper also suggested the presence of an alkaline environment.

In controlled laboratory tests, Alloy 600 can develop intergranular SCC in strongly acidic environments, in reduced sulfur environments if the tubing has a sensitized microstructure, in alkaline environments that can range from strongly alkaline to mildly alkaline, in chloride environments when present in combination with oxygen or copper ions and/or low pH if the alloy is sensitized, and in Pb doped environments that can be acidic, neutral, or alkaline. Of these possibilities, only the reduced sulfur and chloride environments can be firmly eliminated from consideration at Kewaunee since modified Huey testing showed that the tubes were not sensitized.

However, other environmental possibilities can be partially eliminated from consideration. In addition to there being a lack of data from the chemical analyses to support a recent presence of an acidic crevice environment, there is a reluctance to attribute the observed SCC to an acidic environment based on laboratory experience with SCC testing in acidic environments. In laboratory testing, not only are extremely acidic environments required to produce SCC, but these environments more often result in general corrosion. Finally, Pb was present in and beneath surface deposits and on crack fracture faces. Consequently, it is also possible that Pb played a role in the SCC. However, there is also a hesitation to attribute the SCC to Pb enriched environments. Small amounts of PbO frequently induce SCC in Alloy 600 in the laboratory. In contrast, very few instances of field generated cracking have been attributed to Pb even though Pb is nearly universally present in steam generator sludge deposits. (It can be speculated that an inhibitor exists within the more complex field deposits.) Lead can cause purely intergranular, purely transgranular, or mixtures of the SCC modes in Alloy 600. Only when transgranular features are observed in the field, is Pb usually identified with some certainty as having contributed to SCC. No transgranular features were present in the intergranular SCC observed in this examination.

This leaves alkaline environments for consideration. Alkaline SCC is readily generated in the laboratory under a wide range of pH conditions. The chemical analyses of surface deposits and crack fracture faces provided numerous data suggesting the presence of an alkaline environment. It is consequently, concluded that an alkaline environment caused the observed

SCC. The detailed examination of the pulled tubes is documented in a separate report to be published as part of an EPRI program.

2.2 Summary of Examination Results

1. Both tubes developed long axial cracks within the tubesheet crevice region. In the case of Tube R4C81, the cracking continued to 1.0 inches above the tubesheet top. The cracking was confined to below the tubesheet top region in Tube R11C9. The crevice region crack morphology was intergranular stress corrosion with some IGA characteristics. In Tube R4C81, the crack was more than 14.8 inches long by destructive exam, and up to 68% through wall, above the tubesheet top and at least 40% through wall within the tubesheet crevice. In Tube R11C9, the crack was 16.7 inches long and up to 74% through wall.

2. The tubesheet top region of Tube R4C81 showed multiple intergranular stress corrosion cracking with strong IGA characteristics. The predominate cracking mode was axial, but minor circumferential cracking was also present. The most extensive circumferential involvement was actually a zone of IGA formed by a number of axial cracks in which their "IGA skirts" grew together. The deep cracking was confined to within 1.0 inches above the tubesheet top with cracking greater than 40% through wall confined to within 0.6 inches above the tubesheet top. The deepest crack above the tubesheet top was 76% through wall. Shallow (<10%), short axial SCC was sporadically observed up to 2.0 inches above the tubesheet top.

3. Field eddy current data provided a description of most crack locations in which the cracks were greater than 40% through wall.

. The tubesheet crevice axial cracking in Tube R11C9 appeared to be associated with a shallow axial scratch. No such association was observed in Tube R4C81 although similar scratches were present.

5. Neither tube had PWSCC on the ID surface of the mechanical expansion transition.

6. Based primarily on x-ray diffraction, ESCA, and AES analyses of OD deposits and crack fracture faces, it is concluded that an alkaline environment has been recently present in secondary side deposits and within the tubesheet crevice region.

7. It is concluded that alkaline induced stress corrosion was responsible for the observed corrosion degradation on the two pulled tubes. Based on review previous eddy current data, it is believed that this corrosion degradation has been present for at least one cycle. The eddy current signals on which assessment is bassed may not have been identified as an indication using previous standards.

3. EDDY CURRENT REVIEW OF 1990 OUTAGE RESULTS

3.1 Summary of Eddy Current Inspections Results

The results of the pulled tube examination for tube R4C81 show OD stress corrosion cracking (ODSCC) above the top of the tubesheet. The evaluation of the eddy current signals for this tube made at Kewaunee during the most recent outage led to an interpretation of these signals as volumetric indications. While tube R4C81 was designated to be plugged, 24 tubes with indications determined to be volumetric were left in service. Since the possibility exists that the volumetric indications could be ODSCC, the 1989 and 1990 eddy current data for these 24 tubes was reevaluated in the lab and summarized in Section 3.2. Of particular interest in this review were the signals associated with indications of tube degradation and denting at the top of the tubesheet. Since the findings of the pulled tube exam relative to tubesheet crevice degradation were consistent with the previous eddy current evaluation, these portions of the eddy current records were not reviewed. Relevant data on the tubesheet crevice indications from the 1990 outage is summarized in section 3.3 below. A review of denting indications from the 1990 data is summarized in Section 3.4. Section 3.5 is a review of eddy current data of tubes removed from service due to leaks. The conclusions reached in this report are supported by the reevaluation summarized below.

3.2 Indications Above the Top of the Tubesheet Left in Service

The field bobbin coil eddy current data of 1990 and 1989 on 9 tubes in steam generator A and 15 in steam generator B were reviewed in the lab. The tubes were those with indications from a rotating pancake coil (RPC) probe at the top of the tubesheet judged as volumetric during the 1990 inspection and left in service. The RPC data on some of these tubes was reviewed for guidance purposes. All the field bobbin coil indications were called distorted top of tubesheet signals in the field.

Although the eddy current signals are distorted, it was necessary to force voltage calls for these tubes to help support a safety assessment for continued operation which would bound the indications left in service conservatively. A few tubes could be evaluated with reasonably high confidence since the indication voltages were much larger than the dent voltage sometimes the indication was large enough that the dent signal was insignificant. Tables 3-1 and 3-2 give the results tube by tube of the lab evaluation. There are instances where the voltage estimate for 1990 was significantly lower than for 1989 (e.g., R1C23 steam generator B). This results from a large interference from dent signals for the 1989 data. Wherever the dent signal was judged to contribute significantly to the signal distortion making the voltage estimates less dependable, they were marked as such (**). Since the indications are a combination of the dent signal and the flaw signal, it is generally difficult to estimate the dent signal voltage or the flaw voltage with any degree of confidence. Only when the dent voltage is much smaller than the flaw voltage, can the flaw voltage be evaluated with confidence.

Table 3-3 summarizes the result for the 24 tubes in the two steam generators. Three of the tubes show significant change in the signals between 1989 and 1990 with a non trivial 1990 bobbin indications. Of the remaining tubes: fifteen tubes showed no significant changes; five tubes showed some small change in the indications; and one tube showed only a change in the dent indication.

3.3 Indications Within the Tubesheet Crevice Left in Service

During the 1990 Kewaunee refueling outage, expanded scope RPC inspections conducted on the hot legs of steam generator tubes revealed crack indications in the tube sheet crevice region which were not detected with a bobbin coil inspection. The expanded RPC inspection is summarized in table 3-4. A total of 19 (13.0%) and 42(24.9%) of the tubes inspected in steam generators A and B respectively were found to have axial crack indications in the crevice region which were not detected with the bobbin coil inspection.

Five tubes in steam generator A and nine tubes in steam generator B with indications generally more than 5 inches below the top of the tubesheet were left in service. These tubes will be used to track the growth rate of the indications over the subsequent operating cycle. Only axial indications contained within the tubesheet were selected for continued service so that leakage was restricted if the indications propagated to through wall cracks. The tubes selected were also identified as having smaller indications than those selected to be plugged.

As noted in Table 3-4, additional tubes remained in service which were not inspected by the RPC probe. The percentages of tubes inspected with RPC that had indications were applied to the uninspected tubes to conservatively postulate that an additional 142 and 276 tubes with indications in steam generators A and B, respectively, could have been left in service. This estimate is judged to be conservative since the selection criteria for the RPC inspection was focused on the tubes judged by WPS to be more likely to have crevice cracking based on results of previous inspections and location.

The maximum projected number of tubes in service which could conceptually contain axial indications in the crevice region is 147 tubes in steam generator A and 285 tubes in steam generator B. The bounding 285 tube estimate is used as the basis for leakage evaluations in later sections of this report.

3.4 Denting at the Top of the Tubesheet

The 1990 bobbin data on the hot leg side of 1235 tubes in steam generator A and 1249 tubes in steam generator B was revaluated in the lab for indication of denting at the top of the tubesheet. This represents all tubes not sleeved and or plugged at the end of the 1990 steam generator inspection.

Figures 3-1 and 3-2 provide the tubesheet maps for steam generators A and B showing the tubes sleeved and/or plugged and the result of analysis of the in service tubes. It was determined that all tubes are dented to some degree at the top of the tubesheet. Figure 3-3 shows the distribution of dent voltages (in the 400 kHz/100 kHz mix channel) for the hot legs of the two steam generators. Based on the 1985 bobbin and profilometry data available from the cold leg side of 12 tubes, it is concluded that the denting phenomenon took place sometime prior to the 1985 inspection and that there has been little if any progression since that time.

Profilometry measurements of tube dents in the cold leg of steam generator B were performed in 1985. These results can be used to estimate the dent size associated with the voltage measurements of Figure 3-3. Figure 3-4 shows the maximum dent size from profilometry versus the measured bobbin coil voltages. Based on Figure 3-3 and 3-4, the maximum dent size at the top of the tubesheet is about 1 mil and the most frequently occurring voltage of about 2.0 volts corresponds to a maximum dent size of about 0.4 mils.

3.5 Review of Data for R32C29 and R33C40 in Steam Generator A

Kewaunee had a primary to secondary leak rate that peaked at 0.08 gpm (118 gpd) prior to the 1989 refueling and inspection outage. The leakage was traced to tube R32C29 in Steam Generator B which had cracks within the tubesheet crevice. The bobbin coil inspection results show a deep indication between 12 and 14.5 inches above the bottom of the tube. This indication, as shown in Figure 3-5, appears to have ~100% depth. In addition, there were additional indications at other axial locations within the crevice that were 70 to 84% deep.

The RPC data at about the 12 to 14.5 inch elevation is also shown in Figure 3-5. This data indicates a probable through wall crack of about 2 inches axial length. Other axial indications were found that do not appear to be through wall.

The eddy current data for this tube was also reviewed for denting at the top of the tubesheet. A clear dent signal of ~1.8 volts was found. This dent size is typical of the most probable dent size as shown by the dent voltage distribution of Figure 3-3.

In 1987, a plant leak rate peak of 358 gpd was detected and tube R33C40 in steam generator A was identified as the leaking tube. A review of bobbin coil inspection results indicated a deep crack between 10.2 and 13.1 inches above the tube end. This indication appears to be through wall for a length greater than one inch (~1.5 inch). In contrast to tube R32C29, no dent signal was found at the top of the tubesheet. No RPC inspection data are available for this tube.

The leak rate data for these tubes are used in Section 6 as Kewaunee data points for confirmation of the leakage analysis model and for comparisons of leak rate predictions for these data with predictions based on the leak rate test results for the dented tube condition. With the large through-wall crack of ~2" length, the leak flow restriction for R32C29 is dominated by the crevice flow restriction from the dented condition rather than the crack flow restriction. A similar leakage behavior is applied for tube R33C40 except that there is no dent to restrict leakage flow.

4. EVALUATION OF TOP OF TUBESHEET INDICATIONS LEFT IN SERVICE

As indicated in Section 3.2, the eddy current data was revaluated for 24 tubes left in service with indications just above the tubesheet that were classified as volumetric indications at the March 1990 outage. Based upon the R4C81 pulled tube examination results showing that an indication at the top of the tubesheet classified as volumetric by field RPC was an axial crack network, the tubes left in service with similar "volumetric" indications were revaluated as axial crack networks. This section assesses the revised eddy current evaluation of Section 3.2 relative to tube integrity considerations for continued operation to the planned March 1991 refueling outage.

4.1 Crack Growth Considerations

As noted in Tables 3-1 and 3-2 of Section 3, most (15) of the 24 top of tubesheet indications left in service show no significant change in the eddy current voltage signals from 1989 to 1990. Boric acid chemistry was implemented following the 1988 outage. Operating experience with boric acid chemistry in Kewaunee and other plants has demonstrated reductions in ODSCC crack growth and initiation following the boric acid addition. Thus it is reasonable to anticipate continuing small growth rates until the 1991 refueling outage.

The eddy current indications are distorted as a consequence of interference from tube dents at the top of the tubesheet. Thus voltage levels for the indications could not be reliably determined although estimates were made for 5 tubes with a reasonably high level of confidence. Only 9 of the 24 indications showed some change in the signal response. One (R2C81 S/G A) of the 9 tubes with a signal change is associated with a change in the dent signal with no determinable change in the indication response. Five tubes (R1C73, R5C34 in S/G A and R2C79, R3C110, R4C10 in S/G B) show a small change in the distorted indication response. The remaining 3 tubes with signal changes (R2C13, R2C16, R3C79 in S/G B) had indications for which voltage responses could be estimated from the 1990 outage data. These results may be indicative of some crack growth away from the top of tubesheet dent such that the cracks become more visible to the bobbin coil probe. However, no growth rate can reliably be assigned to these indications.

Overall, the top of tubesheet indications are distorted signals which were present in 1989 and generally (15 of 24 tubes) show no growth to 1990. It is judged that with the boric acid secondary chemistry, the ODSCC growth rate following the 1990 outage will continue to be small.

4.2 Bobbin Coil Data Assessment

Where feasible, bobbin coil voltage calls were forced from the distorted indications to provide bounding estimates of the degradation levels as shown in Table 3-1 and 3-2. These values are approximations due to signal influence from the top of tubesheet dents. The estimated voltage values are assessed in this section for leakage potential based upon ongoing work to correlate voltage values to leakage potential for ODSCC at tube support plates (TSPs). The crack morphology of ODSCC at TSPs is similar to that for ODSCC in sludge pile regions as found above the tubesheet at Kewaunee. Thus the development efforts for ODSCC at TSPs can be reasonably applied to assess the Kewaunee indications.

The destructive examination results for Tube R4C81 above the tubesheet (Figure 2-1) show multiple axial crack networks around the circumference of the tube. The extent of cracking around the tube is somewhat more extensive than typically found at TSPs. This effect leads to higher voltage levels than for TSP indications. The bobbin coil voltage is a measure of volumetric levels of degradation and has been shown in laboratory sensitivity tests to increase with crack length, number of cracks around the tube and the loss of ligaments between cracks. Application of the voltage correlation data for ODSCC at TSPs is thus expected to be conservative for this Kewaunee application due to the higher voltages resulting from the increased number of axial crack networks around the tube. The height of 1.1" found for R4C81 degradation involvement at the top of the tubesheet is longer than the 0.75" height typical for ODSCC at TSPs. The principal crack network of R4C81 was 1.1" long with depths up to 68% to 0.6" and < 40% to 1.1" with a short crack up to 76% deep also found by destructive examination. Regardless of this length and depth, The crack morphology shows that this tube would not leak or burst under SLB conditions. The estimated burst pressure is about 4500 psi conservatively assuming a 68% depth over 1.1 inch. Thus this indication is included as a non-leaking tube at 1.8 V, 87% depth (lab review of field bobbin coil inspection) in the voltage data discussed below.

To develop a relation between average voltage and leakage potential, data from pulled tube examinations, laboratory model boiler induced ODSCC cracks, field leakage experience and field data with no identified leakage have been collected. These data are shown in Figure 4-1. Included in the figure is the data point for Kewaunee pulled tube R4C81. The field eddy current data for the leaking tubes found in the field is shown in Table 4-1. The field and laboratory data of Figure 4-1 indicate that operating leakage is not expected for voltages less than about [ ]^{b,c,e} The laboratory, model boiler (MB) data points of Figure 4-1 were also tested for leakage at steam line break (SLB) pressure differentials of 2650 psi. The largest leak rates measured for the model boiler specimens shown in Figure 4-1 were [ ]^{b,c,e} of normal operating and SLB pressure differentials respectively. The model boiler generated crack specimens showed steam line break to normal operating leak rate ratios that were [< 3.0 which indicates no significant plastic deformation of the cracks and that burst pressures for all the model boiler points of Figure 4-1 exceed SLB conditions.]^{b,c,e}

Burst tests were performed for five of the pulled tubes for which the inspection data is shown in Figure 4-1. The burst pressure for all of these tubes exceeded SLB and three times normal operation pressure differentials. The voltages for these tubes were [ ]^{b,c} with corresponding burst pressure of [ ]^{b,c} psi. The overall tests included up to specimens with indications up to [ ]^{b,c} Therefore, the data of Figure 4-1 support about [ ]^{b,c,e} volts as a threshold for no operating leakage and no burst for SLB conditions at a much higher voltage level.

As shown in Table 3-2, the maximum voltage from the 1990 inspection assignable to the distorted top of tubesheet indications is 3.4 V (R1C21, S/G B) with the next highest voltage at 2.8 V (R2C16, S/G B). The maximum voltage assignable to indications in S/G A is 0.6 V (R3C81). The three S/G B indications with a significant change in signal response between 1989 and

1990 had voltage levels of 1.6, 2.8 and 2.5 volts. The Kewaunee voltage levels are low compared to the [ ]^{b,c,e} threshold indicated for leakage from the model boiler tests. Thus, leakage is not expected from the indications above the tubesheet and a large margin exists relative to burst at SLB conditions.

4.3 Conclusions

The following represent the conclusions from the evaluation of ODSCC indications just above the top of the tubesheet.

- o Growth rates are generally small as indicated by the comparison of eddy current signals between 1989 and 1990. This is consistent with expectations based on implementation of boric acid secondary chemistry in 1988.

- o Based on forcing eddy current voltage calls from the distorted signals, the voltage levels of < 3.4 volts are well below values of about [ ]^{b,c,e} volts for which current data indicate that operating leakage might be expected. In addition, the low voltage levels indicate large margins against tube burst at SLB conditions.

- o Destructive examination of pulled tube R4C81, which indicated a sufficiently large signal (1.8 V, 82% depth) to require tube plugging, shows that this tube, with a maximum depth of 68% in the longest crack and 76% in a short crack, had large margins against burst at SLB conditions.

- o Overall, the evaluation supports continued operation for these tubes with significant safety margins until the next planned inspection in March 1991.

5.0 DENTED TUBESHEET CREVICE LEAK RATE TEST

5.1 Background

Denting of the tubes at the top of the tubesheet is caused by localized corrosion of the tubesheet which produces a corrosion product more voluminous than the tubesheet material. This corrosion product initially closes the tube to tubesheet gap and then eventually may deform the tube if the corrosion continues. Determination of the leak rate through and/or around the interface between the unexpanded tube and the denting corrosion product of the tubesheet at the top of the tubesheet was not initially conducive to calculational methods. The resistance to leakage of the interface between the tube and denting corrosion extending over a portion of the tube immediately below the top of tube tubesheet was determined by test. This test supports the analytical efforts to model the denting corrosion leakage, in light of existing porous-media flows and small passage (crack) flow configurations.

5.2 Objective

The objective of this test was to determine tube-to-denting corrosion region resistance to leakage for the case defined in Section 5.1. This region will hereinafter be referred to simply as the "dent". The resistance to flow attributed to the dent will be completely separate from the resistance to flow of the crack itself for test purposes. The latter effect is understood and was not tested in this program. The tests were performed with denting corrosion interface test specimens fabricated of short sections of prototypical tubes mounted in collars which provided approximately the same structural compliance as a unit cell of the tubesheet. The tests were performed at prototypical pressures, temperatures and tube axial loads for normal operation and the limiting faulted primary-to-secondary condition, i.e., steamline break (SLB).

Postulated feedline break conditions would provide the maximum primary-to-secondary differential pressure, 2650 psi, across the tube. However, Kewaunee does not include the feedline break in the licensing basis. The steamline break, with a differential pressure slightly lower than a feedline break, provides the most limiting radiological conditions for postulated accidents involving a loss of pressure or fluid in the secondary system, based on previous experience. To facilitate the comparison of the Kewaunee data with other, similar testing, the estimated feedline break differential was used for these tests. This is the most limiting case because the associated primary-to-secondary side differential pressure causes the greatest leakage flow, everything else being equal. The per-tube reference average acceptable leak rate was obtained by dividing the total primary-to-secondary flow, 260 gpm, (Reference Section 7.0) resulting in the maximum radiological dose at the site boundary, by the total number of tubes postulated to have crevice indications, that is, 285 in the steam generator with the largest number postulated.

The effect of prototypical denting corrosion interface radial loads on leakage through the dent was addressed in the leak test. The radial loads on the tube outside surface at the dent were expressed in terms of radial contact pressures. For example, a load such as primary-to-secondary pressure differential during normal operation causes direct pressure effects on the tube in the dent region to increase the resistance to flow and therefore to reduce the leakage. This effect was included in the laboratory test.

5.3 Major Test Steps

This phase of the program was concerned with the sample preparation, exposure to the denting environment, interim inspection schedule, and physical characterization of the denting process. The dented samples were prepared by two basic isothermal processes: in-situ (no crevice packing) and prepacked (crevice prepacked with magnetite). For the in situ process all of the corrosion was formed in place as a result of the appropriate faulted secondary side chemistry. For the prepacked samples, the crevices at the top of the simulated tubesheet were tightly packed with magnetite formed in the collar before the tube was installed in the collar. The two types of denting processes were judged to simulate the variations in the denting process in the operating steam generators. Some of both the in-situ and prepacked samples were dented in the isobaric configuration, i.e., in the absence of prototypical normal operating primary-to-secondary pressure differential. The remainder of the samples were internally pressurized to simulate the net radial deformation resulting from the small radial outward tube deformation caused by the normal operation primary-to-secondary pressure differential. The outward deformation opposed the smaller deformation radially inward caused by the end cap load due to the same pressure differential.

5.3.1 Preparation of Collared Tube Samples

The tubesheet collars (bi-metallic to control the denting) were fabricated from Alloy 600 rod. Refer to Figure 5-1. Following tubesheet collar fabrication, the A285 carbon steel inserts were installed by welding and the welds were pressure tested to certify them leak tight.

The tube samples were prototypical 0.875 inch OD mill annealed Alloy 600 steam generator tubing, 8.0 inches long, and prior to leak testing, each contained a through wall [ ]^{a,b} diameter hole (approximately equivalent to the annular cross-section of the tube-collar crevice) located 2.0 inches from the dent. This placement of the tube perforation was to simulate the location of the eddy current indications in the Kewaunee steam generator tubes which were typically 5 or more inches below the top of the tubesheet. This relatively large flow area upstream of the denting corrosion caused essentially all of the resistance to flow through the specimen to be at the dent. For the samples dented without pressurization, the tube was perforated before denting. For the pressurized samples no hole was drilled before denting, however, a hole was drilled following denting. Refer to Table 5-1, Test Matrix, for sample types, and Figure 5-1 for Test Sample Assembly.

5.3.2 Leakage Test

Appropriate closures at the ends of the tube were added; the closure at the end of the tube corresponding to the primary side of the tubesheet was fitted with a small port for achievement of the primary pressure and injection of the leakage flow. The secondary side conditions were maintained by placing the entire test sample in an autoclave at the appropriate temperature and pressure. The leakage, if any, issuing from the crevice was captured in the surrounding autoclave and condensed for measurement.

5.3.3 Measurement of Tube Deformations

Interim evaluations were performed during the denting process to assure that the appropriate range of denting conditions were obtained. An eddy current test (ECT) examination was performed using field procedures to confirm that the bobbin signals of the laboratory denting fell in the range of field ECT bobbin dent signals (e.g., 1 to 5 volts). Voltage measurements of the dented tubesheet samples were found to be influenced by the two welds which attached and sealed the carbon steel insert to the Alloy 600 collar. This caused increased reliance on dent size measurements for the tests. To this end, physical measurements using internal micrometers were made to confirm the extent of deformation present. Silastic molding was also applied on the inside of the tube at and on either side of the dent. After solidification, the silastic mold was removed and the diameters measured. This method confirmed the results of the micrometer measurements.

5.4 Determination of Elastic Preload at the Dent

5.4.1 Structural Evaluation

Duplication of the prototypical denting corrosion interface radial pressures in the laboratory was an important part of the leak rate testing of the dented samples. By generating the denting corrosion for the leak test samples in both the pressure differential and isobaric configurations, it was intended to bound the steam generator conditions under which the denting corrosion was formed. It was concluded that the steam generator denting corrosion was formed under pressure differential conditions. In achieving the prototypical tubesheet denting corrosion radial pressures, the contributions of the individual effects to the pressure were determined. These effects included tubesheet bending, primary-to-secondary side pressure differential and tube to tubesheet thermal growth mismatch. Each of these effects may be quantitatively treated. For example, the radial pressure effects applied to the tube by the tubesheet, acting through the denting corrosion, were determined for the tube to tubesheet joint of the Model 51 steam generator.

During plant operation the amount of tube to tubesheet radial pressure, applied through the denting corrosion, depends upon the pressure and temperature conditions experienced by the tube and tubesheet.

The plant operating pressure influences the denting corrosion interfacial pressure directly based on the application of the pressure load to the ID of the tube, thus increasing the amount of interface loading. The pressure also acts indirectly to decrease the amount of interface loading for interior tubes, i.e., located away from the bundle periphery, by causing the tubesheet to bow upward. This bow results in a dilation of the tubesheet holes located on the bundle interior, thus, reducing the amount of tube to tubesheet pressure. However, this has a negligible effect on tubes in the vicinity of the bundle periphery, due to negligible tubesheet bending at the stiff location of the tubesheet, shell and channel head intersection. Because the denting corrosion interfacial pressure loss due to tubesheet bending effects are negligible for the peripheral tubes, i.e., where the dented tubes are located, this mechanism need not be discussed further. At the locations in the tubesheet where the bowing effect is significant the tubes are sleeved.

5.4.1.1. Internal Pressure Tightening

The normal operating differential pressure from the primary to secondary side of the steam generator is approximately 1500 psi. The primary side (internal) pressure acting on the wall of the tube in excess of the secondary side (external) pressure will result in an increase of the tube to tubesheet radial pressure on the order of the differential pressure.

Results from the performance of this calculation were made for both normal and faulted conditions. The results indicated that the increase in radial pressure due to internal pressure tightening is [ ]^{a,c,e} psi for normal operating conditions and [ ]^{a,c,e} psi for faulted (SLB) operating conditions.

Deflection of the tube, to a smaller diameter, is caused by the radial pressure on the tube OD by the denting corrosion. In the elastic range and neglecting axial effects, the diametral deflection is related, as an adequate approximation, to the radial pressure by the hoop stress equation for thin-walled shells under axisymmetric loading. Based on plant and lab tube typical yield strengths of 50 ksi, the tubes remained elastic up to a strain, i.e., diametral dent, of approximately [ ]^{a,e} The corresponding external radial pressure was approximately [ ]^{a,c,e} The pressure was proportionately lower for smaller dents. Therefore, a dent of [ ]^{a,e} in the plant or in the lab results for the dent corrosion exerting a radial pressure of approximately [ ]^{a,c,e} on the tube OD. It was shown in Section 3.4 that the plant dents ranged to approximately 0.001 in.

5.4.1.2 Thermal Expansion Tightening

The mean coefficient of thermal expansion for the Alloy 600 tubing between ambient conditions and 599°F is $7.79*10^{-6}$ in/in/°F. The coefficient for the steam generator tubesheet is $7.16*10^{-6}$ in/in/°F. Thus, there is a net difference of $0.63*10^{-6}$ in/in/°F in the expansion property of the two materials. Considering a temperature difference of approximately 539°F between room temperature and hot leg operating conditions the increase in preload between the tube and the tubesheet was calculated.

The results indicate that the increase in preload radial stress due to thermal expansion could be [ ]^{a,c,e} psi. However, this value does not apply to the plant denting condition since the dents form at prototypical conditions with the thermal reduction of tube to tubesheet gaps present at the time of the dent formation. The lab test likewise involved no thermal expansion tightening because, unlike the plant, the collar was fabricated of the same material as the tube, Alloy 600. It is concluded that the thin carbon steel insert, of approximately 0.19 inch radial extent and welded to the Alloy collar, expanded with the collar. The dents were formed at approximately [ ]^{a,e} and the leak testing was performed at approximately [ ]^{a,e} therefore, essentially no differential thermal expansion effects were present in the test. The reason for using an Alloy 600 tubesheet simulant (collar) for this program was related to resistance to corrosion of the collar during the denting step in the preparation of the samples. It was necessary to limit the axial extent of the denting corrosion to the collar top, to duplicate the plant condition. Because of the aggressive nature of the lab accelerated denting chemistry, the denting corrosion could not be prototypically located if the entire collar were carbon steel. Therefore, the collar was fabricated of Alloy 600, with a small insert of carbon steel at the desired location, i.e., at the top, corresponding to the top of tubesheet location in the plant. Two axial lengths of denting corrosion, i.e., inserts, were used, [ ]^{a,e} Due to the small quantity of carbon steel present in the insert compared to that of the Alloy 600 collar, the strength and thermal expansion properties of the carbon steel were taken to be the same as those of the collar.

5.4.1.3 Main Structural Effects for Leak Test

It was concluded that, during the denting corrosion leakage test, all pertinent mechanical features of the plant should be duplicated as closely as possible. This included the tube to tubesheet gap at the dent, i.e., denting corrosion radial extent, etc. It also included the fluid flow conditions. The most important feature of the test was adequate achievement of the plant denting corrosion interface radial pressure. This parameter was deemed important because it was judged to control the bypass flow, if any, around the denting corrosion. It was judged to have a minor effect on flow through the denting corrosion.

In achievement of the prototypical net radial denting corrosion interface pressure, the two sources of radial pressure were controlling factors. These sources were the denting corrosion and the internal pressure tightening effect.

5.4.2 Normal Operation Condition

The Normal Operation condition will be discussed first. For the plant, typical dents of 0.001 in., the denting corrosion produces an inward-acting radial pressure of approximately [ ]^{a,c,e} The internal pressure tightening effect produces an outward acting pressure of approximately [ ]^{a,c,e} at the tube OD based on the differential pressure across the tube wall in the vicinity of the dent being approximately [ ]^{a,c,e} The differential thermal expansion between the tube and tubesheet has no effect, as discussed earlier. Summing these pressures produces a net tightening pressure of approximately [ ]^{a,c,e} in the plant. (The fact that the calculated net tightening pressure produced slightly smaller than expected dents was assumed to be caused by small inaccuracies in dent determination.)

The laboratory configuration will now be examined in light of achieving the approximately [ ]^{a,c,e} pressure. As stated earlier, no radial pressure due to thermal expansion mismatch was needed in the lab. The internal pressure tightening effect caused the same denting corrosion radial pressure on the tube in the plant as it did in the lab because the differential pressures across the tube were the same. Therefore, to achieve the prototypical net radial pressure in the lab, the denting corrosion contribution approximated the plant value by achieving approximately the same size dents in the lab as were found in the plant.

5.4.3 Steamline Break Condition

The same approach was used to determine the net radial pressure for the faulted, i.e., SLB case. This net pressure was larger than for the Normal Operation case due to the greater pressure tightening effect for SLB. This net pressure consisted of the same approximately [ ]^{a,c,e} due to denting corrosion plus approximately [ ]^{a,c,e} for the internal pressure tightening effect. Therefore, if bypass flow was a factor, it would be expected to have been a more significant factor for the SLB case than for the Normal Operation case. This was because the constant denting corrosion pressure was a larger fraction of the net pressure for the normal operating case than it was for the SLB case. Also the effect of the increase internal pressure on the tightening is less than the effect of the pressure increase on the differential pressure.

5.5 Test Results

5.5.1 General

Four main parameters were varied in the fabrication of the samples. These were:

1. Denting corrosion formation completely in-situ or primarily by prepacking followed by in-situ formation
2. Dent axial length was controlled primarily by the axial length of the carbon steel insert at the top-of-collar location (corresponding to the top-of-tubesheet location in the steam generator).
3. The presence or absence of prototypical normal operating differential pressure across the tube wall during denting.
4. Dent diametral extent.

Six samples, Numbers 3,4,6,7,9, and 13 were prepared by formation of the corrosion in the in situ mode. Of these, four were prepared in the presence of a pressure differential across the tube wall; the remaining one was prepared without any differential pressure.

Three samples, Numbers 5, 11, and 14, were prepared by formation of the corrosion in the prepacked mode; most of the denting corrosion radial extent, and probably most of the axial extent as well, was formed by prepacking. The remaining denting corrosion, only sufficient to permit entry of the tube, as well as that required to dent the tube, was formed in-situ. Samples had no differential pressure during denting; sample No. 11 was prepared under a prototypical normal operating pressure differential of [ ]^{a,e}

5.5.2 Flow Test Results

With the exception of one sample, all nine samples exhibited relatively low leakage at both normal operating and SLB conditions. The term "low leakage" meant lower than the leakage for one similarly degraded tube in the plant which leaked at 118 gpd (0.0819 gpm) prior to the 1989 refueling outage. The observation of excessive leakage for one sample, No. 5, was due to an apparent denting measurement error, which indicated denting where essentially none existed. Therefore, as determined by sectioning and polishing, where in-situ denting following prepacking was indicated, for this sample, essentially no denting existed. Therefore, there was little if any significant leakage flow resistance. The only apparent flow restriction was provided by the prepacked corrosion. The results for this sample should be disregarded in the evaluation of the data.

The average normal operation leakage flow, disregarding Sample 5, was [ ]^{b} with the smallest being zero and the largest being [ ]^{b} The comparable values for the SLB condition were an average of [ ]^{b} with the smallest being [ ]^{b} and the largest being [ ]^{b} For the six samples which exhibited flow at the normal operating condition, disregarding Sample 5,the average ratio between the normal operating flow and the SLB flow was 2.3, whereas the primary-to-secondary side pressure differential between the two conditions was approximately 1.767. Therefore, the flow was slightly greater than proportional to the pressure differential; it was expected to be more closely proportional to the pressure differential.

Because this specimen exhibited a leak rate which exceeded the relatively low limit of the particular system in which it was mounted, it was removed from flow testing for destructive examination. The use of a system with a larger limit, such as used later for other specimens with flows in the range of several liters per hour, probably would have been successful in determination of leak rate.

A brief examination of the results in Table 5-1 shows no obvious relationship between the primary-to-secondary side leakage and the main parameters.

5.5.3 Evaluation of Corrosion Product at Dent Sites

Following the autoclave exposure and leak rate determination, Specimen No. 10 was sectioned axially. Because this specimen exhibited a leak rate which exceeded the relatively low limit of the particular system in which is was mounted, it was removed from flow testing for destructive examination. The use of a system with a larger limit, such as was used later for other specimens with flows in the range of [ ]^{a,e} probably would have been successful in determination of a leak rate. One half section was reduced in axial length and sectioned axially into two short quarter sections that contained the steel insert at the upper end of the collar . One quarter section was mounted transversely to the tube axis and polished on the upper face of the collar. The second quarter section was mounted axially. Both sections contained the collar, the carbon steel insert, the corrosion product at the steel surface, and the tube wall. Photomicrographs were made of both sections in the as-polished conditions.

The corrosion product zones of both mounted specimens were analyzed by scanning electron microscopy (SEM) energy dispersive X-ray spectrometry (EDS), and area scan "dot maps" were made for the elements iron, chlorine and copper. The results showed an iron-rich corrosion product (magnetite) through the entire corrosion product layer, with copper concentrations as "islands" in zones away from the steel-to-corrosion product interface. Chlorine (chloride) was weakly distributed relatively uniformly through the corrosion product. These results were therefore quite typical of observations of denting corrosion products from model boiler tests conducted in copper-containing acid chlorides and from tube support intersections removed from plants that were experiencing active denting in the mid-1970's (References 2 and 3). Despite the acidic nature of the cordoned in the present tests (cupric chloride), the elemental distribution in the corrosion products also resembled microprobe analyses of caustic denting produced in the laboratory in copper-dosed concentrated sodium-potassium hydroxide mixtures (References 4 and 5).

Additional microanalyses are in progress on two other specimens from the test program. The limited results to date indicate, however, that the autoclave exposure conditions are effective in producing relatively typical in-situ denting corrosion compositions.

6.0 Tube Sheet Crevice Evaluation

This section provides the Kewaunee leakage and tube integrity evaluation for crack indications within the tube to tubesheet crevice. The test results of Section 5 for dented tube leak rates are used in a leak rate calculation model to assess leak rates as a function of postulated through-wall crack length. These results are then used to demonstrate acceptable tube integrity for the potential indications within the tubesheet crevice.

6.1 Tube Integrity Requirements

General Design Criteria 14, 15, and 31 of 10 CFR Part 50 Appendix A specify the design requirements for protection against abnormal leakage, rapidly propagating failure, and gross rupture of the reactor coolant pressure boundary. The tube integrity requirements are defined by Reg. Guide 1.121 together with satisfaction of USAR Chapter 14 accident analyses for allowable radiological consequences. The tube integrity analysis presented in this section demonstrates that the plant will remain within the guidelines of the General Design Criteria for RCS integrity.

For thinned or non-thinned tubes with through-wall cracks, the Reg. Guide 1.121 criteria can be summarized as:

- Cracks should not burst under accident conditions

- The maximum permissible length of the largest single crack should have a burst pressure greater than 3 times normal operation differential pressure

- The Plant Technical Specification leakage rate should be less than the leakage rate determined for the largest permissible crack

The USAR accident analyses evaluate the radiological consequences to satisfy 10CFR20 and 10CFR100 criteria. For accidents such as a Steam Line Break (SLB), the release of radioactivity is the result of tube leakage in steam generators. Thus the tube integrity requirements must provide that the SLB leakage limits are satisfied. These leak rate criteria are developed in Section 7 of this report and results in a requirement to limit SLB leakage to 260 gpm.

In the case of cracking within a tubesheet crevice or a tube support plate (TSP) intersection, testing (Reference 1) has shown that tube burst does not occur within the TSP even with nominal (i.e no corrosion) tube to plate gaps. Within a tubesheet or TSP crevice, all burst requirements of Reg. Guide 1.121 are inherently satisfied by the reinforcement provided by the tubesheet or TSP. However, the USAR Chapter 14 leakage requirements for radiological consequences during accident conditions must still be satisfied.

Based on the above requirements, the governing requirement for tube integrity of the Kewaunee tubesheet crevice indications is to show that the SLB leakage limit of 260 gpm is satisfied. This evaluation is given in Section 6.5.

6.2 Crevice Leakage Model

A computer code called CRACKFLO has been developed for predicting leak rates through cracked steam generator tubes. The analytical model assumes one-dimensional flow and accounts for crack entrance pressure losses, tube wall friction, and flashing. The following is a brief discussion on the flow and pressure drop characteristics assumed in the computer program.

As the flow enters the crack from the primary side it encounters a sudden reduction in flow area. This change in area results in a pressure change which is modeled by an empirically based discharge coefficient. Beyond the vena contracta and point of attachment to the crack wall, flashing and friction predominate. The flashing of liquid to vapor generates an acceleration type pressure drop. The combination of surface roughness and number of turns in the flow path determines the friction loss. The overall pressure drop, therefore, is given by the sum of pressure losses due to area contraction, acceleration, and friction. This pressure drop determines the pressure at the exit of the crack. For noncritical flow conditions, the exit pressure equals the secondary side pressure. For critical flow conditions, however, the exit pressure will be higher than the secondary side pressure. As a result, the crack leakage flow will depend on whether or not critical flow conditions exist.

In CRACKFLO, critical flow is evaluated according to Henry's non-equilibrium formulation (References 6 and 7). This method accounts for non-equilibrium effects due to finite evaporation rates. This is expected to be particularly important in flow through large cracks, where the fluid transit time is short. For small cracks characterized by a large wall thickness-to-diameter ratio, non-equilibrium effects are not as important and Henry's model reduces to the homogeneous equilibrium model (H.E.M). In essence, Henry's approach correlates the deviation between the measured and homogeneous equilibrium model predicted flow rates.

Essential to the prediction of leakage flow rate is the evaluation of crack opening area. In CRACKFLO, the crack opening area is determined by the [

]^{a,e}

Crack Model Comparison to Leak Rate Data - Normal Operation Pressure

The analytical model results are compared with experimental test data in Figure 6-1 for normal plant operating conditions. The test data consists of field and Westinghouse laboratory formed cracks. The Westinghouse test specimens include axial cracks formed by fatigue and by stress corrosion cracking in the laboratory. The field test specimens include actual pulled tubes with intergranular stress corrosion cracking. For stress corrosion cracks, the crack opening area is based on the [

]^{a,e} For

fatigue cracks, however, the area ratio is assumed to be one based on experimental observation. As indicated in the figure, good agreement between prediction and measurement is shown. For stress corrosion cracks, however, greater data scatter is shown than for fatigue cracks. For these cracks, the crack geometry is quite complex and difficult to define with any degree of precision. Crack geometry parameters which affect flow are crack opening area, surface roughness, and flow path turns. As a result of these geometry factors, a larger uncertainty in the predicted flow rates is expected for small cracks characteristic of stress corrosion cracking. For large cracks characteristic of fatigue cracks, the crack geometry parameters are apparently well defined and a factor of [ ]^{a,e} uncertainty in the predicted flow rates may be assumed.

Crack Model Comparison to Leak Rate Data - SLB Pressure

The analytical model results are compared with experimental test data in Figure 6-2 for steam line break conditions. As indicated in the figure, good agreement between prediction and measurement is shown. In order to produce this type of agreement, crack opening area is based on the [

]^{a,e}

Dented Crevice Leakage Model

To simplify the study of leakage through a crack in series with denting corrosion, an equivalent flow channel of constant diameter is assumed. This implies that the added hydraulic resistance of the denting corrosion can be characterized by a resistance coefficient, KD. This coefficient is determined experimentally. Once KD is known, the equivalent L/D (length-to-diameter ratio) of the denting corrosion is calculated and added to the crack L/D. For this analysis, the crack opening area serves as the reference flow area.

6.3 Analysis of Denting Corrosion Leakage Tests and Tube R32C29

The dented crevice leakage model requires a hydraulic resistance coefficient for the dented tube geometry. This factor is determined from the tubesheet crevice leakage tests. Parameters which effect hydraulic resistance coefficient include material porosity, particle size, tortuosity of flow path, and annular gap between magnetite and Alloy 600 tubing. Moreover, these parameters are dependent on dent size, insert length, tube internal pressure during denting, and material composition. Since many of these variables are difficult to quantify, the hydraulic resistance coefficient has been defined in terms of pressure drop divided by dynamic head. Table 6.1 summarizes hydraulic resistance coefficients (KDs) for the tubesheet crevice leakage tests. As indicated, KD varies [ ]^{a,e} (Note: while more tests were performed, the test results listed in Table 6.1 are enveloping and form the basis for the tube integrity assessment.)

Prior to the 1989 refueling and inspection outage, Kewaunee had a plant leak rate that peaked at 0.08 gpm (118 gpd). The leakage was traced to tube R32C29 in steam generator B which had cracks within the tubesheet crevice. The eddy current data indicated a through wall crack with a crack length of ~2 inches. Assuming that the leak rate is limited by the dent restriction, a hydraulic resistance coefficient equal to [ ]^{a,e} is estimated. Other notable plant leakages include a 358 gpd leak rate detected in 1987 (R33C40) and a 34 gpd leak rate detected in 1986 (tube unknown). For these plant leak rates, KD equal to [ ]^{a,e} are estimated. As indicated in Table 6.1, Test no. 5 with KD equal to [ ]^{a,e} for normal plant operation bounds the Kewaunee leakage data.

6.4 Crevice Leakage Assessment

Figures 6.3 and 6.4 present leak rate versus crack length for normal plant operation and steam line break conditions, respectively. The KD factors shown in Table 6.1 were used to simulate the flow resistance of denting corrosion. For dented tubes, both figures show an asymptotic leak rate as crack length increases above a certain value. For these cracks, the dent restriction is more limiting than the restriction of the flow through the crack. Based on Test No. 5, (Test Nos. correspond to Table 5-1) the asymptotic leak rate is reached for crack lengths greater than [ ]^{b,e}. For KD values characteristic of Test Nos. 3 and 4, dramatic reductions in the leak rate are shown. Moreover, the asymptotic leak rate is reached much sooner [ ]^{b,e} for these tests.

6.5 Tube Integrity Evaluation

This section utilizes the leak rate analysis results of the previous section to demonstrate tube integrity against the Regulatory guidance as described in Section 6.1. The governing requirement for tube integrity for cracks within the tubesheet crevice is to limit potential SLB leakage to less than a limit of 260 gpm (see Section 7 for the development of this leak limit). In the return to power report of Reference 1, a preliminary estimate of 190 gpm for the SLB leak limit was applied. The tube integrity evaluation of this section is performed for the 260 gpm limit. To facilitate comparisons with the Reference 1 results, both the 190 and 260 values are used to develop the numbers in Table 6-3. In Reference 1, the tube integrity evaluation was performed based upon crevice packing limiting the annular gap in the tubesheet crevice to [ ]^{a,e} The evaluation of this section is based upon the leakage flow restriction obtained from the tube denting at the top of the tubesheet. This change from crevice gap to dent restriction was made as the presence of dents can be verified by eddy current inspection while tubesheet crevice deposits cannot readily be verified. The expected presence of crevice deposits in addition to the tube denting would further limit SLB leakage to lower values than the evaluation of this section based on the dented tube leakage tests of Section 5.

Table 6-2 summarizes the data base obtained from the tests and the evaluation of the larger leak rates from Kewaunee operating experience. The leak rate tests measure leakage from a large hole in the tube which simulates a negligible crack flow restriction. Then the tests represent the asymptotic leak rate for large through-wall cracks for which a crack length of 1.0" is used for analytical comparisons. The test leak rates are volumetric measurements of the fluid leaking from the test specimen cooled to about 100°F so that a density adjustment which increases the volumetric flow rate is required for plant operating conditions. This adjustment has been included in Table 6-2 for the leak rates assigned to 1.0" crack column in the table.

As indicated in Tables 6-1 and 6-2, the leak rate from test sample number 5 is on the order of [ ]^{b} than any other test, about [ ]^{b} than the operating experience for tube R32C29. This test leak rate result should envelope the largest leak observed at Kewaunee, associated with tube R33C40. Tube R33C40 had no eddy current dent signal while tube R32C29 had a clear dent signal at the top of the tubesheet. Based upon examination of the Test no. 5 sample, it is speculated that the laboratory time of approximately [ ]^{a,b} was too short to harden the prepacked magnetite as typical of less accelerated corrosion leading to tube denting. Destructive examination showed no significant denting and the leak rate of this sample is used as a bounding, upper leakage limit to demonstrate tube integrity and to bound the operating leakage experience at Kewaunee. Test 5 and Tube R33C40 leak rates are considered to be typical of non-dented tube conditions.

Except for test 5, the test results indicate large through-wall crack leak rates in the range of [ ]^{b} for normal operation conditions. Thus, it would be expected that many or most of the tubes with potential through-wall cracks would result in negligible leakage. This is particularly applicable with the further expectation that through-wall crack penetration would generally be < 1.0" long such that the crack flow restriction further reduces leakage below the values of Table 6-2. As shown in Figures 6-3 and 6-4, the leak rates approach the asymptotic (large crack) values of Table 6-2 for crack lengths greater than about [

]^{b} Above about [ ]^{b} long cracks, the leak rates are limited by the dent flow restriction while shorter crack leak rates are more limited by the crack flow restriction.

The operating experience at Kewaunee shows some leakage over eight fuel cycles with the first leaking tube in 1978. The 1978 leaking tube had a very small leak rate estimate of 0.02 gpd. Six of these leakage events show leaks between <1 gpd and 51 gpd. The 51 gpd leakage was attributed to two leaking tubes. The three cases of plant leakage experience given in Table 6-2 are believed to have resulted from single tube leakage. The plant leakage trends of the few (25% of the the leakage events) significant (>50 gpd) leaking tubes, is consistent with the test data which show that dented tube conditions are expected to result in low leakage. The results shown in Table 6-2 and Figures 6-3 and 6-4 show that the test results bracket the Kewaunee leakage experience. That is, most (75% by field experience) of the tubesheet crevice cracks that are postulated to proceed to through wall are expected to result in low [ ]^{b,e} leakage at normal operating conditions and the order of 2 to 2.5 times as large at SLB conditions.

Very conservative assumptions with regard to through-wall cracks are applied for the tube integrity assessment. Except for Test 5 and tube R33C40 operating experience, the results of Table 6-2 show that asymptotic, large crack leak rates are expected to be less than the 0.014 gpm (200 gpd) administrative operating leak limit for the current cycle at Kewaunee. Thus it is expected that crevice leakage from more than one tube could be required before the leak limit is exceeded. In this case, it can be conservatively assumed for the tube integrity evaluation that any tube which leaks will be a large crack that leaks at the asymptotic leak rate (1.0" crack column) of Table 6-2. The allowable number of tubes with through-wall cracks can then be estimated by dividing the 260 gpm SLB leak limit by the asymptotic leak rate per tube. The results for Tests 3 and 4, as examples, as well as Kewaunee tube R32C29 are shown in Table 6-3. As noted in Table 3-4, the maximum number of in-service tubes which could potentially have crevice indications is 285 tubes in steam generator B. It is seen from Table 6-2 that the allowable number of tubes having crevice cracks, with leak rates typical of Tests 3 or 4 or Kewaunee tube R32C29, substantially exceeds the potential 285 tubes with indication. All unsleeved tubes, approximately 1250 tubes in each steam generator, could have large through-wall cracks without exceeding the 260 gpm SLB leakage limit based on these results.

For leak rates such as Test 5 and Kewaunee tube R33C40 conditions without denting for which the leak rate from one tube could exceed the Kewaunee administrative leakage limit of 200 gpd, it is assumed that only one tube contributes to the operating leakage but all tubes with potential cracks would leak under a postulated SLB event at the same rate as the tube leading to plant shutdown. Under this assumption, the crack length leading to a 200 gpd leak is calculated for Test 5 leak rates and this resulting crack length is used to calculate a corresponding SLB leak rate per tube. By dividing the 260 gpm SLB leak limit by the leak rate per tube, a lower bound on the acceptable number of tubes with through-wall cracks is calculated. This result is shown in Table 6-3. The allowable number of tubes with through-wall cracks for the Test 5 conditions is [ ]^{b,e} which exceeds the maximum 285 tubes with crevice indications potentially left in service in steam generator B. Similarly, the tube R33C40 evaluation permits [ ]^{b,e} tubes with through wall cracks based on the Kewaunee administrative leak limit of 200 gpd. It is also conservatively shown that even if the Test 5, large crack, asymptotic SLB leak rate of [ ]^{b} per tube is assumed, the allowable number of tubes with this leak rate would be about [ ]^{b,e} tubes. One tube with the Test 5 normal operating leak rates would have a leak rate of [ ]^{b} which would significantly exceed the current operating administrative leak rate limit and result in a unit shutdown.

Based upon the above assessment of the dented tube leak rate test results and the Kewaunee leakage experience, it can be concluded that:

o For the expected dented tube leak rates such as Tests 3, 4, 6, 7, 13 and 14 or the leak rate experienced by Tube R32C29, all currently open, unsleeved tubes (~1250 tubes) could have large (> 1" long) through-wall cracks without exceeding the SLB leak limit of 260 gpm.

- For the upper bound, non-dented leak rates obtained in Test 5, even the large crack leak rates permit about [ ]^{b,e} tubes with through-wall cracks without exceeding the SLB leak limit and without an operating leak limit below about [ ]^{b,e}. With the Kewaunee administrative leak limit of 200 gpd, the allowable number of tubes with the upper bound leak rates is approximately [ ]^{a,e} tubes. These allowable numbers of tubes with through-wall cracks resulting in conservatively high leak rate estimates, exceed the maximum number of 285 tubes with potential crevice indications.

- While the 200 gpd administrative operating leak limit at Kewaunee is not essential to maintaining tube integrity for crevice indications, this leak limit will be maintained over the current cycle as additional safety margin for crevice or top of tubesheet indications.

- With an operating leak limit of 200 gpd, operation of the Kewaunee steam generator with tubesheet crevice indications up to the 1250 active, unsleeved tubes would not create a safety issue such as potentially exceeding SLB leakage limits. The Kewaunee eddy current review indicated that all unsleeved tubes are dented at the top of the tubesheet. This with the results of all leak rate tests with dented tube crevice conditions including tube R32C29 which show low leak rates would support operation with cracks in all unsleeved tubes. A statistical distribution of Table 6-2 leak rates between the 1250 unsleeved tubes would also be expected to result in SLB leak rates less than the 260 gpm limit. For example, assigning 350 tubes to the R32C29 leak rate and 300 tubes each to the Tests 3, 4 and 5 leak rates results in less than a 260 gpm SLB leak rate. Similarly, a distribution on crack depths and lengths would likely reduce the number of tubes with through-wall penetration to less than the allowable numbers of Table 6-3. Therefore, the risk of exceeding SLB leak limits is negligible.

7.0 Radiological Evaluation

7.1 Review of Accident Analysis

The accidents addressed in the Kewaunee Updated Final Safety Analysis Report (USAR) that consider primary to secondary leakage in the offsite dose calculation are the SG tube rupture and steam line break (SLB). Of these, the steam line break is most limiting with regard to leakage due to differential pressure.

7.2 USAR SLB Analysis

The SLB analysis in the USAR Section 14.2 has no explicit primary to secondary leak rate because the assumption is made that all of the primary coolant activity is transferred into the secondary side of the steam generator in the faulted loop. Section 3.2 of Reference 1 considered in detail the effect on the SLB of operation with crevice indications. The radioactive material transfer to the steam generator in the analysis inherently bounds an evaluation using a finite leak size since a primary to secondary leak can not transfer the entire activity in the coolant to the steam generator. However, this essentially infinite leak rate assumption does not provide a useful means of evaluating a condition that may result from a primary to secondary leak. Hence, a radiological evaluation was performed to determine the maximum allowable steam generator primary-to-secondary leak rate following a steam line break and at a primary to secondary leakage limit that does not effect other the response of other plant systems to the SLB.

The evaluation was based on the assumptions used in the steam line break analysis of record presented in USAR Section 14.2.5. The salient assumptions include primary coolant activity corresponding to one percent fuel defects and an iodine decontamination factor of 0.1, for the steam generator in the faulted loop. The offsite dose acceptance criteria was assumed to be 30 rem thyroid, i.e. 10 percent of the 10 CFR 100 guideline. Iodine spiking is not addressed in the Kewaunee USAR Chapter 14 analysis or in the Technical Specifications. Hence, it can be concluded that iodine spiking is not considered in the current Kewaunee licensing basis. The estimated allowable leak rate based on a two hour dose at the site boundary is 2600 gpm, and based on an eight hour dose at the low population zone boundary is 13860 gpm. The leak rate based on the site boundary dose is clearly more limiting and will be used as the basis for the allowable leak rate determination.

The USAR analysis uses a value of 0.1 for the iodine decontamination factor. This is inconsistent with current practices and a more conservative value of 1.0 is used to determine the allowable leak rate for the evaluation of the tubesheet crevice indications. The allowable leak rate for this evaluation based on the assumptions noted above is 260 gpm. This value is somewhat larger than that calculated in Reference 1 as explained below. In many cases both the number from Reference 1 and the 260 gpm value are used to assess the leak rate tests and evaluations. It is noted that this radiological evaluation was done solely as a means to provide a conservative evaluation criteria for the tubes with RPC indications known or postulated to remain in service. It does not represent an effort to change the licensing basis of the plant with regard to iodine decontamination factors.

The allowable steam line break primary-to-secondary leak rate presented in Reference 1 (190 gpm) was based on an initial primary coolant iodine activity corresponding to 1% defective fuel. FSAR Table D.4-1 specifies these concentrations in units of micro curies per cm^3 at 578^{O}F. In order to convert the concentrations to μCi/gram, for the iodine release calculation, the concentrations were multiplied by the ratio of the hot and cold coolant densities, i.e., approximately 62 lb/ft^3 / 44 lb/ft^3 or 1.4. Thus, the coolant concentrations in μCi/gm, at operating conditions, are assumed to be 40% greater than the FSAR values specified in μCi/cc. It was subsequently determined that measured coolant activities are reported to the NRC (as required by the plant technical specifications) in μCi/cc measured at atmospheric conditions and not corrected for density. Hence, it can be argued that FSAR concentrations should have been specified in units of μCi/gm. The revised allowable leak rate of 260 gpm is based on the above.

In addition to the steam line break analysis, an evaluation was performed to determine the expected site boundary thyroid dose that would result if the entire reactor coolant iodine inventory, based on normal operating conditions, were released to the environment. The value used above to calculate the 260 gpm limit is based on the iodine inventory used in the FSAR which is in excess of the limit on coolant activity in the Technical Specifications. Actual coolant activity measurements from normal full power data over the last two years was reviewed, and it was determined that the highest dose equivalent I-131 concentration was less than 4.5E-4 microcuries/gram. Thus based on actual reactor coolant operating conditions, the 260 gpm primary to secondary leak rate specified previously would result in an offsite dose that is an extremely small fraction (approximately 1/5000 of the 30 REM limit. The dose estimate based on operating conditions demonstrates the very conservative nature of the design basis approach.

8. 1991 OUTAGE PLANS

8.1 Inspection Plan

During the 1991 refueling outage Wisconsin Public Service will be performing a very aggressive and extensive steam generator tube eddy current inspection program. The major thrust of this program will be based on rotating pancake coil RPC inspection in the tubesheet area. This tubesheet RPC inspection will include all unsleeved, open tubes in the hot leg tubesheet region of both steam generators, approximately 1250 tubes per steam generator. Additionally all inservice steam generator tubing will be bobbin tested; and a random 10% sample of existing sleeves will be tested by cross-wound bobbin. The balance of the testing program will consist of a sampling of support plate and U-Bend RPC.

8.2 Sleeving Considerations

In an attempt to resolve the long term concerns associated with crack indications in the tubesheet crevice region Wisconsin Public Service will continue to pursue steam generator tube sleeving. The majority of sleeves to be installed during the 1991 outage will be 27 inches in length as opposed to 30 and or 36 inch sleeves installed in previous outages. The 27 inch sleeving technology expands the current steam generator sleeving boundary by approximately 622 tubes per steam generator which corresponds to an 84 % coverage of the tube bundle. It is anticipated that during the 1992 refueling outage sleeving technology will be used that extends the sleeving boundary to all but the outermost tubes.

9. SAFETY EVALUATION

This evaluation is written to assess the impact on the safe operation of the Kewaunee Nuclear Power Plant of steam generator tubes remaining in service with indications of tube degradation. The indications of interest are at the top of the tubesheet and within the region of the crevice between the tube and tubesheet. The criteria of 10CFR 50.59 are used to evaluate whether operation with these indications of degradation is an unreviewed safety question.

9.1 Introduction

During the Spring 1990 refueling outage at the Kewaunee Nuclear Power Plant eddy current inspections using a rotating pancake coil (RPC) found indications of steam generator tube degradation in the tubesheet crevice region which were not readily discernible using the standard bobbin coil eddy current probe. As a consequence an expanded RPC inspection found similar indications in several tubes. An evaluation of the indications was made and the indications judged to be most significant were removed from service. Some of the indications were allowed to remain in service to provide a means to assess the growth rate of the degradation during future inspections. In addition to the indications remaining in service some of the tubes not inspected by RPC were assumed, by projection, to have degradation which would produce an indication if inspected by RPC. Based on the rate of occurrence in inspected tubes, approximately 285 tubes with these known and postulated RPC indications may have remained in service in steam generator B. Steam generator A has a smaller number. An evaluation was made prior to the end of the outage to assess the impact of leaving the known and postulated indications in service. This current evaluation has been prepared to address additional information from a review of eddy current information and from a metallurgical exam of the pulled done subsequent to restart of the unit following the outage.

A metallurgical examination of pulled tubes subsequent to the outage was done to assess the correlation of eddy current indications to actual tube conditions. The examination generally confirms the estimate of size and extent of crevice corrosion from the eddy current indications. The examination could neither confirm nor exclude the presence of tightly packed deposits in the crevice. The leak rate considerations of this evaluation do not rely on the presence of a tightly packed crevice to restrict leakage from a crack in the crevice region rather, the identifiable condition of denting at the top of the tubesheet is evaluated.

In addition to the indications within the crevice, indications at the top of the tubesheet were observed. These indications were attributed in the field to shallow volumetric degradation. The results of the metallurgical examination of a pulled tube revealed that the indications were the result of a network of short axial cracks, not of wastage or other volumetric degradation. Based on the comparison of the eddy current signature of this tube, the tubes remaining in service with degradation originally classified as volumetric are now conservatively evaluated for safe operation as axial crack networks.

9.2 Regulatory Basis

General Design Criteria 14, 15, and 31 of 10 CFR Part 50 Appendix A specify the design requirements for protection against abnormal leakage, rapidly propagating failure, and gross rupture of the reactor coolant pressure boundary. The NRC Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes", issued for comment, addresses tubes with through-wall cracking. The tube integrity analysis demonstrates that the plant will remain within the guidelines of the General Design Criteria for RCS integrity. The Regulatory Guide utilizes safety factors on loads for tube burst and collapse that are consistent with Section III of the ASME Code. In accordance with paragraph C.3.d (1) of Reg. Guide 1.121, the analytical and loading criteria applicable to tubes with through-wall cracks in thinned or non-thinned tubes are:

1. Through-wall cracks in minimum thickness tubes should not propagate and result in tube rupture under accident conditions.
2. The maximum permissible crack length of the largest single crack should be such that the burst pressure is at least 3.0 times the normal operation pressure differential.
3. The leakage rate limit under normal operation set forth in the plant technical specifications should be less than the leakage limit determined for the largest permissible crack.

9.3 Evaluation

Tubesheet Crevice Indications

The evaluation of the tubesheet crevice indications considers the structural strength of the tube and the projected leak rate against a steam line break (SLB) leak rate criteria. An administrative leak rate limit of 200 gpd supports operation of the plant. The tube integrity criteria, which this safety evaluation supports take into account the reinforcing effect of the tubesheet. The presence of the tubesheet constrains the tube and complements its integrity in that region by precluding tube deformation beyond the diameter of the tube hole in the tubesheet.

Tube Burst Capability Discussions

The steam generators at Kewaunee have tubes which were mechanically expanded into the tubesheet for a short length at the bottom of the tubesheet. In the remaining depth of the tubesheet above the expanded portion of the tube there is a small annular gap between the tube outside surface and the tubesheet hole. Tubes with through wall axial cracking that is confined to within the tubesheet thickness can not burst as a result of that degradation due to support provided by the tubesheet. The tube to tubesheet annular gap limits the amount of expansion which a degraded tube can undergo to less than that required for a tube burst for any type or extent of degradation.

Tube Leakage Considerations

Although tubes are not expected to burst within the tubesheet under SLB conditions, it cannot be assured that the cracks will not develop a leak during the SLB. Primary to secondary leakage has always been assumed in the Kewaunee licensing basis shown by the assumption of 1% failed fuel inventory being present in the faulted steam generator for dose assessment considerations. The maximum amount of leakage permissible during SLB is used as a basis to establish the acceptable number of tubes with through wall cracks in the crevice. Making the conservative assumption that all projected RPC indications grow through wall as a result of the steam line break, the maximum leak rate for each indication can be determined. Dividing this maximum leak rate per indication into the total permissible leak rate during the SLB determines the acceptable number of indications in a steam generator tube bundle that may remain in service and still result in acceptable radiological consequences.

During the operating history of the Kewaunee steam generators the crevices between the tubes and tubesheet at the top of the tubesheet have been closed due to denting of the tube by corrosion of the tubesheet. The corrosion is primarily in the form of magnetite and results in no gap or a very small gap between the tube and tubesheet. The evaluation of maximum leakage rates uses a leakage rate unrestricted by denting or packed crevice at the top of the tubesheet. The evaluation also considered the leak rate of leakage restricted by the presence of denting at the top of the tubesheet. The leakage is restricted compared to a crack in a free span section of a tube or in an unrestricted crevice. Testing of the effect of a crevice closed by a dent have been performed and demonstrate a small acceptable leak rate for cracks in the crevice region.

In addition to the restriction of flow due to the presence of dents at the top of the tubesheet, the length of the postulated cracks in the crevice region will limit the flow rate out of a tube. The crack leakage model accounts for crack entrance pressure losses, tube wall friction, and flashing. The leakage model also evaluates the crack opening area based on the length of the crack along with other parameters such as tube wall thickness and pressure differential. In addition to the leakage model, tests and field experience of leaking tubes with effectively no dent at the top of the tubesheet were reviewed to develop values for leakage without the restriction. In a tube with no restriction due to denting at the top of the tubesheet, the crack opening restriction represents the primary resistance to the leakage flow. As noted previously the inside surface of the hole in the tubesheet limits the opening of the crack to less than a condition which would result in a tube rupture.

The basis of the leak rate analysis is that one indication has grown to a through wall crack sufficient in length to have a leak rate just less than the administrative limit. Furthermore all of the remaining indications are assumed to have grown to be cracks which would open up during a steam line break yet are not contributing to the operating leakage. The leak rate used for the analysis was that derived from an asymptomatic test specimen with effectively no denting.

For the leak rate analysis all of the tubes with projected indications are assumed to leak during steam line break conditions at the same rate as the lead crack which caused the operating leakage. An evaluation was done to demonstrate that a large number of tubes would, with the predicted leak rate, have an acceptable leak late during a postulated steam line break. To determine the acceptable number of potential cracks remaining in service, the flow through an individual dent must be defined. Since a relationship between crack length and leakage rate during normal operation can be established, an administrative leak rate can be established which will limit the size of the leak rate of any through wall crack during operation.

The flow restriction used in the analysis has been validated by an evaluation of tube leak due to a through wall crack in the crevice region found during a outage. At the time of the 1989 outage the plant was shutdown with a primary to secondary leak rate well below the Technical Specification limits. The

1989 eddy current record for the tube to which the leak was attributed has been reviewed. The record has an indication from which a crack length can be estimated. The estimated crack length, size of the dent at the top of the tubesheet and primary to secondary leak rate are consistent with the estimated leak rate using the leakage model. A review of data from a leaking tube at the 1987 outage indicated no dent at the top of the tubesheet. The primary to secondary leakage from this tube is consistent with the test of a crevice with no denting.

Top of Tubesheet Indications

The presence of an eddy current signal from the dent at the top of the tubesheet tends to obscure the signal resulting from any coincident tube degradation. This is particularly the case for the short, tight axial crack network degradation found in the pulled tube at the top of the tubesheet location. It is difficult if not impossible to assign a depth to such an indication. An alternate approach has been developed for these short tight cracks to use the eddy current voltage directly to verify adequate tube integrity.

The short tight cracks of the type found in the metallurgical exam do not have a significant impact on tube integrity. The short crack lengths are not prone to opening even if the crack has propagated through wall and the corrosion products remaining in the crack minimize the potential for any leakage through the crack even if through wall. Testing of tubes with axial crack networks at tube support plates has demonstrated that the eddy current voltage level associated with a tube leak is larger than that found at the top of tubesheet locations in Kewaunee. The voltage level of a crack subject to rupture during SLB conditions is much larger than those in Kewaunee.

A review of eddy current records from 1990 and 1989 indicate that the indications of degradation at the top of the tubesheet have generally not become significantly larger during the previous operating cycle. The addition of boric acid into the secondary side water chemistry has been incorporated at Kewaunee and is continuing. The addition of boric acid is a well established method of minimizing the growth or stopping completely some types of degradation including the type evidenced at the top of the tubesheet. The minimal change in indications between the 1989 and 1990 outages provides evidence that boric acid addition is successful at Kewaunee, thus, rapid growth in the degradation at the top of the tubesheet would not be expected during operation. Since significant growth of the degradation is not expected during operation, the margin between the voltages associated with the top of the tubesheet degradation during 1990 outage and the voltages associated with degradation which actually leaks or ruptures during testing provides an appropriate safety margin.

Radiological Evaluation

The steam line break documented in the Kewaunee USAR assumed that all of the coolant activity was transferred to the secondary system at the start of the accident and did not consider a specific primary to secondary leak rate. Because of this, a radiological evaluation was performed to determine the maximum allowable steam generator primary to secondary leak rate following a steam line break. The evaluation was based on, with one conservative exception, the assumptions used in the steam line break analyses of record presented in USAR Section 14.2.5. The salient assumptions include primary coolant activity corresponding to one percent fuel defects deposited into the steam generator in the faulted loop. The USAR assumes an iodine plate out factor of 0.1. The analysis for the leak rate evaluation used no iodine decontamination factor. The offsite dose acceptance criteria used was 30 rem thyroid, i.e., 10 percent of the 10 CFR 100 guideline. The estimated allowable leak rate which resulted is 260 gpm.

With an allowable SLB leakage rate of 260 gpm, the acceptable number of through wall cracks in the tubesheet crevice region, corresponding to an administrative operating leak rate of 200 gpd, is 388. This number of tubes is based on the leak rates from the testing on the asymptomatic specimen with out denting corrosion at the top of the tubesheet. The test were run for normal operating and SLB differential pressure. The projected number of RPC indications of tube degradation in unsleeved tubes is 285 in steam generator B which is the steam generator with the larger number of indications. This number of indications is an acceptable number. The indications of tube degradation at the top of the tubesheet do not have to be accounted for in this number. The network of short axial cracks associated with these indications would not be expected to result in any significant leakage.

Evaluation Summary

The following functional areas: LOCA and LOCA related accidents, Non-LOCA accidents, steam generator tube rupture, containment integrity, I& C systems performance, Equipment qualification, Fluid system performance, Radiological consequences are not adversely affected by operation of the plant with steam generator tubes with indications of tube degradation as described in this report.

9.4 ASSESSMENT OF UNREVIEWED SAFETY QUESTION

The safety significance of both known and potential indications of tube degradation in the tubesheet crevice region and the top of the tubesheet has been evaluated using the guidance of NSAC-125 and does not represent an unreviewed safety question on the basis of the following justification.

1. Will the probability of an accident previously evaluated in the FSAR be increased?

   No. The accidents of interest are steam line break and steam generator tube rupture. The probability of a SLB is independent of steam generator tube integrity and has been shown to be small. Steam generator tubes with through wall cracking that is confined to within the tubesheet do not burst during normal operation or postulated accident conditions even with nominal tube to tubesheet annular gaps. The criteria of Reg. Guide 1.121 for tube burst are inherently satisfied, even for through-wall cracks, due to the presence of the tubesheet. The network of short axial cracks suggested by indications at the top of the tubesheet would have sufficient strength during normal operation or postulated accident conditions to resist tube rupture using safety margins consistent with Reg. Guide 1.121 Therefore, a single tube rupture event is not expected to occur. Therefore the probability of a steam generator tube rupture has not been increased.

2. Will the consequences of an accident previously evaluated in the FSAR be increased?

   No. Although tubes are not expected to burst within the tubesheet, it cannot be assured that the cracks will not leak during the Chapter 14.0 accidents discussed in the Kewaunee USAR. As previously noted, the accidents affected by primary-to-secondary leakage and steam release to the environment are SG Tube Rupture (SGTR), and steam line break (SLB). Of these, SLB is most limiting relative to the potential for off-site doses. It has been shown that the projected number of tubesheet indications would not adversely affect these Chapter 14.0 radiological analyses. The leakage postulated in the conservative analysis has been shown to be bounded by the original licensing assumptions. In addition, the conservative dose assessment presented in Section 3.3 demonstrates continued conservatism with respect to 10 CFR 100 limits. The tube degradation associated with the indications at the top of the tubesheet will not result in any significant leakage during normal operation or postulated accident conditions. The growth of this degradation has apparently been arrested.

3. May the possibility of an accident which is different than already evaluated in the FSAR be created?

   No. The SLB behavior is not significantly affected by specifically accounting for primary to secondary leakage. Due to the reinforcing effect of the tubesheet and the short length of degradation at the top of the tubesheet, neither a single or multiple tube rupture event would be expected in the Kewaunee steam generators during all plant conditions. The safety issue associated with tubesheet crevice indications which may represent through-wall degradation is primary to secondary leakage during normal, upset, and accident conditions. The implementation of a more restrictive leak rate limit of 200 gpd is expected to preclude the potential for excessive leakage during subsequent plant operation.

4. Will the probability of a malfunction of equipment important to safety previously evaluated in the FSAR be increased?

No. The presence of localized degradation in the steam generator tubes is not expected to affect the overall safety and functional requirements of the Kewaunee steam generator tube bundles. The steam generator tube bundle will continue to sustain with recommended margins, the loads during normal operation and the various postulated accident conditions without loss of safety function. The function of other safety related equipment is not affected.

5. Will the consequences of a malfunction of equipment important to safety previously evaluated in the FSAR be increased?

   No. The worst case consequences which could occur during plant operation is primary-to-secondary leakage during normal operating and plant transient conditions. It has been shown, for the limiting case of a postulated steam line break event, that the radiological consequences of leakage from the tubesheet crevice indications in the Kewaunee steam generators are acceptable, i.e., the consequences do not exceed a small fraction of 10 CFR 100 limits.

6. May the possibility of a malfunction of equipment important to safety different than already evaluated in the FSAR be created?

   No. As discussed above in response to questions 1, 3, and 4, the steam generator tubes will continue to sustain their overall tube bundle integrity requirements.

7. Will the margin of safety as defined in the bases to any technical specification be reduced?

   No. As indicated within the above evaluation, the conclusions provided within the USAR for steam generator tube integrity remain valid because acceptance criteria are met. Even under the worst case conditions, the growth of the tubesheet crevice indications to a through wall crack could not lead to a steam generator tube rupture and that the most limiting effect would be a possible increase in leakage following a steam line break event. The Bases of the Technical Specification for tube plugging or repair includes the safety factors of Reg. Guide 1.121 which are also used in the evaluations supporting this safety evaluation as noted in Section 9.2. The bases for Technical Specification 3.1.D, RCS Leakage, is not altered. In addition, this consequence of increased leakage has been evaluated for the Kewaunee steam generators conservatively assuming that each indication which remains in service could represent a through wall crack. It has been determined that the number of indications involved would not result in radiological consequences in excess of a small fraction of 10 CFR 100 limits. The bases for the iodine limit in Technical Specification 3.4.A.4 are not altered.

9.5 CONCLUSIONS

Operation of the steam generators in the Kewaunee Nuclear Power Plant for the for the remainder of the fuel cycle which started in April, 1990 with known and projected steam generator tube indications in the tubesheet crevice and at the top of the tubesheet does not represent an unreviewed safety question in accordance with 10 CFR 50.59 criteria.

10. REFERENCES

1. WCAP-12558, "Kewaunee Steam Generator Tubesheet Crevice Indications Return to Power Report", April 1990.

2. EPRI NP-3024, "Characterization of Single Tube Model Boiler Dented Intersection Specimens", May 1983.

3. EPRI NP-2791, "Proceedings: Support-Structure Corrosion in Steam Generators", January 1983.

4. EPRI NP-3040, "Neutralization of Tubesheet Crevice Corrosion", May 1983.

5. EPRI NP-4802, "Evaluation of Environmental Effects on Intergranular Attack of Alloy 600", September 1986.

6. Henry, R.E., "The Two-Phase Critical Discharge of Initially Saturated or Subcooled Liquid", Nuclear Science and Engineering, 41, 336-342 (1970).

7. Henry, R.E. and Fauske, H.K., " The Two-Phase Critical Flow of One-Component Mixtures in Nozzles, Orifices, and Short Tubes", Journal of Heat Transfer, May 1971.

8. Tada, Paris, and Irwin, "The Stress Analysis of Cracks Handbook", Paris Productions and Del Research Corp., 1985.

Table 2-1

SUMMARY OF NDE RESULTS ON PULLED KEWAUNEE STEAM GENERATOR TUBES

Tube	Visual	Dimensional	Radiography	Lab Eddy Current	LAB REVIEW OF Field Eddy Current	UT
R4-C81	IGA-type cracks at and just above T/S top. Tubing below 1st SP failed by tensile overload (45° shear features).	Tubing within T/S elongated 5%. Roll transition average radial expansion is 12 mils.	360° band of IGA 0.1 to 0.4 in. above T/S top. Isolated indications as low as 0.5 in. below T/S top to as high as possibly 1.4 in. above T/S top.	Bobbin: 97% indication at T/S top RPC: Multiple short indications at T/S top (pit like). Maximum depth is 80%.	Bobbin: greater than 80% indication T/S top. Small dent at T/S top. RPC: Axial indication at T/S top. Max. depth 80%.	Short axial and short circumferential indications above top.
R11-C9	Many axial scratches, some old, some new. One of largest is an old axial scratch at 280° that extends from 3.6 in. to approximately 18.0 in. above T/S bottom. It is wider (40 mils) and deeper (~2 mils) near bottom. An axial crack is present within this scratch from at least 12.2 to 14.1 in. above T/S bottom.	Tubing with T/S elongated 6%. Roll transition average radial expansion is 15 mils.	Axial crack indications present within axial scratch from 3.6 to 14.2 in. above T/S bottom.	Bobbin: 52% OD indication at 5.6 in. above T/S bottom, 88% indication at 11.3 in., 61% indication at 11.8 in., and a 59% indication at 12.4 in. Absolute mode drift possible with T/S crevice. RPC: Axial indication from 3.8 in. to 13.2 in. above T/S bottom (no RPC data available above 13.2 in.), deepest regions were at 13.2, 11.0 and 5.4 in. above T/S bottom.	Bobbin: Indications between 5 to 11 in. above tubesheet bottom, up to 80% deep. Small dent at T/S top. RPC: Axial indications within crevice region from 3.5 to 13 in. above the tubesheet bottom.	Long axial indication at 280° from 3.0 to possibly 18.8 above T/S bottom. A number of short axial indications may exist at other circumferential locations. Two of the more intense of these were located from 14.0 to 15.6 in. above T/S bottom.

---

*All reported axial positions on these tubes have been corrected for tube pulling elongation in order to directly compare laboratory and field positions.

Table 2-2

CORROSION DEGRADATION SUMMARY

Location	Tube R4-C81	Tube R11-C9
Roll Transition	ID - No PWSCC OD - Uniform IGA (2% Deep)	ID - No PWSCC OD - Uniform IGA (2-3% deep)
Tubesheet Crevice Region	OD - Uniform IGA (2% deep) - Long axial intergranular SCC near 180°. Not obviously associated with any surface scratch. Macrocrack extends from below 7.4 in. above T/S bottom to 1.0 inch above T/S top. Within crevice region the crack probably ranges from 20 to at least 40% in depth. Crack is composed of separately nucleated short axial cracks with very little circumferential separation to the main crack near 175°. - Less deep, short axial cracks exist parallel to the main crack near 175°.	OD - Uniform IGA (2-3% deep) - Long axial intergranular SCC near 280°. associated with a pre-operation surface scratch. Crack extends from 3 to approximately 20 inches above T/S bottom. Crack is 40 to 74% deep from 3.7 to 14 inches above T/S bottom. Crack appears to be continuous without distinct separate nucleation points. When SCC approaches the tube mid-wall, the crack morphology changes to IGA
Tubesheet Top	OD - Main crevice crack at 180° extends above T/S top for 1.0 inches. It is 40 to 68% deep for the first 0.6 inches. - Many shorter but slightly deeper axial intergranular cracks exist around the circumference from the T/S top to 0.8 inches above. They have strong IGA characteristics. Maximum depth is 76% throughwall. - Less prominent are multiple circumferential intergranular cracks and/or IGA zones that exist around the circumference. These short cracks also have strong IGA characteristics and extend from the T/S top to 0.3 inches above the top. Maximum depth is 20% for cracking. - Minor (<10%) isolated cracking exists from 1.0 to 2.0 inches above T/S top.	OD - No IGA - One area with minor intergranular axial SCC (6% deep).

TABLE 3-1

Kewaunee S/G A (Eddy Current Review Results)

		1990	1990 Bobbin		1989 Bobbin		
R	C	Field Call	Indication	Dent	Indication	Dent	Remarks
1	49	PIT	TSH + 0.5" Dented Indication	1.8V	TSH + 0.5" Distorted Indication	2.17V	No significant change
1	73	PIT	TSH + 0.8 DI (0.1V)**	2.96V	TSH + 0.5 DI 0.24V**	3.05V	Some Change
1	74	THN	NI; distorted TTS	2.6V	NI; distorted TTS	3.1V	No significant change
1	76	THN	NI; distorted TTS	1.9V	NI; distorted TTS	1.9V	No significant change
5	79	THN	TSH + 0.8	1.2V Distorted TS Signal	TSH + 0.6" 0.5V**	1.6V	No significant change
2	81	THN	NI Distorted TSS	2.6V	NI Distorted TSS	1.6V	Change in Dent signal
3	81	THN	NI on TSH; Distorted TSS	1.9V Distorted TS Signal	NI on TSH; Distorted TSS		No significant change
			TSH - 0.4" 0.6V ID**		TSH - 0.5 0.5V ID**		No significant change
2	82	PIT	Distorted Indication	1.8V	Distorted Indication	3.3V	No significant change
5	84	THN	Distorted indication	2.0V	NI	1.2V	Some change

NI, distorted TTS - No measurable indication
* - reasonably high level of confidence in measurements
** - Low level of confidence in measurements
Distorted indication - No depth measurement possible

TABLE 3-2

Kewaunee S/G B (Eddy Current Review Results)

			1990 Bobbin		1989 Bobbin		
R	C	1990 Field Call	Dent	Indication	Dent	Indication	Remarks
1	12	THN	2.9V	TSH + 0.3" Distorted Indication	2.5V	TSH + 0.3" Distorted Indication	No significant change
1	18	THN	2.9V	TSH + 0.0" distorted* 1.5V	2.24V	TSH + 0.16" 1.5V*	No significant change
			TSH - 0.15" ID indication				
1	16	THN	2.9V	Distorted indication	2.65V	Distorted Indication	No significant change
1	19	THN		TSH + 0" Distorted** 2V	Low level Dent	TSH + 0" Distorted) (not measured)	No significant change
				TSH + 0.4" (Low level Indication)		TSH + 0.4" (Low level Indication)	No significant change
1	21	THN		TSH + 0.27" distorted* 3.4V	Low level Dent	TSH + 0.2" 2.7V*	No significant change
1	23	PIT	2.29V	TSH + 0.4" distorted* 0.7V	2.2V	TSH + 0.25" 1.3V**	No significant change
2	12	PIT	3.34V	NI; distorted TTS	3.25V	NI	No significant change
2	13	PIT		TTS + 0.35" Distorted Indication 1.6V*	2.23V	TSH + 0.15" Poor indication	Significant change

TABLE 3-2 (Con't)

Kewaunee S/G B (Eddy Current Review Results)

		1990	1990 Bobbin		1989 Bobbin		
R	C	Field Call	Dent	Indication	Dent	Indication	Remarks
2	16	PIT		Distorted** 2.8V	2.9V	NI, TS Signal Distorted	Significant change
2	79	THN	3.9V	NI, Distorted TTS	2.3V	NI, Distorted TTS	Some change
2	81	PIT	2.6V	Distorted TTS	2.5V	Distorted TTS	No significant change
3	11		3.3V	Distorted Indication	2.3V	Distorted Indication	Some change
3	78	THN		TSH + 0.5" 2.4V*		2.4V*	No significant change
3	79	PIT		TSH + 0.5 2.5V**	2.9V	TS Signal Distorted	Significant change
4	10	THN	3.7V	NI; TS Signal Distorted	2.8V	TS Signal Distorted	Some change

NI, distorted TTS - No measurable indication
* - reasonably high confidence level in estimates
** - Low confidence level in estimates

TABLE 3-3

Kewaunee S/G Summary of Review of Top of Tubesheet Indications

	No of Tubes Evaluated	No significant Change	Some Change	Change in Dent	Significant Change in Indication
S/G A	9	6	2	1	0
S/G B	15	9	3	0	3

Table 3-4
Kewaunee Steam Generator Tubesheet Crevice RPC Summary

	S/G A	S/G B
Sample size of bobbin inspection of tubes with no bobbin indication tested by RPC	146	169
Tubes identified to have axial indications in the crevice	19 (13.0%)	42 (24.9%)
Tubes identified to have axial indications in the crevice left in service to track growth rates	5	9
Tubes remaining in service which were not in the RPC samples	1096	1110
Postulated number of tubes that may contain axial indications for tubes not in the RPC samples	142	276
Maximum projected number of tubes inservice which may contain axial indications	147	285

TABLE 4.1

FIELD EXPERIENCE
SUSPECTED TUBE LEAKAGE FOR ODSCC AT TSPs[1]

Plant	Inspection	Bobbin Coil		Comments
		Volts	Depth	
B-1	Outage following suspected leak			
E	Outage following suspected leak			
	Outage following suspected leak			

c

Note:

1. Field experience noted is for nominal 0.750"Ø tubing with 0.043" wall thickness. No data are known to be available for tubes with 0.875"Ø.
2. Reported voltages were adjusted to normalization in this report of 4 volts for 20% ASME flaw.

Table 5-1 KEWAUNEE TUBESHEET CREVICE LEAK RATE TEST RESULTS

Sample number	Differential pressure during denting: Y/N (Y:1500 psi)	Sample type: In situ prepacked IS/PP	Axial length CS insert, (Inch)	Average diametral dent, (mils)	Dent ECT (Volts)	Leak Rate, Collected @Rm Temp., Normal Op. l/hr. (gpm)	Leak Rate, Collected @Rm Temp., SLB l/hr. (gpm)
3	Y						
4	N						
5	N						
6	Y						
7	Y						
9	N						
11	Y						
13	Y						
14	N						

b

Table 6-1 Kewaunee Dent Leak Rate Tests
(Determination of Dent Flow Coefficient)

SAMPLE CHARACTERIZATION

Test #	Prepack? Y/N	Dent Size mils	Insert Length (inch)	ΔP for denting Y/N	Leak Test ΔP PSI	Q$^{(1)}$ l/hr	$W_{leak}^{(2)}$ lbm/sec x10^4	KD in^{-4}x10^{-8}
3								
4								
5								
13								
(Plant Leak Flow Rate 118 gpd)					1450			
(Plant Leak Flow Rate 358 gpd)					1450			
(Plant Leak Flow Rate 34 gpd)					1450			

a,b,e

a,e

Notes

1. At room temperature

2. At 600°F

Table 6-2. Data Base for Kewaunee Crevice Leak Rate Evaluation

Test No	Average Dent-mils	Dent Length	Prepacked at Denting	P,psi at Denting	Test Leak Rate (gpm)(1) Normal Op.	Test Leak Rate (gpm)(1) SLB	>1.0" Crack Plant Leak (2)(gpm) Normal Op.	>1.0" Crack Plant Leak (2)(gpm) SLB
Laboratory Test Data								a,b,e
3	[							
4								
5								
6								
7								
9								
11								
13								
14								]
Plant Leakage Experience								a,b,e
R32C29	0.4(3)	~0.25"	Unknown	1450	--	--	0.082	[(4)
R33C40	None		Unknown	1450	--	--	0.25	(4)
Unknown			Unknown	1450	--	--	0.024	(4)]

Notes:

1. Test leak rates measured at ~100°F.
2. Plant leak rates measured at ~550°F. Leak rates represent asymptotic values for large cracks (1.0" as typical) for which the crack flow restriction is negligible.
3. Approximate average dent size based on Figure 3-4 at 1.8 volts.
4. [ ]a,b,e
5. No dent or significant magnitite deposit found in the crevice after leak testing. It is assumed there was insignificant laboratory denting time to harden the magnitite. Prepacked crevice was washed out upon initial leak testing. Test results typical of a non-dented tube.

Table 6-3. Allowable Number of Tubes With Through-Wall Cracks in Crevice Region

Operating Leak Limit	Single Crack Length Leak at Operating Limit	SLB Leak Rate @ Single Crack Length	Allowable SLB Leak Limit	Allowable No. of Tubes/S/G with Cracks
		<u>WCAP 12558 Return to Power Analysis (0.001 inch gap)</u>		
0.14 gpm (200 gpd)	[	$]^{a,e}$	190 gpm	860
		<u>Analyses Based on Top of Tubesheet Dent</u>		
<u>Kewaunee Leaking Tube Simulation</u>				
Tube R32C49 0.14 gpm (200 gpd)	[	$]^{a,e}$	260 gpm 190 gpm	[$]^{a,c}$
Tube R33C40[1] 0.14 gpm			260 gpm 190 gpm	
<u>Dented Tube Tests</u>				
Test No. 4 0.14 gpm			260 gpm 190 gpm	
Test No. 3 0.14 gpm			260 gpm 190 gpm	
Test No. 5[1] 0.14 gpm			260 gpm 190 gpm	
			260 gpm	388

Note 1. Results for no denting at top of tubesheet.

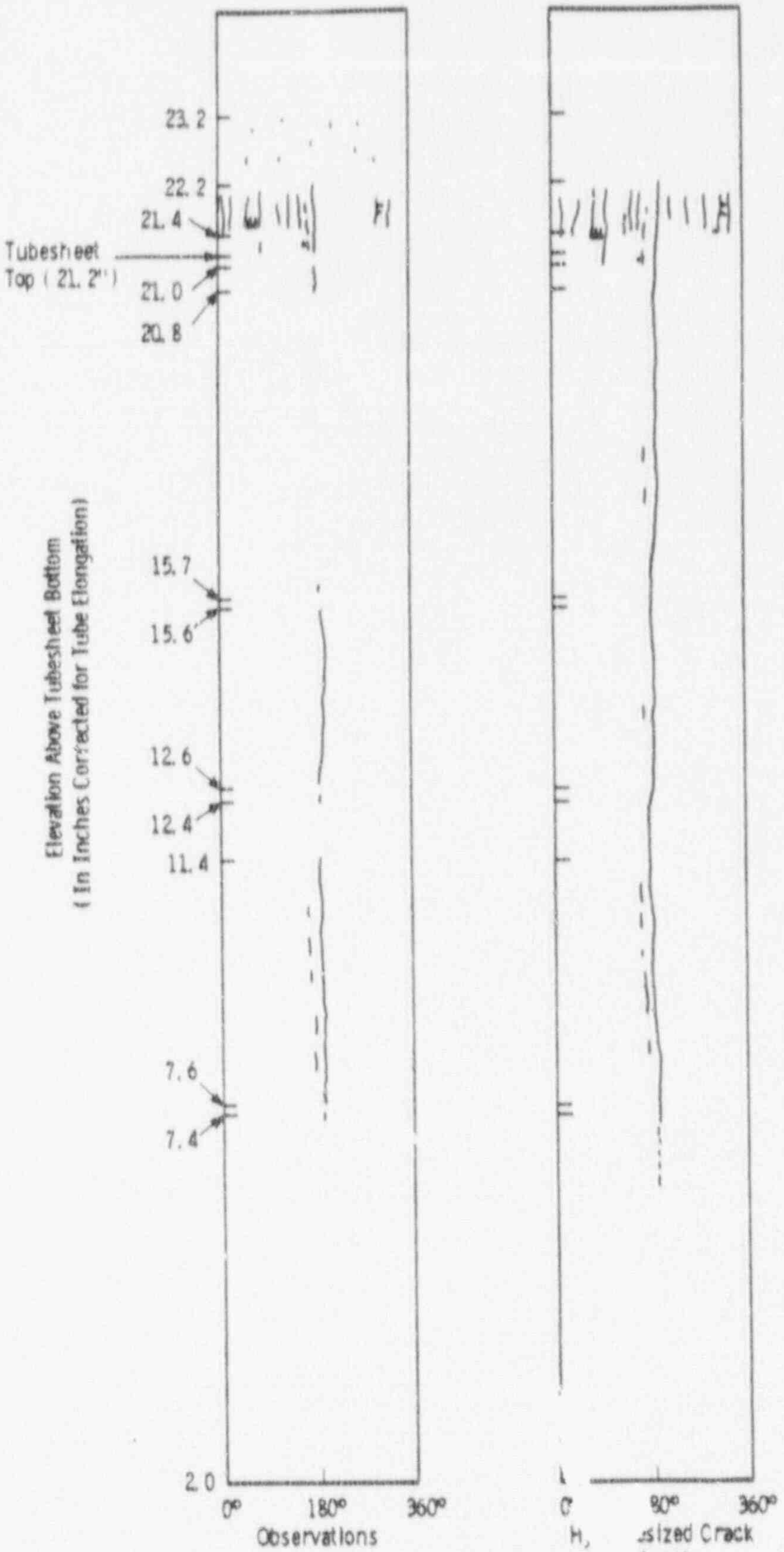


Figure 2-1. Crack Network Observed on Tube -C81.

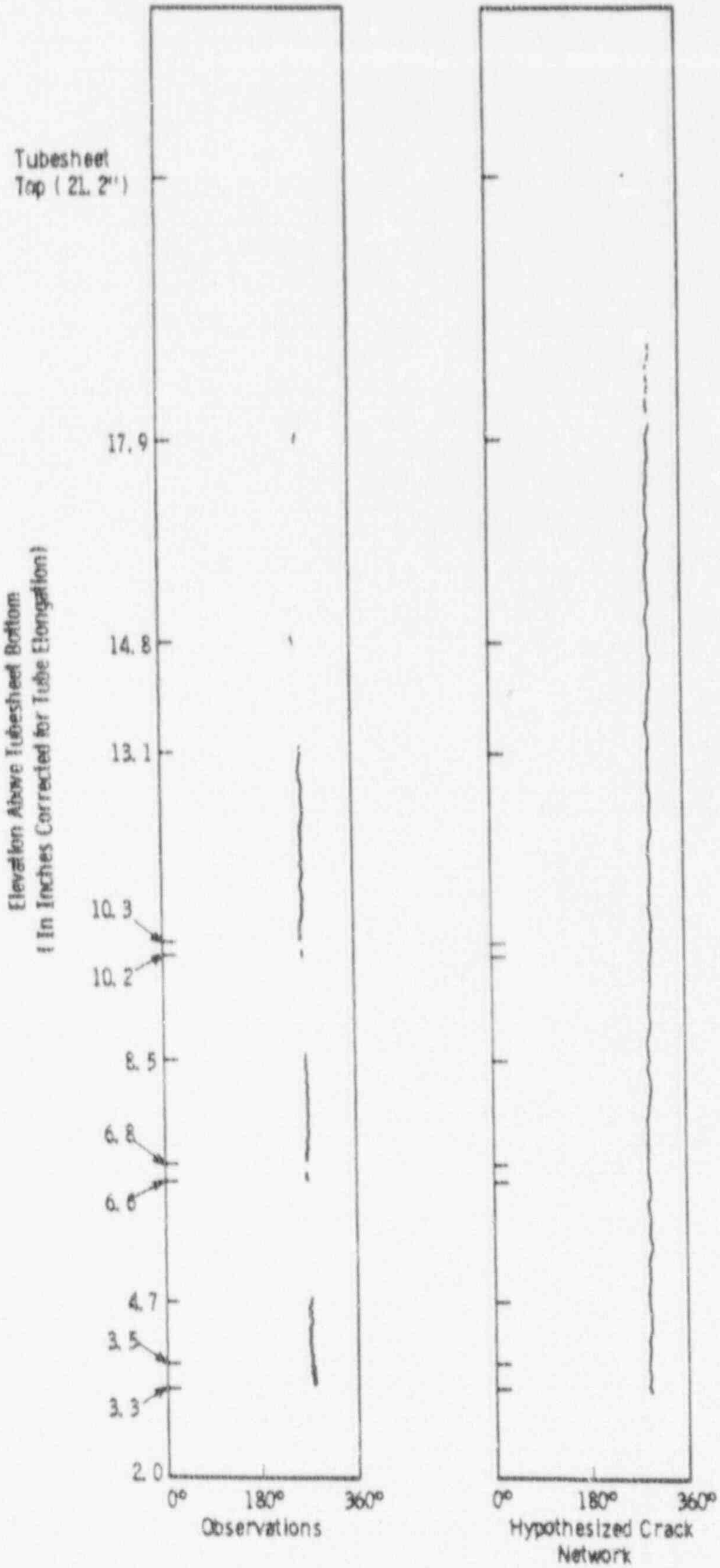


Figure 2-2. Crack Network Observed on Tube R11-C9.

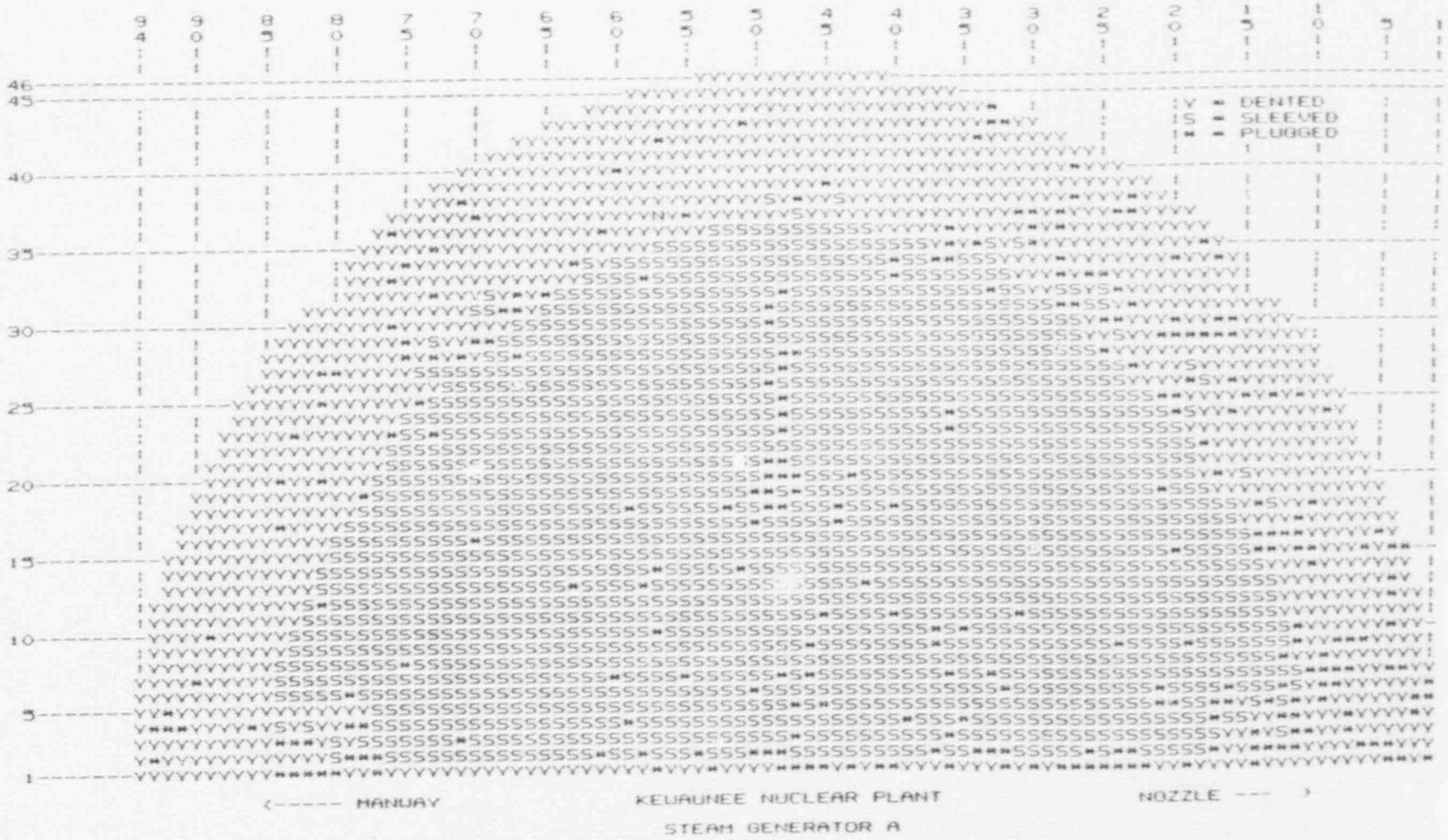


Figure 3-1 S/G "A" Dent Analysis Program

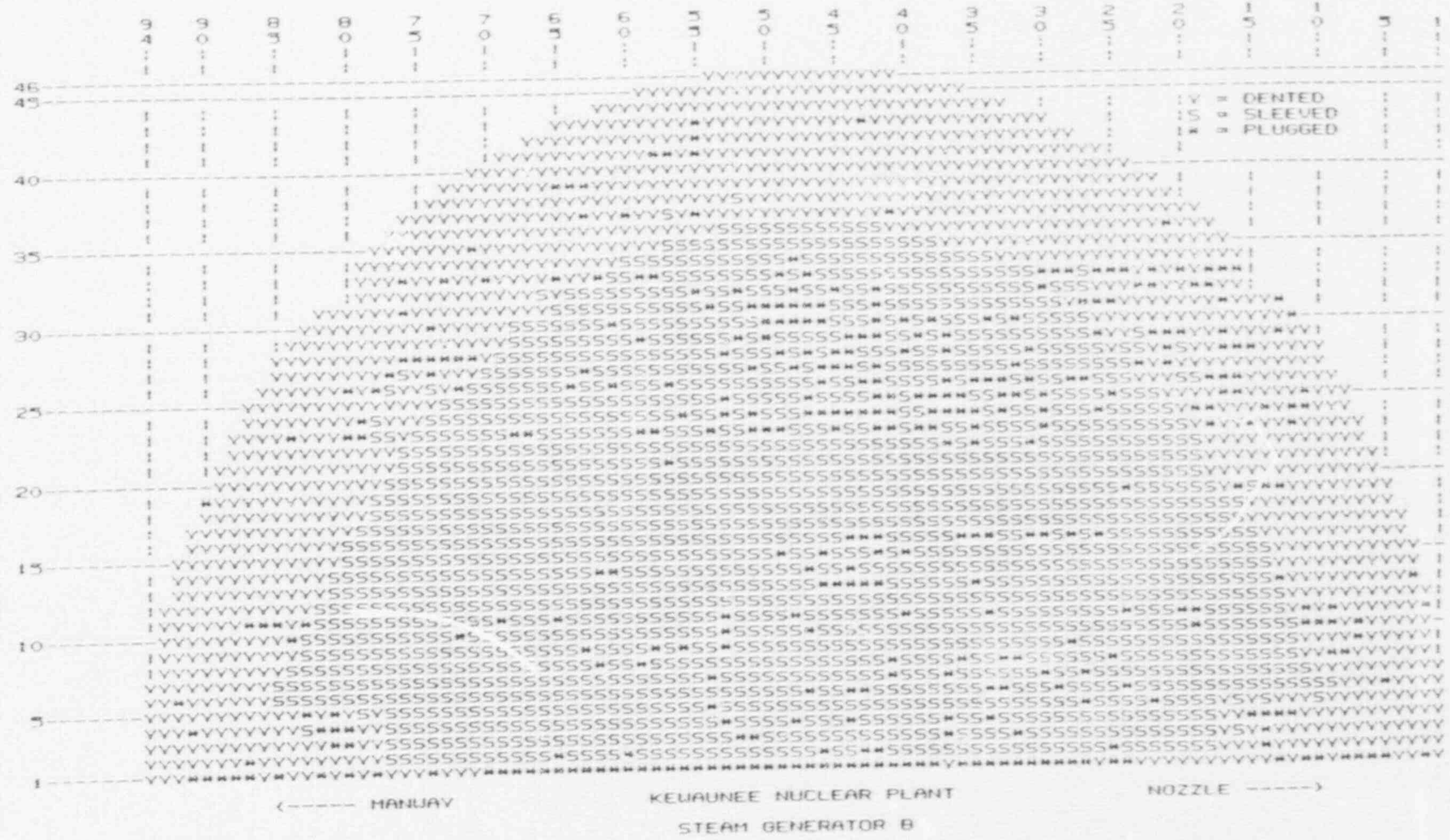


Figure 3-2 S/G "B" Dent Analysis Program

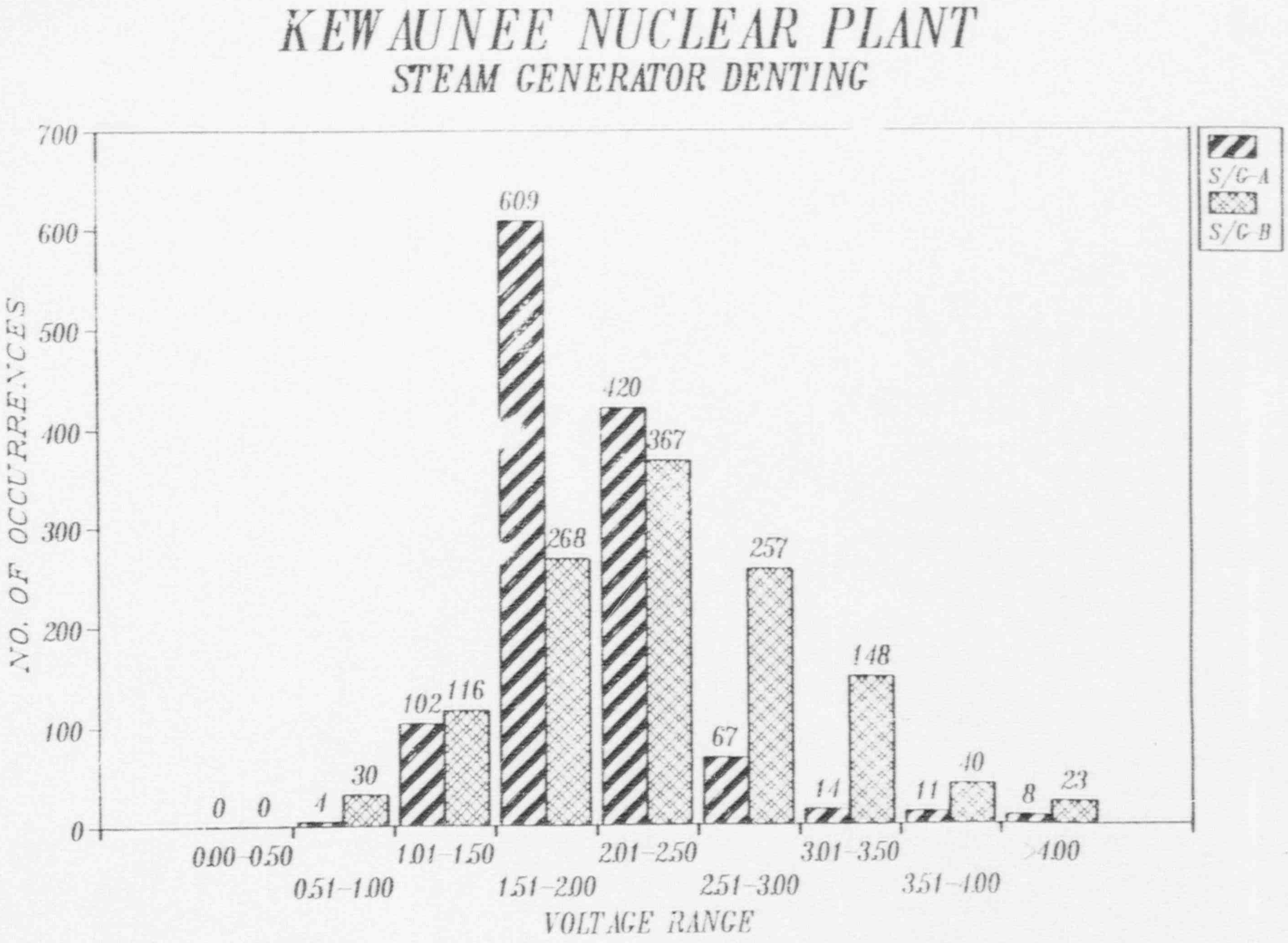
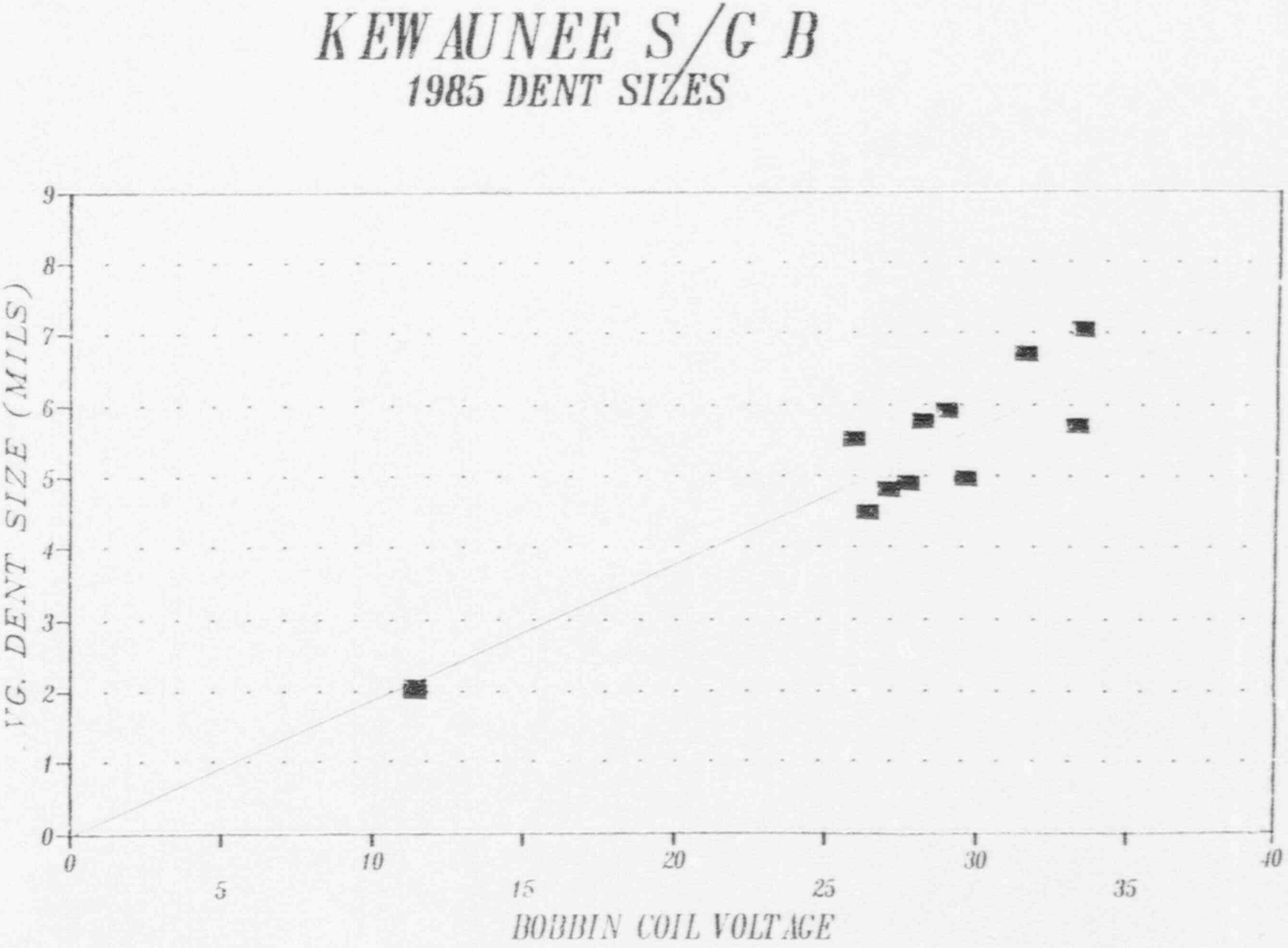
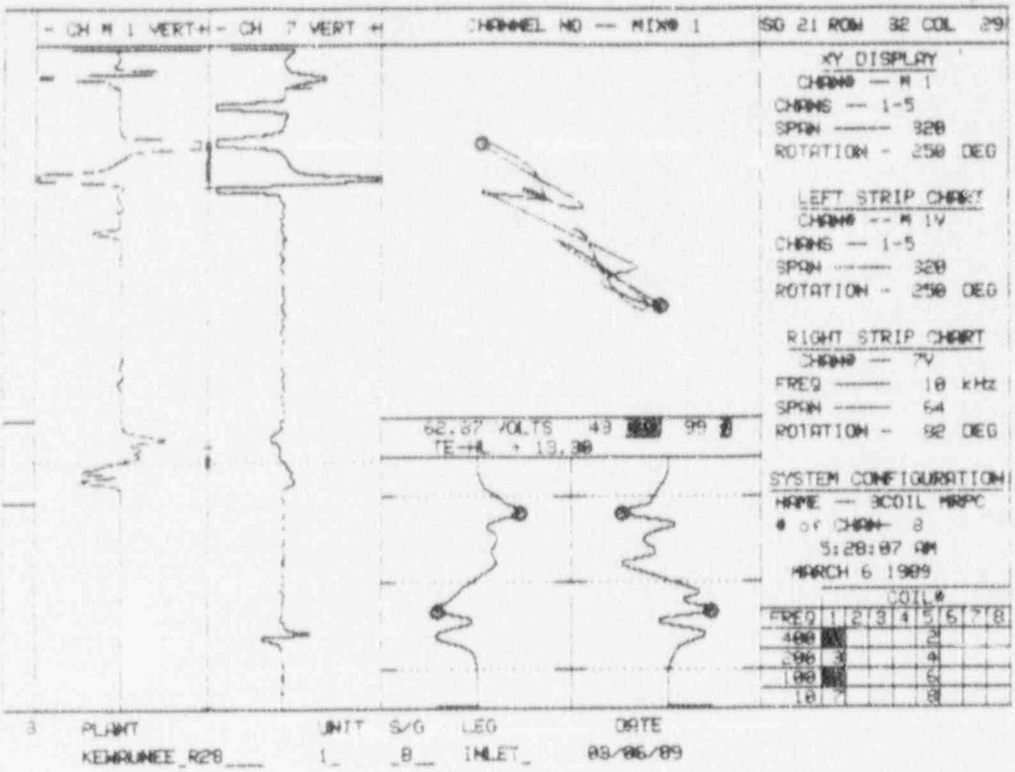


Figure 3-3 Comparison of Dent Voltages



KEWAUNEE S/G B
1985 DENT SIZES

Figure 3-4 Average Dent Size



SG 21 ROW 32 COL 29

XY DISPLAY
CHAN# — M 1
CHANS — 1-5
SPAN ——— 320
ROTATION - 250 DEG

LEFT STRIP CHART
CHAN# -- M 1V
CHANS — 1-5
SPAN ——— 320
ROTATION - 250 DEG

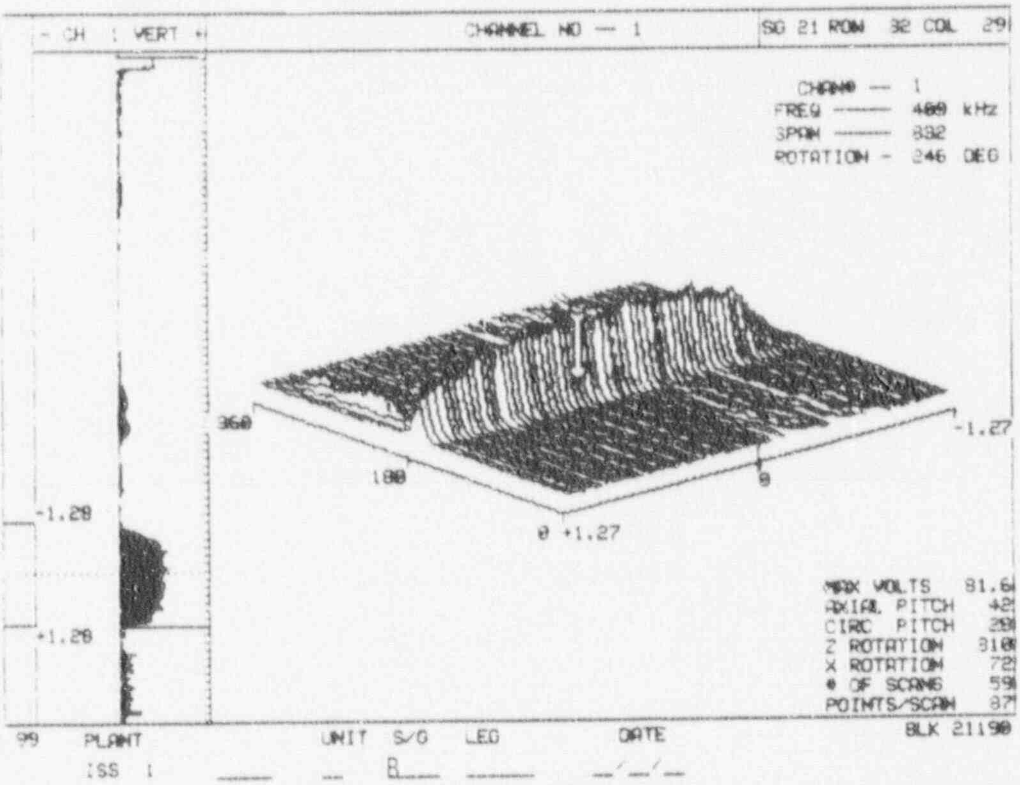
RIGHT STRIP CHART
CHAN# — 7V
FREQ ——— 10 kHz
SPAN ——— 64
ROTATION - 92 DEG

SYSTEM CONFIGURATION
NAME — 3COIL MRPC
# of CHAN— 8
5:28:07 AM
MARCH 6 1989

	COIL#							
FREQ	1	2	3	4	5	6	7	8
400	1				2			
200	3				4			
100	5				6			
10	7				8			

3	PLANT	UNIT	S/G	LEG	DATE
	KEWAUNEE_R20___	1_	_B__	INLET_	03/06/89

Bobbin Coil Data



SG 21 ROW 32 COL 29

CHAN# — 1
FREQ ——— 400 kHz
SPAN ——— 832
ROTATION - 246 DEG

MAX VOLTS 81.6
AXIAL PITCH 42
CIRC PITCH 29
Z ROTATION 310
X ROTATION 72
OF SCANS 59
POINTS/SCAN 87

BLK 21190

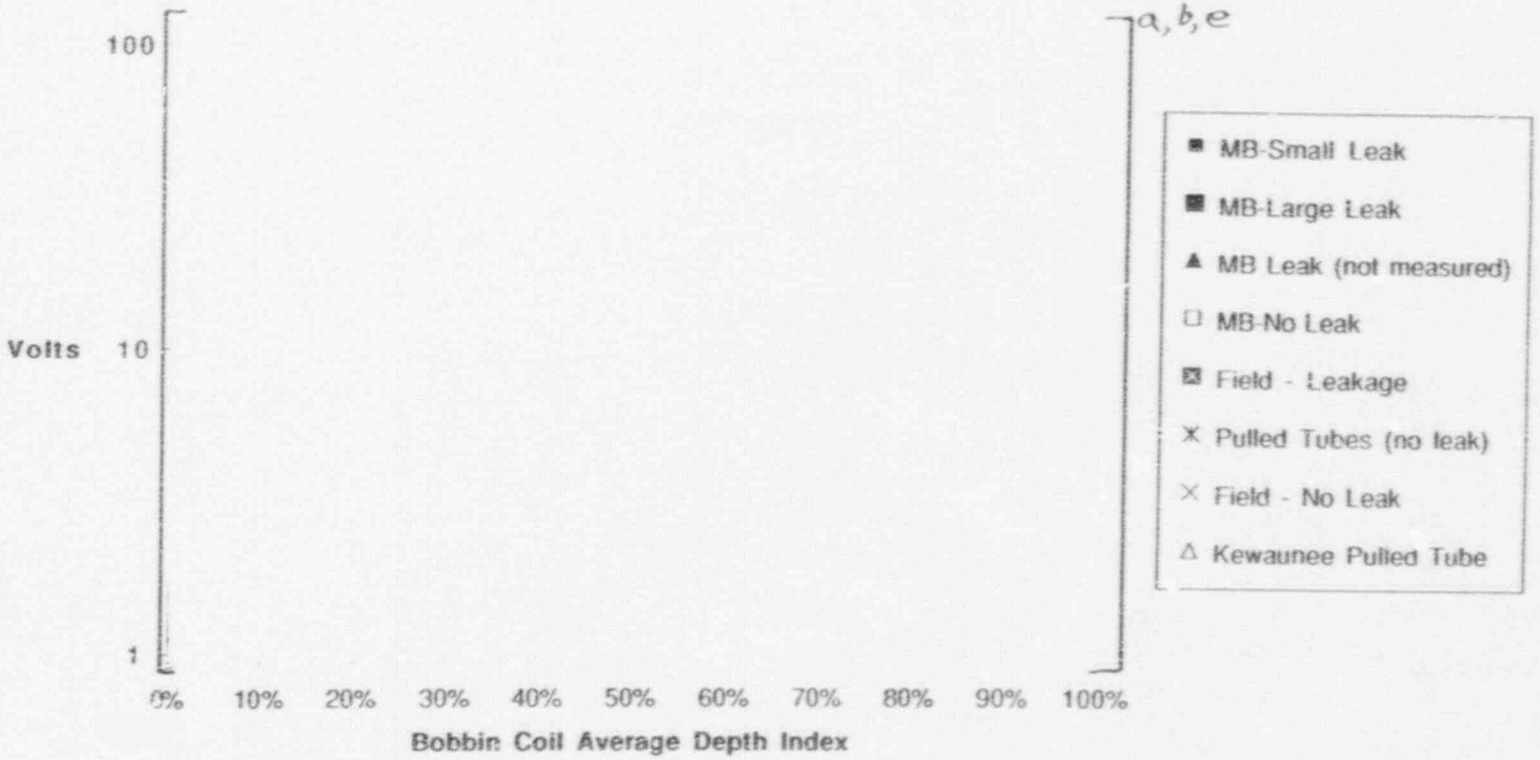
99	PLANT	UNIT	S/G	LEG	DATE
	ISS 1 ____	__	B__	_____	__/__/__

RPC Data

Figure 3-5 Inspection Results for Tube R32C29

Figure 4-1

Normal Operating ΔP Leak Rate Data Base



Note: Voltage Normalized to 4V for 20% ASME flaw.

Chart NΔP LkRt Data Base 12/12/90

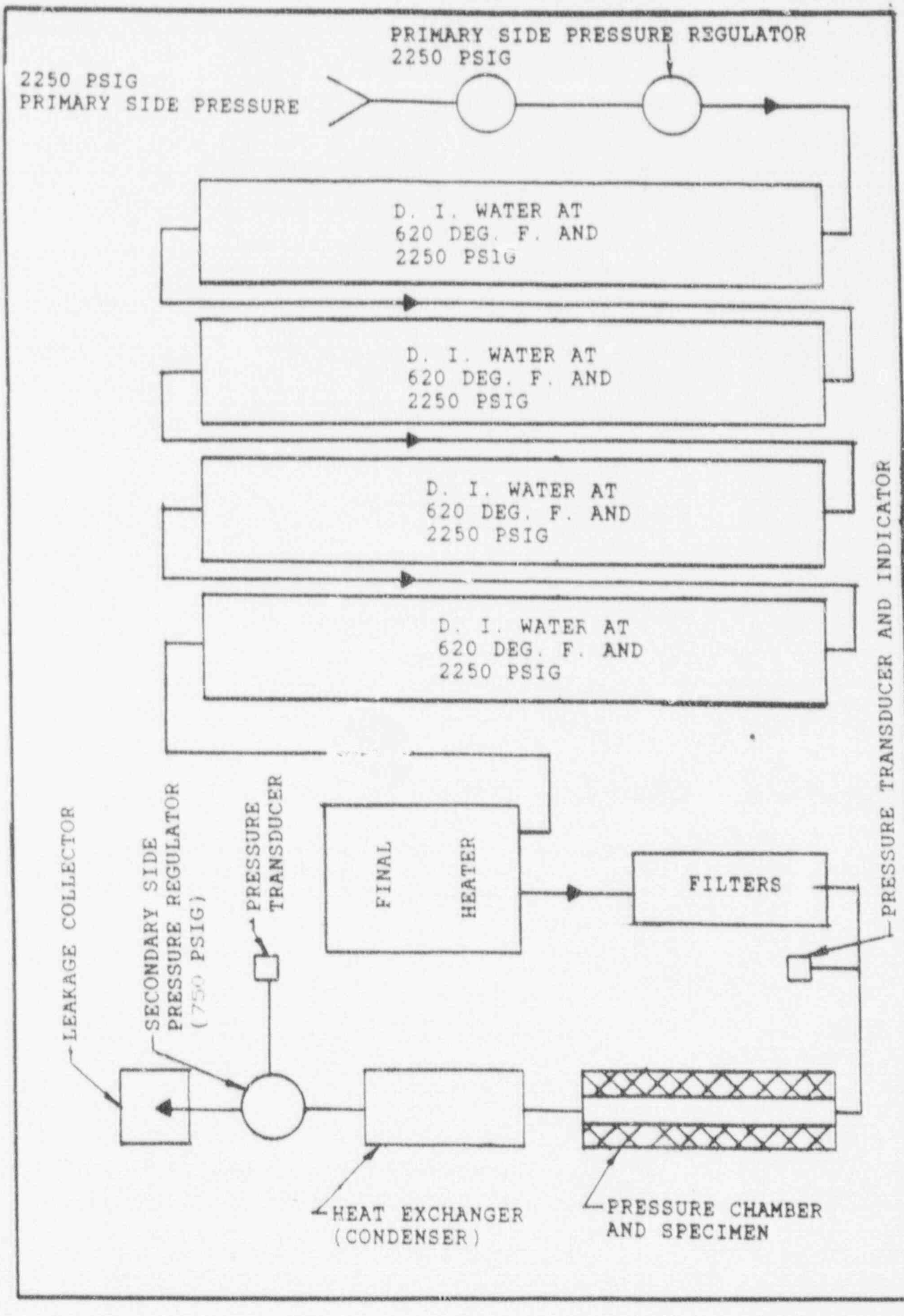
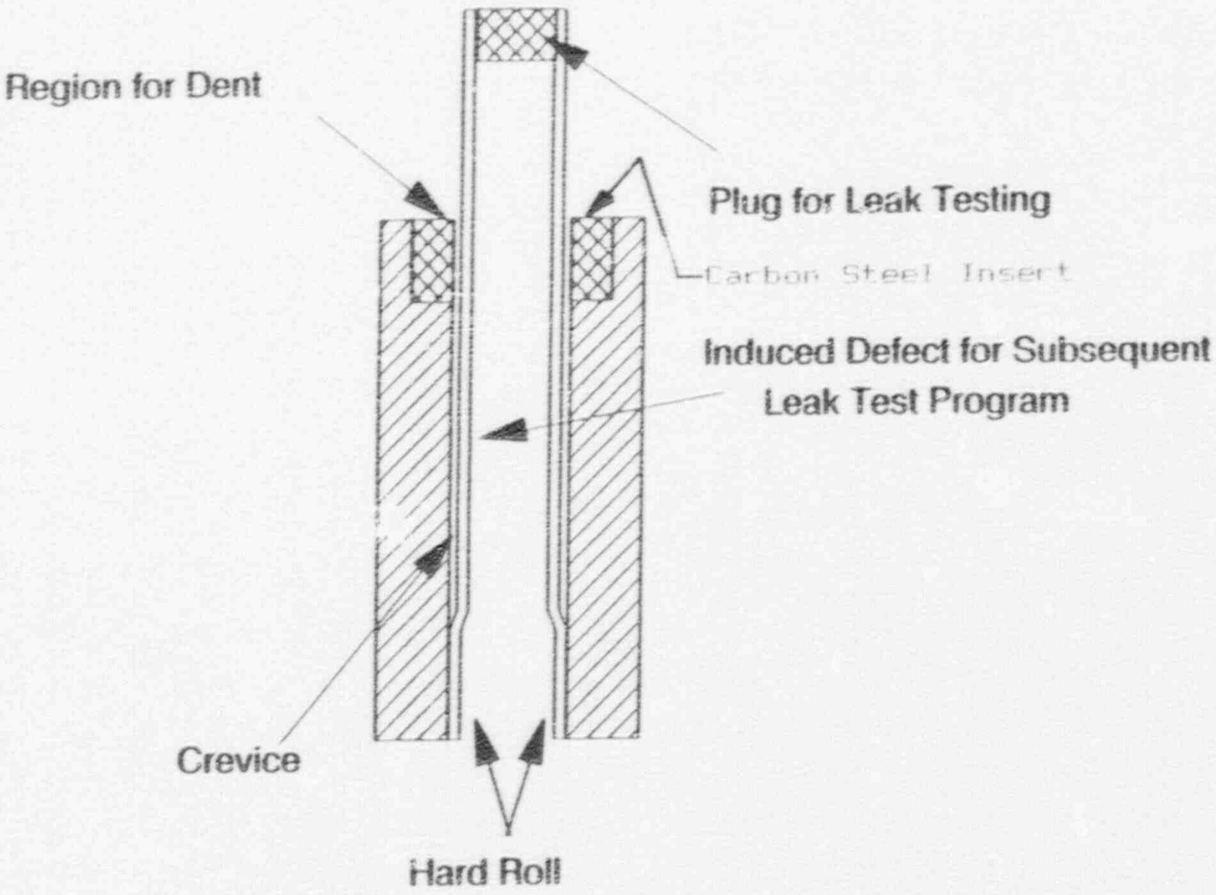


Figure 5-2 HIGH FLOW RATE SYSTEM

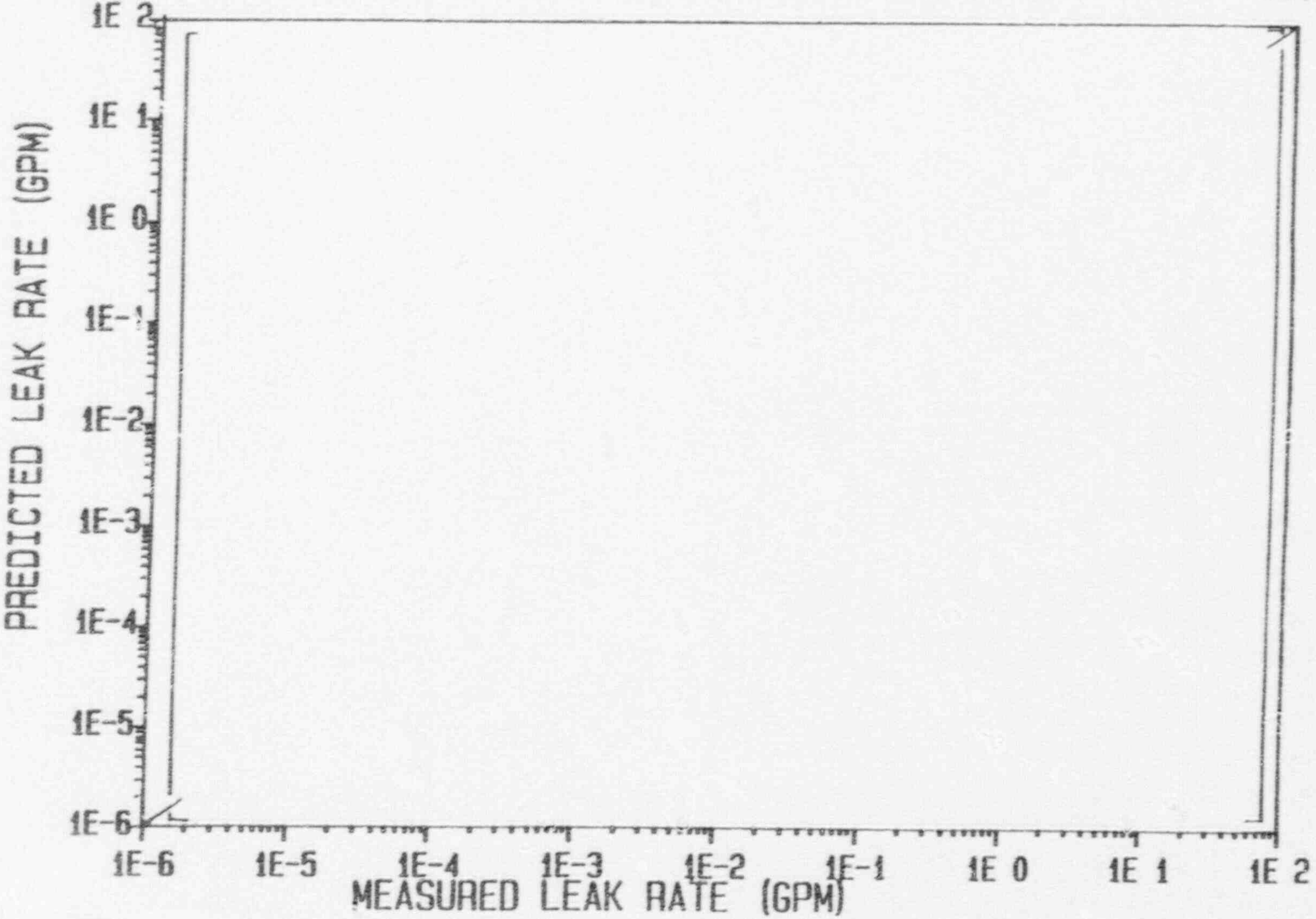


Schematic Illustration of Tubesheet Dent Simulant

Figure 5-1

FIGURE 6.1

COMPARISON BETWEEN PREDICTED & MEASURED LEAK RATES



a,c,e

FIGURE 6.2

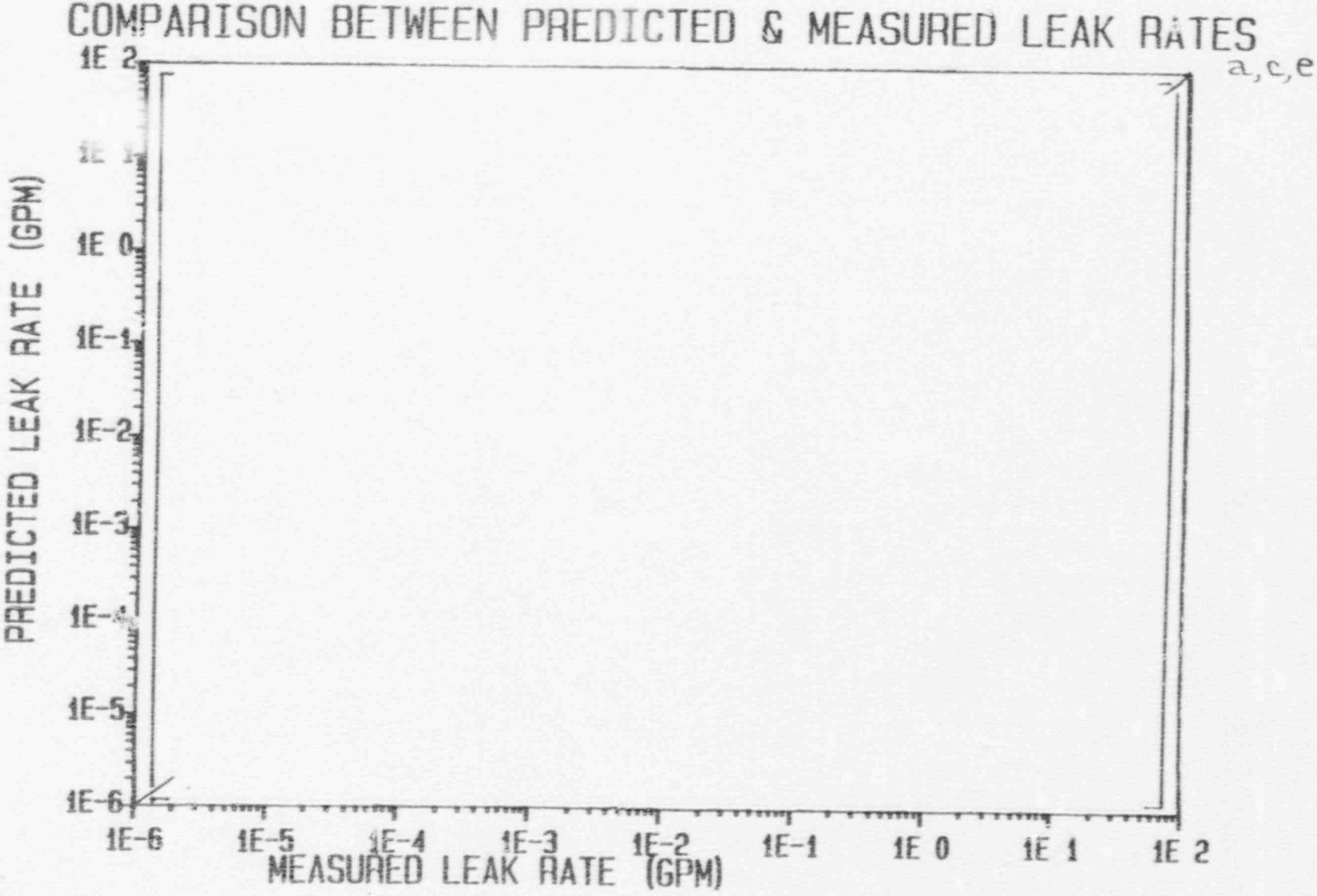

COMPARISON BETWEEN PREDICTED & MEASURED LEAK RATES
a,c,e
PREDICTED LEAK RATE (GPM)
1E 2
1E 1
1E 0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-6
1E-5
1E-4
1E-3
1E-2
1E-1
1E 0
1E 1
1E 2
MEASURED LEAK RATE (GPM)

FIGURE 6.3

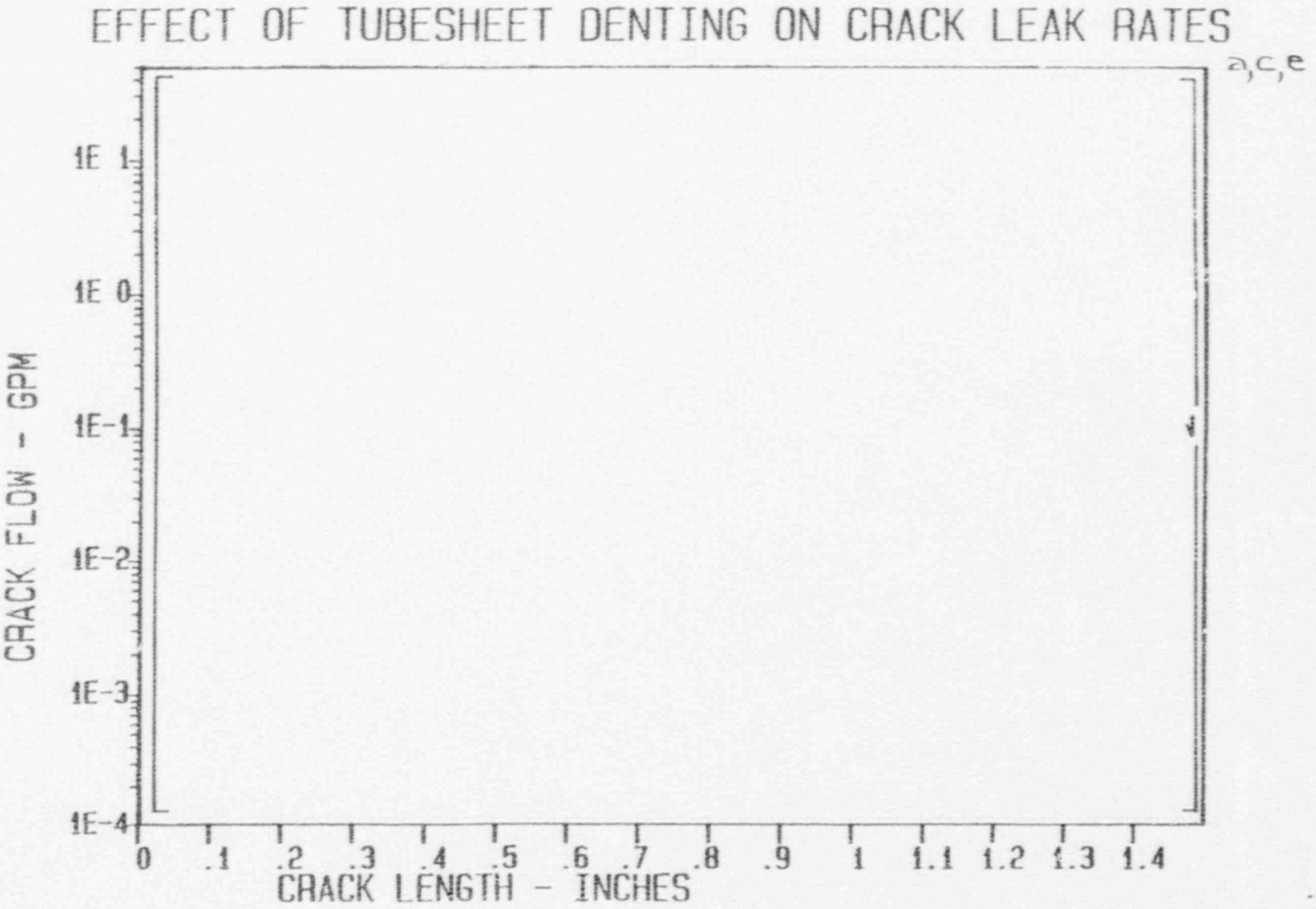
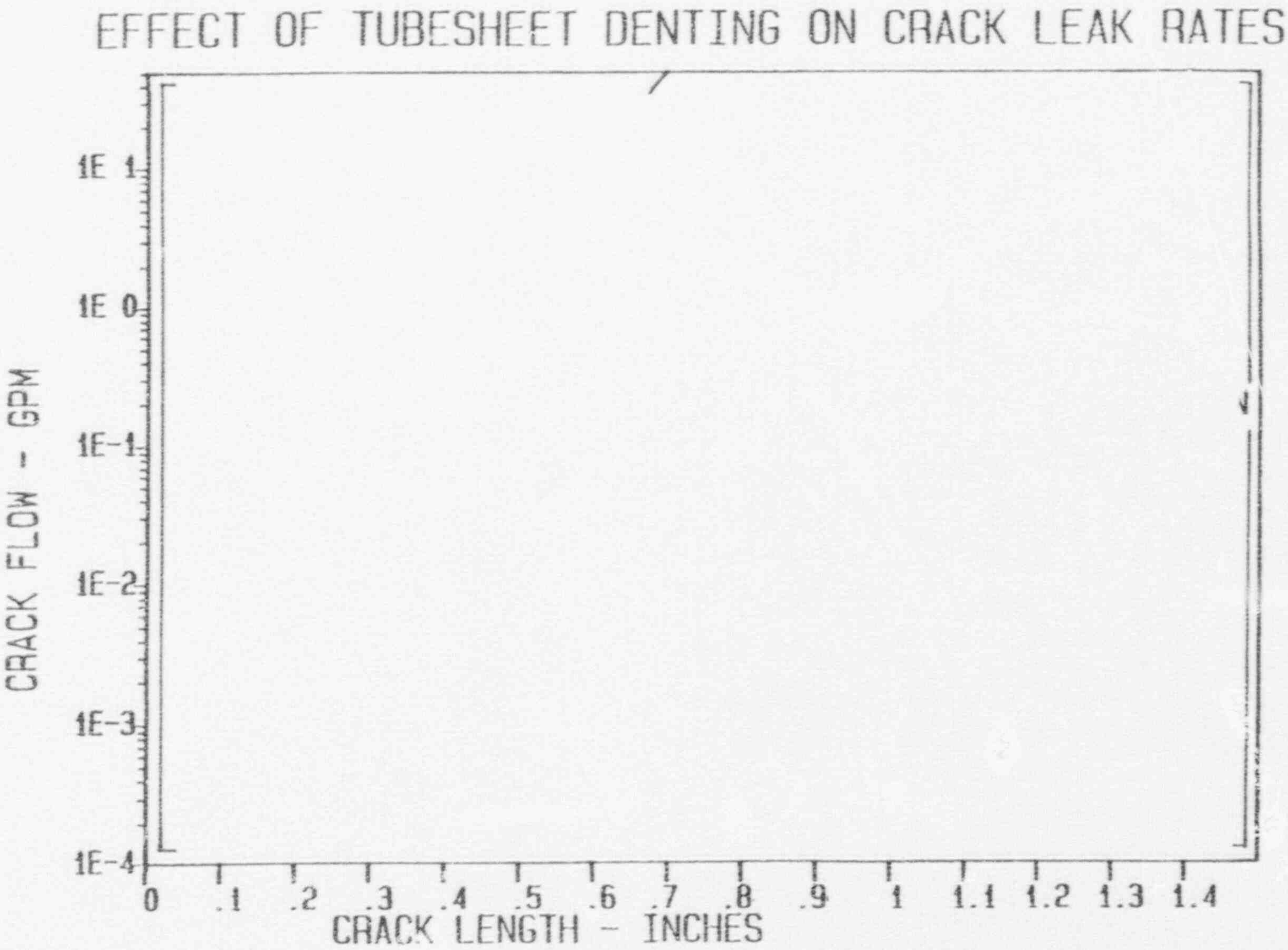

EFFECT OF TUBESHEET DENTING ON CRACK LEAK RATES
a,c,e
CRACK FLOW - GPM
1E 1
1E 0
1E-1
1E-2
1E-3
1E-4
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
1.1
1.2
1.3
1.4
CRACK LENGTH - INCHES

FIGURE 6.4


EFFECT OF TUBESHEET DENTING ON CRACK LEAK RATES

a,c,e