NON-PROPRIETARY

COMBUSTION ENGINEERING, INC.

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Palisades Steam Generator
Tube Repair Sleeving

Combustion Engineering, Inc.
Nuclear Power Systems
Windsor, Connecticut

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ABSTRACT

A technique is presented for repairing degraded steam generator tubes in pressurized water reactor Nuclear Steam Supply Systems (NSSS). The technique described alleviates the need for removing steam generator tubes from service due to loss of structural capabilities. In this manner, the design generating capacity of the original NSSS need not be reduced. This work was performed under contract with Consumers Power Company for use in the Palisades Plant steam generators.

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1.0 INTRODUCTION

In accordance with Regulatory Guide 1.83 (Reference 1-1), Pressurized Water Reactor (PWR) steam generators are periodically non-destructively examined using eddy current techniques. As a result of these examinations, tubes may be found that have sustained a metal loss or wall thickness reduction. Present technical specification requirements are to plug tubes when the wall thickness reduction reaches certain levels. In order to maintain tube integrity, even during postulated accident conditions such as a design basis earthquake, a main steam line break or a loss of coolant accident, tubes can become candidates for plugging long before their mechanical integrity is lost.

The installation of a structural sleeve to span the reduced wall thickness region would allow the tubes to be fully used until the wall is penetrated and leakage exceeds existing limits. Sleeving of such tubes would minimize the number of tubes that would require plugging and maintain the maximum heat transfer surface area and primary coolant flow area in the steam generator. Sleeving would therefore permit plant operation at maximum capacity under original design limitations without any loss of tubing mechanical strength.

The steam generator sleeving concept consists of installing, inside the steam generator tube, a slighly smaller diameter sleeve with a nominal .032 inch wall to span the degraded area of the parent steam generator tube. This system is schematically shown in Figure 1-1. Both ends of the inserted sleeve are hydraulically swaged into an interference fit with the parent tube. This hydraulic swaging is done away from the degraded portion of the parent tube in an area where no tube support structures exist, ensuring no effect on either the degraded area or the function of support structures. The rationale for installing the sleeves in this manner is that the criteria for plugging a steam generator tube is based upon ensuring that the structural strength of the tube is adequate to prevent rupture during postulated accident conditions. By installing a sleeve to span the degraded area, the structural integrity of the tube is reestablished. Even in the event of full penetration of the steam generator tube, the sleeve will provide the required structural link

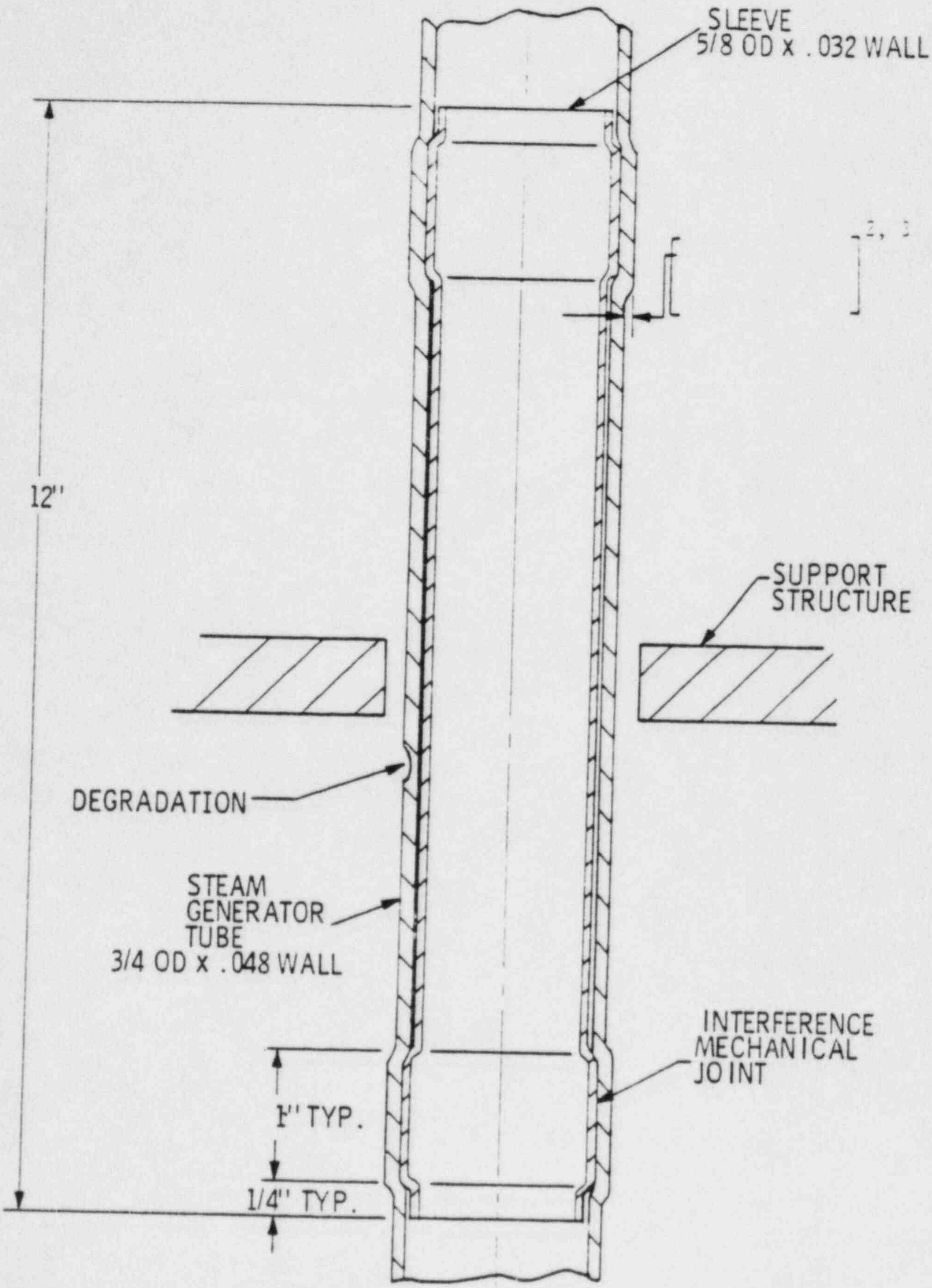
and a high restriction to leakage between the primary and secondary systems, thus ensuring that a double ended break of the tube cannot occur. The 0.032 inch wall of the sleeve is appreciably greater than the parent wall thickness of 0.043 inches with 64 percent degradation, which has been determined acceptable under the accident loads potentially produced by a loss of coolant accident (LOCA) in combination with a safe shutdown earthquake (SSE).

Sleeving of steam generator tubes has previously been undertaken by various organizations and several approaches to the problem have been developed. The primary objective of all of these previous approaches has been to insure leak tightness after the repair. The approach taken here is that the sleeve is to reestablish the structural integrity of the tube and that the need for absolute leak tightness is of secondary consideration. As the sleeve provides a structural link between two ends of even a severed tube, it prevents release of all but minute quantities of primary coolant to the secondary side.

While the information and data in this report pertain to the Consumers Power Company Palisades plant steam generators, the sleeving process is applicable to all PWR generators. To qualify the sleeve for other applications, specific sizing and environmental conditions must be addressed and would require reanalysis to insure applicability.

1.1 REFERENCES FOR SECTION 1.0

1-1 Inservice Inspection of Pressurized Water Reactor Steam Generator Tubes, USNRC Regulatory Guide 1.83, Revision 1, July 1975



STEAM GENERATOR TUBE SLEEVE

Figure 1-1

2.0 SUMMARY AND CONCLUSIONS

Development of the steam generator tube sleeve encompasses mechanical, chemical, metallurgical and analytical considerations. These processes demonstrate that the steam generator tube sleeve assembly described herein is structurally adequate to withstand normal, transient and accident conditions which occur or are postulated to occur in the Palisades steam generators. Fluid flow, coolant chemistry, thermal, and pressure conditions to date have experimentally shown no detrimental effect upon the integrity of the sleeve to tube joint and the resulting assembly strength. Structural analyses of the tube/sleeve assembly have established its integrity under design basis earthquake, main steam line break, loss of coolant accident, combinations of these and both primary and secondary flow induced vibrations. Based upon these experimental and analytical results, the sleeve is acceptable as a repair device to span a degraded area of a steam generator tube as it will provide a positive and reliable structural link between sound portions of the tube.

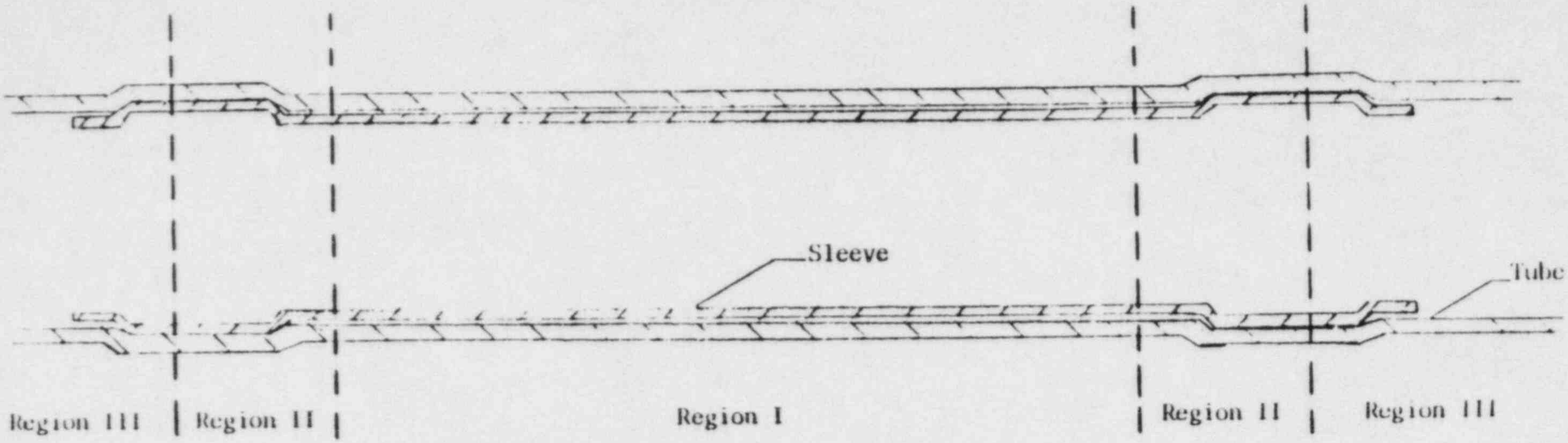
Sleeve joints will only be formed in tube areas where degradation is not detected. The sleeve is capable of providing adequate structural reinforcement in spanning circumferential or other tube wall defect regions up to 100 percent in depth. Once the tube degradation becomes a through wall hole, primary to secondary coolant leakage becomes a limiting condition per the plant operating technical specification. After a tube has been sleeved, it shall be plugged per Table 2-1 criteria. Region I, shown in the table, is the initially degraded area of the tube. The sleeve prevents the tube from separating even for a through wall tube defect of complete circumference. The sleeve may be degraded up to 34 percent in this region with a 100 percent wasted tube and still have strength enough to prevent a double ended break even under postulated accident conditions. In Region II, the inboard portions of the tube/sleeve expansion joint, some tube wall is necessary to ensure the tube to sleeve link. A 64 percent degraded tube is being verified adequate for ensuring this link. A maximum sleeve wall degrad-

ation of 34 percent was shown acceptable to maintain tube to sleeve joint integrity with the maximum permissible degraded tube. In the outboard portions of the tube/sleeve joint and in the tube only sections (Region III), the present Palisades plugging criteria for tube wall degradation is used since no joint strength results from tube material in this region.

Fourteen eight-inch sleeves of otherwise identical design were installed in the Palisades B steam generator during the March 1976 outage. These sleeves have performed without any detected interruption to normal plant operations. These sleeved tubes will be inspected by eddy current test and other techniques at the next outage. It is expected that corrosion and other testing will properly anticipate the results of these examinations.

Table 2-1

Maximum Allowable Operation Limits for Sleeved Palisades Steam Generators



Region I

Tube: 100% degradation acceptable

Sleeve: <34% degradation

Region II

Tube: <65% degradation

Sleeve: <34% degradation

Region III

Tube: Per current Palisades technical specification

Sleeve: 100% degradation acceptable.

3.0 ACCEPTANCE CRITERIA

The prime objective of the repair sleeve is to reestablish the structural integrity of the steam generator tube so that a double ended break cannot occur. Numerous tests and analyses were performed to demonstrate the capability of the sleeve to perform this function under normal operating and postulated service conditions. Design operating conditions for the Palisades steam generators are defined as:

Primary Side:	600^{o}F, 2100 psia (current)
	600^{o}F, 2500 psia (under consideration)
Secondary Side:	486^{o}F, 600 psia (maximum ΔP condition)
	514^{o}F, 770 psia (100% power)
	518^{o}F, 800 psia (under consideration)
	70^{o}F, 1300 psia (hydrostatic test)

Table 3-1 provides a summary of the criteria employed in demonstrating that the sleeve is an adequate method for repairing degraded steam generator tubes. Justification for each of the criterion is provided. The section of this report describing test or analyses which verify tube/sleeve characteristics for a particular criterion is referenced in the table.

3.1 REFERENCES FOR SECTION 3.0

3-1 Testimony of James Knight before the Atomic Safety and Licensing Board in the matter of Northern States Power Company, Docket Nos. 50-282 and 50-306

Table 3-1

Repair Sleeving Criteria

Criterion	Justification	Reference
1. Tensile separation of tube and sleeve by 1/4 inch to require greater than 1000 lb force.	Greater than 3/8 inch separation allows contact between adjacent steam generator tubes. For a maximum ΔP of 2500 psi an axial load of 330 lb force results.	Section 8.0
2. Rapid tube/sleeve ID pressurization to 2500 psi without total tube/sleeve separation.	Prevention of double ended tube break under MSLB conditions required, 2500 psi is maximum anticipated primary pressure.	Section 8.0
3. Collapse of tube/sleeve assembly at greater than 1300 psi external pressure.	Prevention of tube/sleeve collapse under LOCA conditions required, 1300 psi is maximum anticipated secondary pressure.	Section 8.0
4. Pressurization of tube/sleeve ID to 5100 psi without tube/sleeve burst.	Factor of safety greater than three required between anticipated maximum operating ΔP and that necessary for burst, 1700 psi is maximum normal operating ΔP.	Section 8.0
5. Thermal and pressure cycling to 600°F/2200 psi primary with 514°F saturation secondary for 100 cycles without loss of tube/sleeve functional integrity	Tube/sleeve joint integrity required for startup/shutdowns.	Section 8.0
6. Primary coolant flow at 600°F/2200 psi, 25 gpm for 1000 hours without loss of tube/sleeve functional integrity	Tube/sleeve joint integrity required for primary flow conditions.	Section 8.0
7. Exposure of tube/sleeve assembly to Palisades primary and secondary chemistries without loss of functional integrity, crevice corrosion or aggravation of tube corrosion.	Tube/sleeve assembly required to function under Palisades chemistries.	Section 6.0

Table 3-1

Repair Sleeving Criteria
(Continued)

Criterion	Justification	Reference
8. Tube/sleeve assembly functional integrity must be maintained during LOCA & SSE, MSLB & SSE, Reference 3-1 criteria and primary and secondary flow induced vibrations.	Tube/sleeve integrity required under postulated accident conditions.	Section 7.0
9. Nondestructive examination of tube and sleeve	Periodic examination of tubes and sleeves required to verify structural adequacy	Section 5.0

4.0 DESCRIPTION OF TUBE/SLEEVE ASSEMBLY

The physical layout of a tube/sleeve assembly is shown in Figure 1-1 and the Reference 4-1 and 4-2 drawings. The approach shown utilizes a sleeve of slightly smaller outside diameter than the steam generator tube inside diameter so that it can be inserted into the parent tube. After the sleeve has been positioned to span the questionable area of the parent tube, both ends of the sleeve are locally expanded until intimate contact with the parent tube is achieved. Then, by means of injecting a fixed volume of water, both the tube and sleeve are further expanded approximately [2, 3
inches] diametrically so that a swaged joint is formed. The tube will then maintain its mechanical integrity even in the event of the complete removal of the parent tube in the area spanned by the sleeve. The sleeve wall thickness is slightly less than the parent tube wall but of greater cross section than the minimum required for the parent tube. The sound sleeve is thus capable of fulfilling the structural design requirements of the steam generator tube. The mechanical attachment of the sleeve to the parent steam generator tube allows for easy inspection to prove that the interference joint has been successfully made. No cleaning or other surface preparation of the parent tube is required. In fact, the [ ] condition of the parent 2, 3
tube has been shown to improve the structural characteristics of the assembly and provides an effective barrier to corrosion.

The sleeve is a seamless annealed tube of Inconel 600 (ASTM-SB-163), with a [ ] coating. The Inconel 600 is the same as the steam gen- 2, 3
erator tube material thus preventing thermal stress ratcheting which would be possible with dissimilar materials. Further, Inconel 600, has well defined and previously accepted performance characteristics in a steam generator. The [ ] coating provides greater separation resistance between tube and 2, 3
sleeve. Annealing of the sleeve tubing removes cold work effects and lessens the tendency of the sleeve to spring back after having been expanded to form the tube/sleeve joint.

The sleeve inside diameter is [ ] inches to provide 2, 3
a narrow clearance fit for the U-cup seals of the forming tool.

The sleeve wall thickness of .032 inches is adequate on the basis of comparison with acceptable steam generator tube walls and allowable degradation. Tests and analyses have shown this to be true structurally. A sleeve length of 12 inches was selected to provide maximum defect spanning capabilities consistent with minimum installation clearances. A 12-inch length provides a margin of $\pm$ 2 1/2 inches in locating a sleeve to span two defects an anticipated maximum of four inches apart. The lead-in of 1/4 inch on the sleeve minimizes crevice corrosion and fretting difficulties, but permits taking full advantage of the strength of the expansion joint. The one inch long expanded mechanical interference joint provides adequate strength margins for the tube/sleeve assembly, yet does not compromise the span length of the sleeve. A diametrical deformation of[ ]provides an adequate structural fit without failing the tube or sleeve material or unnecessarily restricting secondary coolant flow. 2, 3

The mechanical interference joint is formed by hydraulic means. The hydraulic fluid used is demineralized water thus eliminating one source of corrosion producing elements to the sleeve or steam generator tube. The tool used to form these joints is shown in Figure 4-1. The tool expands the sleeve and tube by injecting hydraulic fluid into the region to be formed until a sufficient volume has been injected to expand the tube and sleeve the required amount. The fluid is maintained in the region to be expanded by two U-cup urethane seals. The hydraulic process was developed for its simplicity, speed and ease in adapting to a remote sleeve installation.

The tube/sleeve joint forming process is a three step process. Initially a
[ ]pressure is applied to the system for hydrostatic leak detection. 2, 3
After confirming that there is no leakage, pressure is stepped up to approximately[ ] to seat the sleeve against the tube. If there have been 2, 3
no leaks up to this point, a carefully controlled amount of hydraulic fluid is forced into the forming tool resulting in the tube and sleeve being expanded into a joint. The joint shown in Reference 4-1 is formed at[2, 3
]. Because of the injection of a fixed amount of hydraulic fluid, overexpansion of the tube and sleeve is precluded. The sleeve is carefully cleaned in the manufacturing process, and the cleanness is maintained to prevent the introduction of corrosive elements.

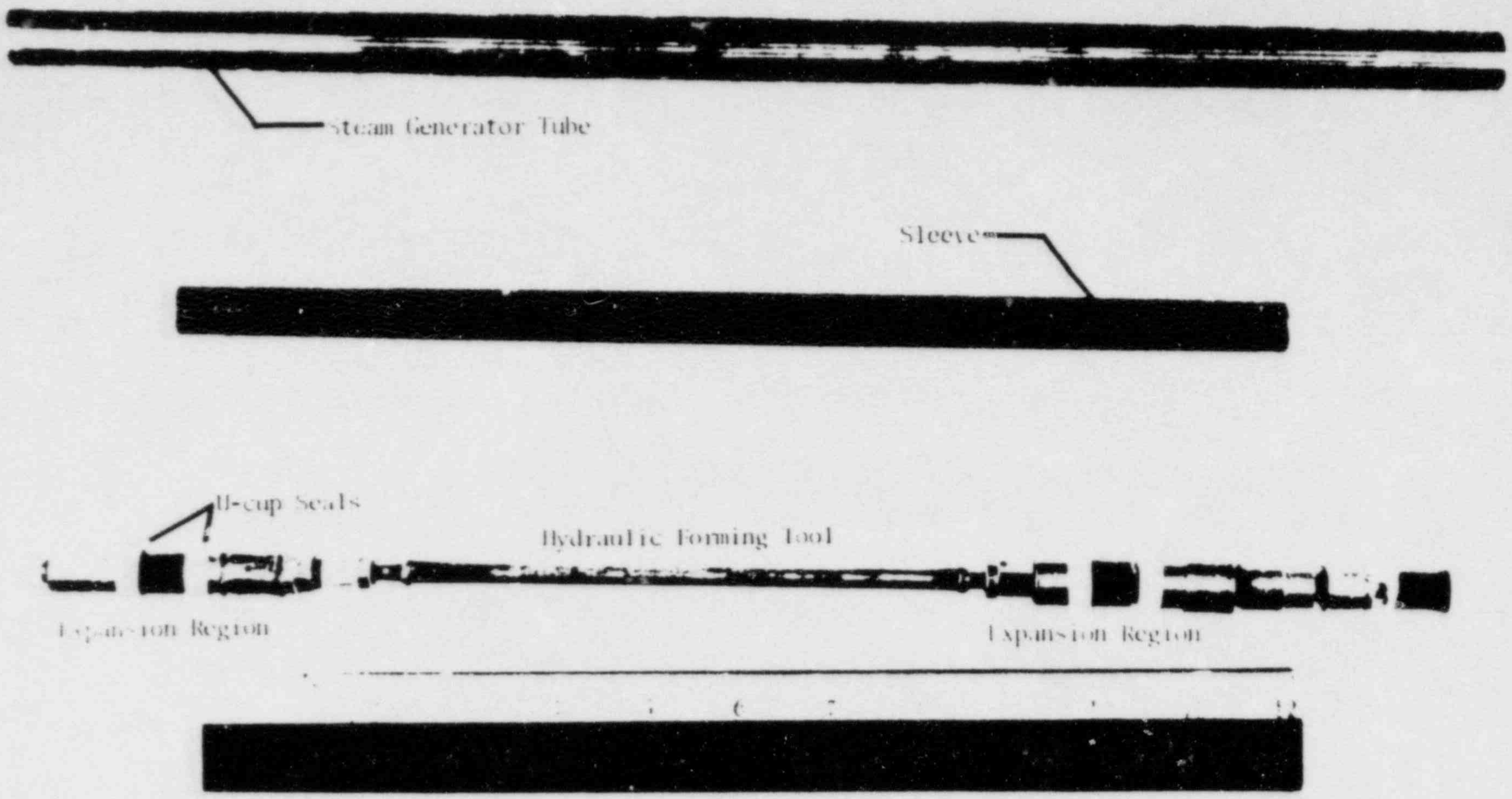
4.1 REFERENCES FOR SECTION 4.0

4-1 Sleeve Installation, CE Drawing No. D-19173-501-004-01

4-2 Long & Short Sleeves, CE Drawing No. C-19173-501-007-02

Figure 4-1

Tube, Sleeve and Hydraulic Forming Tool



5.0 NONDESTRUCTIVE EXAMINATION OF TUBE/SLEEVE ASSEMBLY

The tube/sleeve assembly is a primary pressure boundary and as such, it must be periodically verified that serious weakening of this assembly is not occurring. The ability to monitor the condition of the installed sleeve and the parent tube for this potential weakening is essential to the viability of the sleeving concept.

5.1 SUMMARY AND CONCLUSIONS

Initial inspections of the expanded portions of the steam generator tube/sleeve assembly with the standard .540 inch diameter eddy current probe produced signals which saturated the test equipment and made evaluation of defects impossible. Techniques have been developed for eddy current testing both the expanded and unexpanded regions of sleeved steam generator tubes. These techniques, used in combination with considerations of primary to secondary leak rates, will provide conservative criteria for determining tube and/or sleeve wall degradation. The techniques developed are in conformance with the guidance supplied in Reference 1-1.

For either the expanded or unexpanded region of the assembly, it is possible to detect significant amounts of degradation penetrating from the tube outer surface, to differentiate between this condition and any other combination of degradation which might exist, and to estimate the depth of penetration from the Lissajous pattern phase angle. This can be done uniquely on the basis of one examination (see the phase angle ranges of 110^0 to 160^0, 110^0 to 160^0, and 210^0 to 310^0 in Figures 5-1, 5-2 and 5-3, respectively). Utilizing the techniques developed in this program, 3/16 inch diameter (in conformance with industry ECT standards) tube wall degradation proceeding from the outer surface was detected when the penetration reached about 40% of tube wall.

Degradation which has nearly penetrated the tube wall, or has fully penetrated the tube wall either with or without minor sleeve outside surface degradation; and degradation of the tube inner surface with no sleeve degradation are both readily detectable in either the expanded or unexpanded

region of the tube/sleeve assembly. These two classes of degradation cannot, however, be distinguished from each other during one examination on the basis of the defect signal phase angle. (See the phase angle ranges of 70° to 110°, 50° to 110°, and 160° to 210° on Figures 5-1, 5-2 and 5-3, respectively). The above degradation situations can generally be separated on the basis of phase angle results from a previous examination which shows the defect. In certain situations, consideration of primary to secondary side leak rate may be useful in making the subject discrimination. With the program eddy current test techniques, 3/16 inch diameter tube wall degradation proceeding from the inner surface can be detected with confidence when the penetration reaches about 35 percent of tube wall. It is not possible to estimate the depth of degradation proceeding from the tube inner surface on the basis of the defect signal phase angle.

Degradation which has fully breached the tube wall and penetrated some distance into the sleeve, and degradation which has penetrated into the sleeve wall from its outer surface without tube involvement can be detected in either the expanded or unexpanded region of the tube/sleeve assembly. Discrimination between these two classes of degradation can be accomplished in the same manner described for the two classes of degradation in the previous paragraph (see the phase angle ranges of 0° to 70°, 350° to 50°, and 40° to 160° on Figures 5-1, 5-2 and 5-3, respectively). Once discrimination between these two classes of degradation is made, an estimate of the depth of penetration can be made from the defect phase angle for either category of degradation. A 3/16 inch diameter sleeve degradation proceeding from the sleeve outer surface can be confidently detected when the penetration reaches about 30 percent of the sleeve wall. (See Figure 5-17 d). Samples are being made to investigate the minimum detectable level of sleeve degradation.

Inspection of the expanded region of the tube/sleeve assembly and the adjacent area at the end of the sleeve is performed with an axially wound differential coil probe (See Figure 5-4). This probe must be rotated 360° with a fixed axial position, then moved an appropriate axial increment and again rotated 360°. This procedure is repeated until the required coverage is completed. For operation at a single frequency, 200 KHz gives the best overall results for the tube/sleeve assembly. The phase angle versus depth

of defect curve for this test applied to the subject region is presented in Figure 5-1. A shortcoming of this probe design is its relative insensitivity to axisymmetric defects (such as wastage of the same depth 360° around either the tube or sleeve at a given axial position). This is analogous to the insensitivity of the circumferentially wound probe to long axial defects with gradual changes in depth.

For the tube/sleeve assembly region between the expansion joints, inspection may be performed as indicated in the previous paragraph, or the examination may be made with the standard .540 inch flex probe operated at 400 KHz. The coverage of the flex probe is limited to areas removed at least 3/8 inch from the edge of the expanded region. The phase angle versus depth of defect curve for the flex probe test at 400 KHz is presented in Figure 5-3. The same type curve for the axially wound probe operating at 200 KHz in this region is presented in Figure 5-2. The final choice between these test options will consider both the required examination time for the entire tube/sleeve assembly and the inspection advantages associated with each approach.

More specific results and conclusions from this test program are presented in Section 5.4.

5.2 TEST EQUIPMENT

The test equipment utilized in this program included a number of experimental probes as well as the following test hardware:

1. The Eddy Current Testor (EM 3300)

   This is the signal conditioning unit which allows the selection of necessary test parameters (frequencies), excites the test probe, and whose output contains the eddy current information which may be recorded and/or displayed on a self-contained oscilloscope. The currently recommended settings on this unit are as follows:

a. From .5 to 5 volts/division on vertical and horizontal channels.

b. Sensitivity (emit gain) of approximately 50 for the flex probe and 70 for the axial probe tests.

c. Frequencies of 200 KHz for the axial probe and 400 KHz for the flex probe inspections.

2. The Data Reduction System

This consists of a vector analyzer (electronic protractor) which is used in conjunction with the memory storage oscilloscope to measure the phase angles from the signals of the artificial imperfections in both the sleeve and the tube. These phase angle readings are used to establish a phase angle versus depth curve for predicting depths of imperfections without actual physical measurement.

5.3 CALIBRATION STANDARDS

In order to evaluate the capability of eddy current test techniques, tube/sleeve assemblies were fabricated which contained a significant variety of degradation depths and locations. Figure 5-5 illustrates the range of locations in the assembly for the artificially introduced defects.

For defects on the tube and sleeve outer surface fully in the unexpanded region (defect locations 15 and 16 of Figure 5-5), the range of depths studied varied from just over 20 percent to 100 percent of wall for both the sleeve and tube. Defect location 17 on the tube inner surface was studied for two depths. This area of the tube and sleeve represents the location of original degradation. Inspection in this region of the tube allows a record to be kept of wall thickness changes. Full degradation of the tube wall will require special attention to any sleeve degradation because of strength considerations (Table 2-1).

Defect locations 3 through 14 of Figure 5-5 are located in, or closel adjacent to, the critical tube/sleeve assembly expansion joint. It is

in this region that the tube/sleeve axial strength is developed. A knowledge of any degradation in either the tube and/or the sleeve in this area is important in determining the continued structural adequacy of the repair sleeve and tube. Defect depths studied in the subject locations vary from about 20 percent to 100 percent of the component walls.

For defects on the tube outer surface near the end of the sleeve (defect locations 1 and 2 of Figure 5-5) degradation is introduced to allow a determination of how the eddy current test capabilities are influenced by the sleeve termination. Defects studied in these locations are approximately 40 percent of the tube wall.

Essentially all tube and sleeve degradation areas were introduced with an electric discharge machine (EDM). In three areas on the tube outer surface, wastage was simulated with a controlled acid attack. In two areas of the tube and two areas of the sleeve, intergranular attack (IGA) was induced at a location which was to correspond to the middle of the bulge after expans[illegible]. Figures 5-6 and 5-7 present detailed information on those calibration tube defects primarily utilized in the program to this point.

The capability to perform meaningful eddy current examination of defects at locations 1 through 17 is sufficient to demonstrate the ability to evaluate all probable significant areas of degradation in the tube/sleeve assembly. In certain circumstances, consideration of primary to secondary leak rates will assist in such an evaluation. Initial results from the eddy current evaluation of the defects at the subject locations are presented in Section 5.4. (Final results including a characterization of the statistical variation in phase angle as it relates to defect depth will be presented later.)

5.4 RESULTS

5.4.1 EXPANDED REGION OF TUBE/SLEEVE ASSEMBLY

In and closely adjacent to the expanded area of the tube/sleeve assembly (defect locations 3 through 14 on Figure 5-5) phase angle versus defect depth relationships were studied for various probe concepts and various test frequencies. The result of these studies indicated that an axial

wound differential coil probe rotated at a series of fixed longitudinal positions in the expansion provided the most success of any of the candidate probes (See Figure 5-4). Use of this probe configuration in the stated manner improved the signal to noise ratio such that significant defects could be detected and have their signals interpreted. In this discussion, noise is the signal from a defect free bulge while signal refers to the response from a defect in the bulge. Figure 5-8 shows the typical noise signal for various positions in the expanded area tested with the axial would probe. In general, these signals are a very flat pattern of from 1 to 5 volt amplitudes. The signals obtained while the axial probe is centered at the outboard end of the expanded region are not as clean as would be desirable. This is thought to result from the fact that in this position, a portion of the probe coil extends beyond the end of the sleeve, and the end of the sleeve may not lie in one plane after the expansion operation. In some cases, the signals for a 360^0 probe rotation at this position resemble a defect signal (see the lower right hand illustration on Figure 5-8). Of course, defect signals are traced much more rapidly if they have limited circumferential extent. By proper frequency selection, these noise signals can be placed at a phase angle separated from most defect signals of interest. As a matter of background information, the signal from a "clean" expansion tested with a standard .540 inch diameter flex probe typically has a signal voltage of about 70 volts. This total signal cannot be displayed on present equipment; however, since it saturates when input signals reach about 15 volts.

The optimal frequency for testing the expanded region of both the sleeve and tube with the axial wound probe is approximately 200 KHz. At this frequency, good detection capability is possible in both the sleeve and the tube. In addition, phase angle results for any given depth of defect are reasonably close to the values for the same defect depths in the unexpanded region. This could reduce the importance of knowing the precise longitudinal position of the probe in the assembly if the decision is made to test the entire length of the tube/sleeve assembly with the axial wound probe.

Figure 5-1 presents a plot of phase angle versus defect depth for the axial wound probe operating at 200 KHz on the defects at locations 1 through 14 (See Figures 5-5, 5-6 and 5-7). Figure 5-9 present signals for defects of various depths penetrating from the tube outer surface. Figure 5-10 presents signals for defects initiating at the tube inner surface and penetrating part of the way through the wall, with no sleeve degradation. Figure 5-11 presents signals for defects which completely penetrate the tube wall and all or part of the sleeve wall as well as signals for defects which start at the sleeve outer surface and penetrate part of that component wall with no degradation of the parent tube.

For the test results depicted on Figure 5-1, calibration is accomplished by setting the phase angle of the signal from a .080 inch diameter tube through wall hole at 90°. With this setting the locus of the noise signal from the clean bulge lies essentially on the horizontal plane (phase angle of 0). This setting is arbitrary; however, the interval between these two signals will remain the same at this test frequency regardless of where the phase angle for the calibration hole is set. It should be noted that probe motion phase angle cannot be measured consistently with the axial wound probe.

An evaluation of Figure 5-1 indicates that there are three distinct regions of the curves. Region 1 contains phase angles from approximately 110° to 160°. These phase angles represent degradation in the tube only, penetrating from the outer surface. The range of depths represented by these phase angles are from almost complete penetration of the tube down to degradation near the limits of detectability . Numerically this is from about 90 percent of the tube wall (55% of combined wall) to 40 percent of the tube wall (25% of combined wall). Note that in Region 1 the phase angles are unique and allow the analyst to identify the component being degraded and make an estimate of the depth of degradation on the basis of a single examination.

Region 2 contains phase angles from about 70° to 110°. This phase angle range may represent two basic classes of degradation. The first is degradation penetrating from the tube outer surface and going almost completely through the tube wall, or completely penetrating the tube wall

and involving a portion of the sleeve. The second class of degradation involves penetration of the tube from its inner surface. As an example, the phase angles for complete penetration of the tube wall from the outer surface and a 40 percent of tube wall degradation penetrating from the tube inner surface are essentially the same (around 90^0 to 100^0). It is necessary to use the results from a previous examination which shows the defect to distinguish between these two classes of degradation. Once this is done, an estimate of the depth of degradation penetrating from the outer surface can be made on the basis of the phase angle. Presently it is not possible to make this estimate for degradation penetrating outward from the tube inner surface.

Region 3 contains phase angles from 0^0 to about 70^0. This phase angle range may represent two basic classes of degradation. The first is degradation which has completely penetrated the outer tube and a part or all of the sleeve. The second class includes degradation penetrating from the sleeve outer surface part or all the way through the sleeve with no tube degradation. As an example a phase angle of 50^0 could represent either complete penetration of the tube wall and approximately 80 percent penetration of the sleeve or about 30 percent penetration of the sleeve wall from the outer surface with no tube degradation. Again, it is necessary to use the results from a previous examination which shows the defect to distinguish between these classes of degradation. Limited selective leak testing might also allow this distinction to be made. Once the classes of degradation are separated, estimates of the penetration depth can be made from the phase angle for either category of degradation.

The previously described situations relative to distinguishing between degradation in various locations, and the ability to estimate their depth exist for all test frequencies evaluated (from 100 KHz to 600 Khz).

One other point of interest should be noted on Figure 5-1. The data for outer surface tube degradation at the end of the sleeve, and just beyond the sleeve termination, do not fit the curve for defects "inside" the tube/sleeve assembly. This is considered to result from the fact that

testing defect locations 1 and 2 are essentially testing the tube without the sleeve, and different characteristics are to be expected. Future work will have to define appropriate curves for this region by implanting a range of defect depths for testing (presently only 40 percent nominal depths of degradation are available).

A shortcoming associated with the test using the axial wound probe rotated in the tube is the relative insensitivity to axisymmetrical defects.

5.4.2 UNEXPANDED REGION OF TUBE/SLEEVE ASSEMBLY

For this region of the assembly, inspection may be performed with the axial wound probe at 200 KHz operating with circumferential motion. This would be the same type of inspection used in the expanded region. Figures 5-12, 5-13 and 5-14 present signals for defects in the unexpanded region of the tube/sleeve assembly tested in this manner. An equally valid option is to do the inspection with a standard .540 inch flex probe operating at 400 KHz. This option would only be valid for regions of the tube/sleeve assembly removed at least 3/8 of an inch from the edge of the expansion. Figures 5-15, 5-16 and 5-17 present signals for defects in various areas of the unexpanded region produced by tests with the .540 inch diameter flex probe. The choice between these two techniques will be made after an evaluation of the inspection speed obtainable with the axially wound probe and the relative ability of the two probes to examine defects in the vicinity of dents.

Figure 5-2 presents a plot of phase angle versus defect depth for the axial wound probe operating at 200 KHz on degradation in the subject region. All the results and conclusions for this situation are virtually unchanged from those presented in Section 5.4.1, except that the phase angles for Regions 2 and 3 are slightly different. The similarity between Figures 5-1 and 5-2 indicate that results for the axial probe are not strongly influenced by the particular axial position of the probe along the tube/sleeve assembly during the test, except that the influence of axial position is strong at the end of the sleeve.

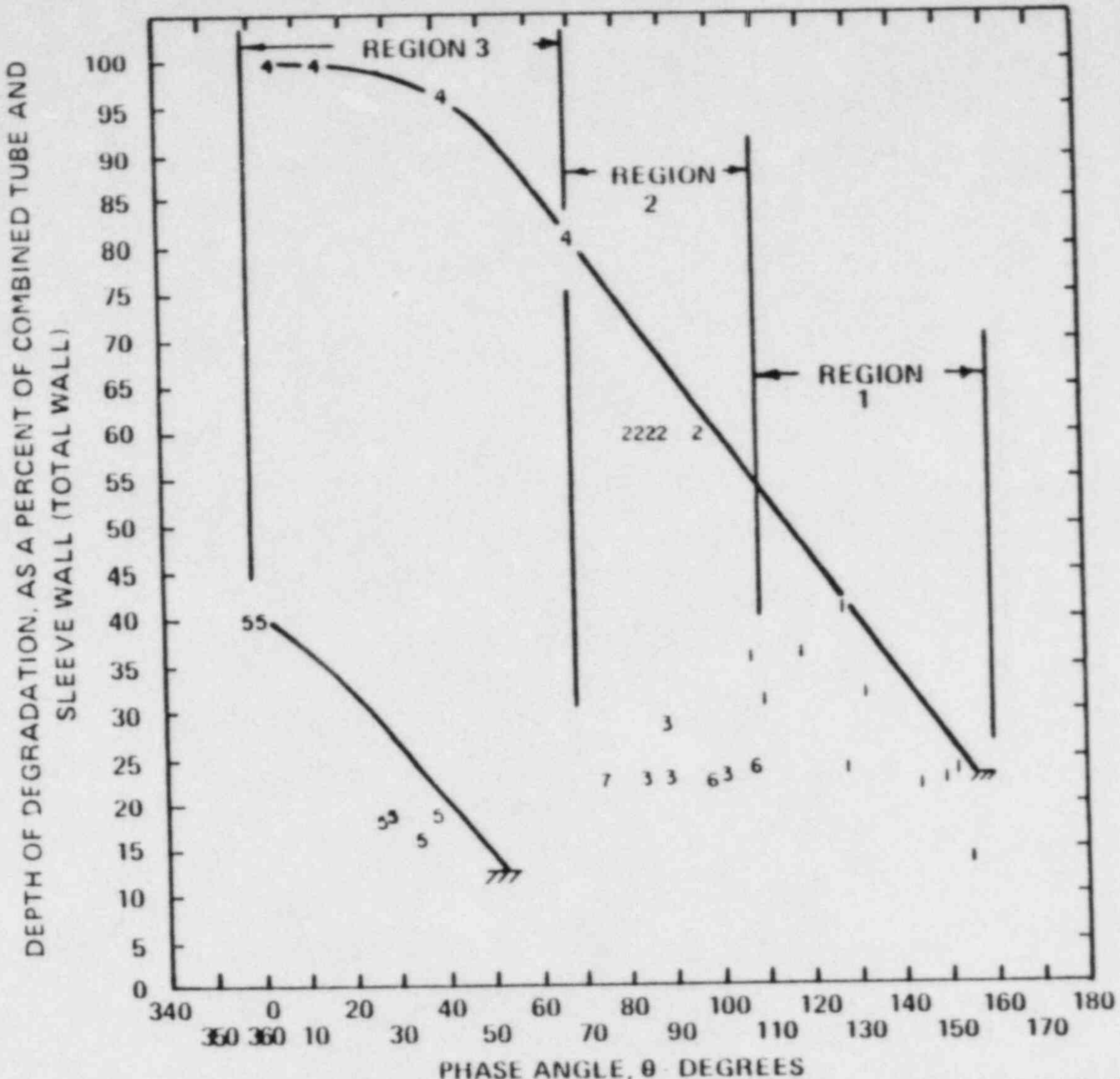
If the decision is made to examine the unexpanded area of the tube/sleeve assembly with a standard .540 inch diameter flex probe, then the phase angle versus depth of defect curve presented on Figure 5-3 is appropriate for a 400 KHz test. From an examination of Figure 5-3, it is obvious that the conclusions relative to distinguishing between degradation in various areas and the capability to estimate degradation depth from Section 5.4.1 are also applicable for this test. The calibration for the tests which define Figure 5-3 is accomplished by setting the phase angle of a signal from a .100 inch diameter hole through the tube and sleeve at approximately 40°. With this initial setting the probe motion line has a phase angle of about 10°. Definition of the phase angle for the probe motion line is more unreliable in a sleeved tube than in a standard steam generator tube because there is little actual motion of the probe in the sleeve. Because of this, it is not used in the calibration approach.

In several areas it has been noted that certain pairs of degradation conditions give essentially the same phase angle (tube through wall hole and tube inner surface degradation without sleeve degradation or tube through wall hole plus some sleeve outer surface degradation and sleeve outer surface degradation with no tube degradation). It is considered that these situations result from the degradation at the tube/sleeve interface shadowing the material behind it so that the presence or absence of that material has little influence on the interface degradation signal.

Figure 5 1

PHASE ANGLE VERSUS DEPTH OF DEFECT CURVES EXPANDED REGION OF TUBE/SLEEVE ASSEMBLY

200 KHz, AXIAL WOUND PROBE



LEGEND

1 TUBE OUTER SURFACE DEFECTS 40% 90% OF TUBE WALL

2 TUBE THROUGH WALL DEFECT

3 TUBE INNER SURFACE DEFECTS 35% 50% OF TUBE WALL

4 TUBE THROUGH WALL PLUS 50% 100% OF SLEEVE WALL

5 SLEEVE ONLY OUTER SURFACE DEFECTS 30% 100% OF WALL

6 TUBE OUTER SURFACE DEFECTS BEHIND END OF SLEEVE

7 TUBE OUTER SURFACE DEFECTS 1/8" BEYOND SLEEVE END

NOTES 1. PHASE ANGLE MEASUREMENT CONVENTION

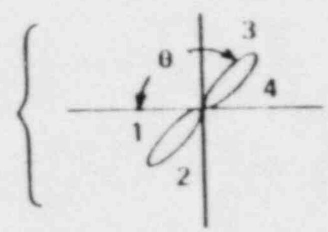
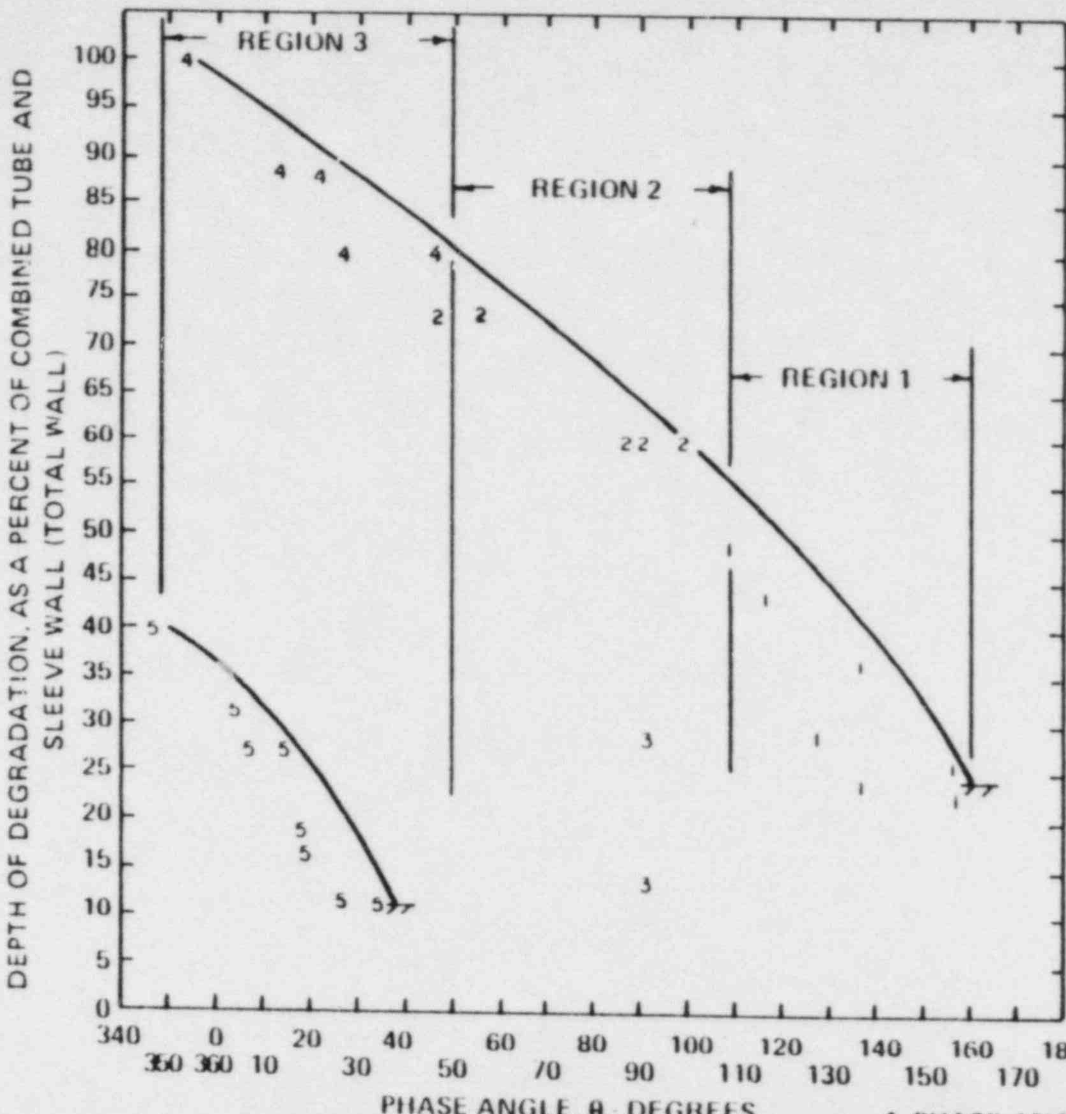


Figure 5-2

PHASE ANGLE VERSUS DEPTH OF DEFECT CURVES - UNEXPANDED REGION OF TUBE/SLEEVE ASSEMBLY

200 KHz, AXIAL WOUND PROBE



LEGEND

1. TUBE OUTER SURFACE DEFECTS 40% - 90% OF TUBE WALL
2. TUBE THROUGHWALL PLUS 0 - 50% SLEEVE WALL
3. TUBE INNER SURFACE DEFECTS 35% - 50% OF TUBE WALL
4. TUBE THROUGHWALL PLUS 50% - 100% OF SLEEVE WALL
5. SLEEVE ONLY OUTER SURFACE DEFECTS - 30% - 100% OF WALL

NOTES 1. PHASE ANGLE MEASUREMENT CONVENTION

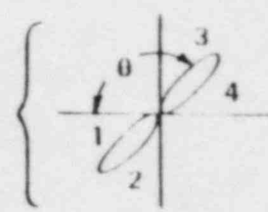
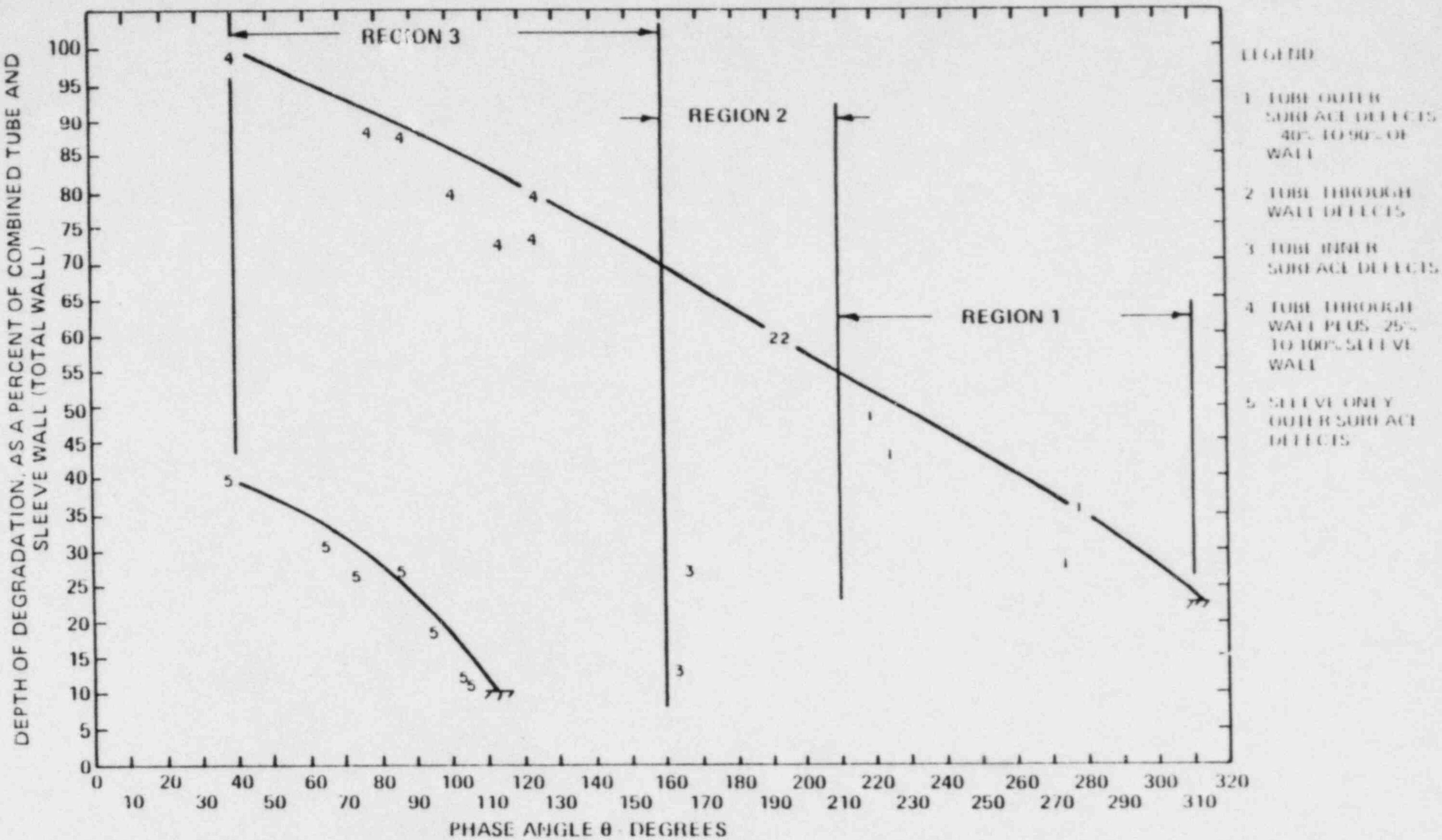


Figure 5 3

PHASE ANGLE VERSUS DEPTH OF DEGRADATION CURVES - UNEXPANDED REGION OF TUBE/SLEEVE ASSEMBLY
400 KHz, STANDARD 0.540" FLEX PROBE



NOTE 1. PHASE ANGLE MEASUREMENT CONVENTION

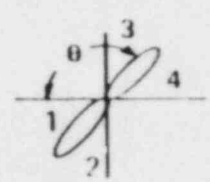


Figure 5-4
AXIALLY WOUND DIFFIRENTIAL COIL
ECT PROBE

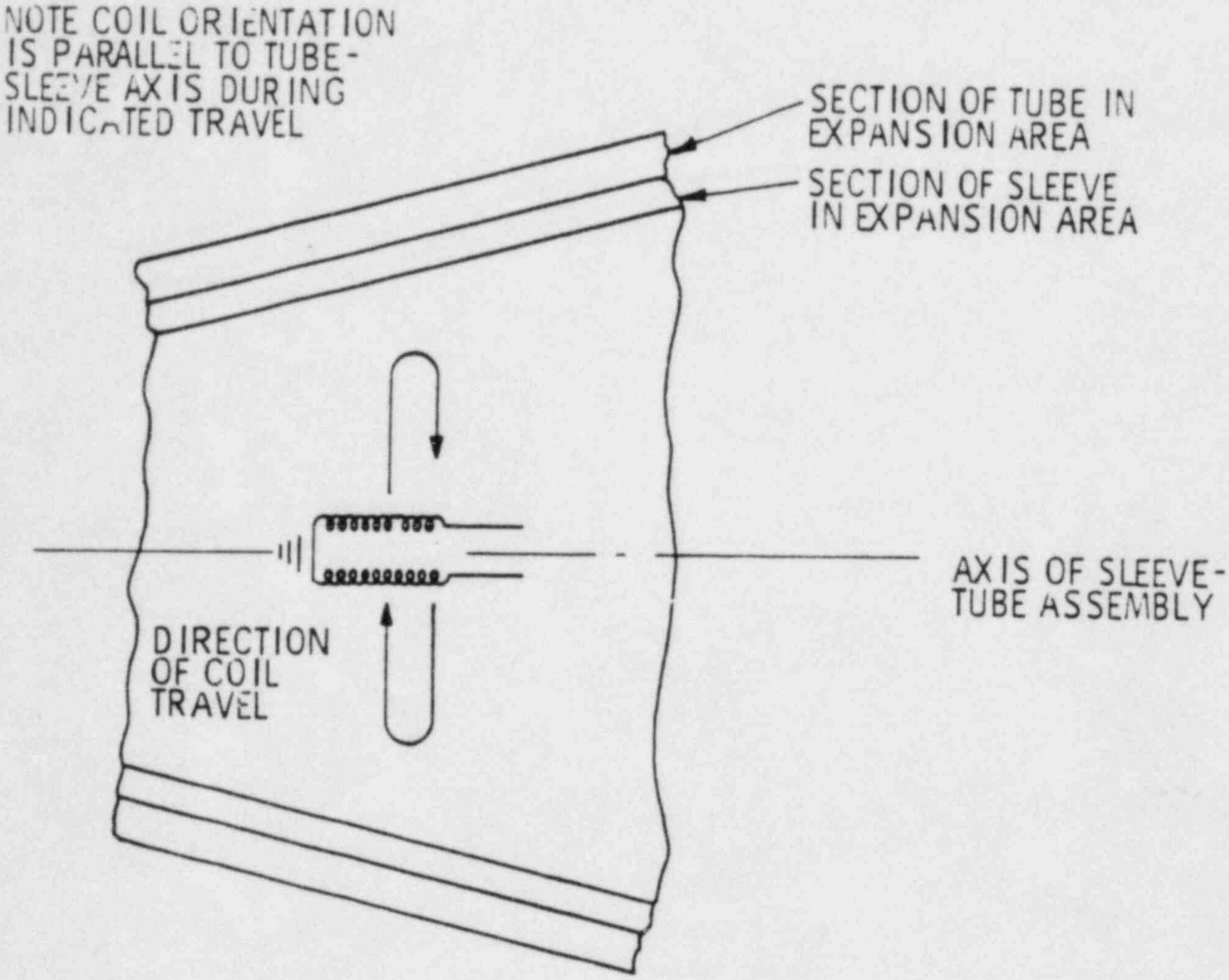
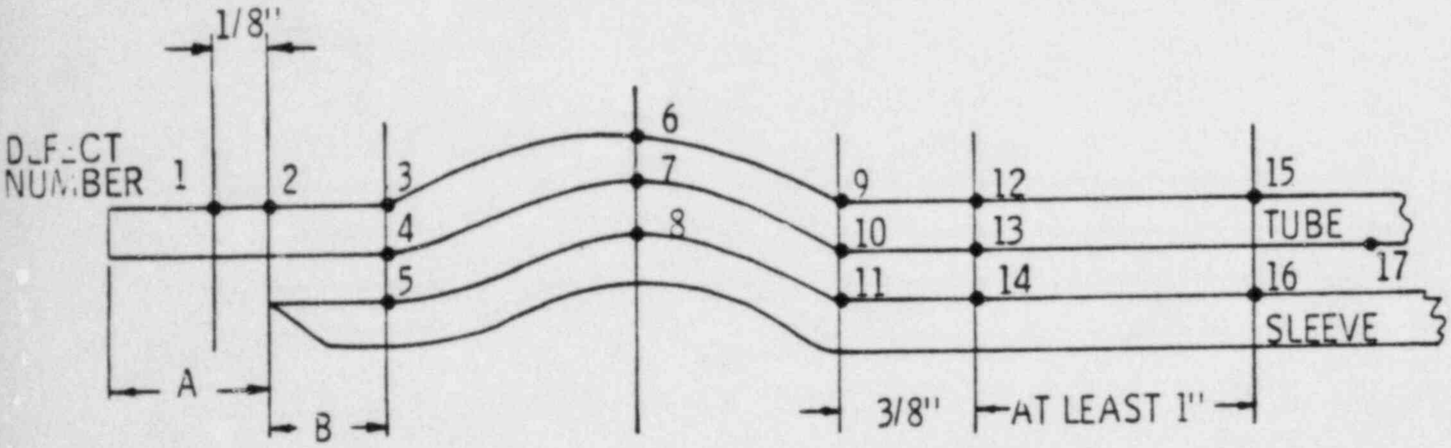


Figure 5-5

DEFECT LOCATIONS IN CALIBRATION SAMPLES



1. DEFECT LOCATION No. 1 HAS THE EDGE OF THE DEFECT 1/8" FROM THE END OF THE SLEEVE
2. DEFECT LOCATION 9 and 12, 10 AND 13, AND 11 AND 14 ARE SPACED 3/8" FROM DEFECT CENTERLINE TO DEFECT CENTERLINE, RESPECTIVELY
3. DEFECT LOCATIONS 15, 16 AND 17 ARE OFTEN CONTAINED IN SECTION OF TUBE/SLEEVE ASSEMBLIES WITHOUT AN EXPANSION JOINT. THIS ALLOWS THESE DEFECTS TO BE MOVED WITH RESPECT TO EACH OTHER SO THAT SITUATIONS VARYING FROM ALIGNMENT TO COMPLETE SEPARATION MAY BE INVESTIGATED

Figure 5-6

Calibration Standard Defect Information

Sample Number	Dimensions A (Inches)	Dimensions B (Inches)	Defect Information: Position Number	Actual Depth	Cross Section	Component	% of Component Wall	% of Total Wall	Type	Comments
1	0	2	6	.049"	.080"ϕ	Tube	100	60	EDM	
2	0	2	9	.019"	.187"ϕ	Tube	39	23	EDM	
3	0	2	6-7-8	.081"	.065"ϕ	Tube/Sleeve	100/100	100	EDM	
			9-10-11	.079"	.095"ϕT .065"ϕS	Tube/Sleeve	100/94	98	EDM	
4	0	2	11	.032"	.065"ϕ	Sleeve	100	40	EDM	
			8	.032"	.065"ϕ	Sleeve	100	40	EDM	
6	0	2	6	.033"	1/2"ϕ	Tube	67	41	Acid Wastage	
			6	.026"	1/2"ϕ	Tube	53	32		
			15	.021"	1/2"ϕ	Tube	43	26		
12	0	2	6-7-8	.066"	.095"ϕT .065"ϕS	Tube/Sleeve	100/53	81	EDM	
			15	.019"	.187"ϕ	Tube	38	23	EDM	
			6	.020"	.187 ϕ	Tube	39	24	EDM	
14	1	1/4	2	.019"	.187"ϕ	Tube	38	23	EDM	
			6	.049"	.065"ϕ	Tube	100	60	EDM	
			9	.049"	.065"ϕ	Tube	100	60	EDM	
16	1	1/4	1	.019"	.187"ϕ	Tube	39	23	EDM	
			9	.011"	.187"ϕ	Tube	23	14	EDM	
18	1	1/4	3	.029"	.109"ϕ	Tube	59	36	EDM	
			9	.025"	.109"ϕ	Tube	51	31	EDM	
			6	.029"	.109"ϕ	Tube	59	36	EDM	

Figure 5-6

Calibration Standard Defect Information
(Continued)

Sample Number	Dimensions A (Inches)	Dimensions B (Inches)	Defect Information: Position Number	Actual Depth	Cross Section	Component	% of Component Wall	% of Total Wall	Type	Comments
39	1	1/4	6	.029"	.109"φ	Tube	59	36	EDM	
40	1	1 3/4	8		1/4"x1"	Sleeve			IGA	
			8		1/4"x1"	Sleeve			IGA	
41	1	1 3/4	6		1/2"φ	Tube			IGA	
			6		1/2"φ	Tube			IGA	
44	1+	1/4	3	.020"	.187"φ	Tube	40	24	EDM	
			12	.019"	.187 φ	Tube	39	23	EDM	
45	1+	1/4	3	.049"	.25" φ	Tube	100	60	EDM	
			5	.012"	.187"φ	Sleeve	38	15	EDM	
46	1+	1/4	6	.049"	.25" φ	Tube	100	60	EDM	
			8	.015"	.187"φ	Sleeve	47	19	EDM	
			12	.049"	.25" φ	Tube	100	60	EDM	
			14	.014"	.187"φ	Sleeve	44	17	EDM	
			15	.049"	.25" φ	Tube	100	60	EDM	

Figure 5-7

Calibration Standard Defect Information

Sample Number	Dimensions A (Inches)	Dimensions B (Inches)	Defect Information: Position Number	Actual Depth	Cross Section	Component	% of Component Wall	% of Total Wall	Type	Comments
46	1+	1/4	16	.014"	.187"ϕ	Sleeve	44	17	EDM	
47	1+	1/4	2	.019"	.187"ϕ	Tube	39	23	EDM	Rounded End
48	1+	1/4	9	.049"	.25" ϕ	Tube	100	60	EDM	
			11	.015"	.187"ϕ	Sleeve	47	19	EDM	
49	1+	1/4	6-7-8	.081"	.25" ϕ	Tube/Sleeve	100/100	100	EDM	
			7	.015"	.187"ϕ	Tube	47	28	EDM	
50	1+	1/4	4	.019"	.187"ϕ	Tube	39	23	EDM	Rounded End
			10	.019"	.187"ϕ	Tube	39	23	EDM	
			13	.019"	.187"ϕ	Tube	39	23	EDM	
Tube E Sleeve A	Not Applicable		15-16	.081"	.098"ϕ	Tube/Sleeve	100/100	100	EDM	
			16	.025"	.095"ϕ	Sleeve	78	31	EDM	
			16	.022"	.095"ϕ	Sleeve	68	27	EDM	
			16	.023"	.050"ϕ	Sleeve	71	28	EDM	
			16	.015"	.095"ϕ	Sleeve	46	18	EDM	
			16	.009"	.095"ϕ	Sleeve	28	11	EDM	
			16	.010"	.187"ϕ	Sleeve	32	13	EDM	
			16	.032"	.098"ϕ	Sleeve	100	40	EDM	
			15-16	.071"	.095"ϕ/ .098"ϕ	Tube/Sleeve	100/68	88	EDM	
			15-16	.064"	.095"ϕ/ .098"ϕ	Tube/Sleeve	100/46	80	EDM	
			15-16	.059"	.187"ϕ/ .098"ϕ	Tube/Sleeve	100/32	73	EDM	

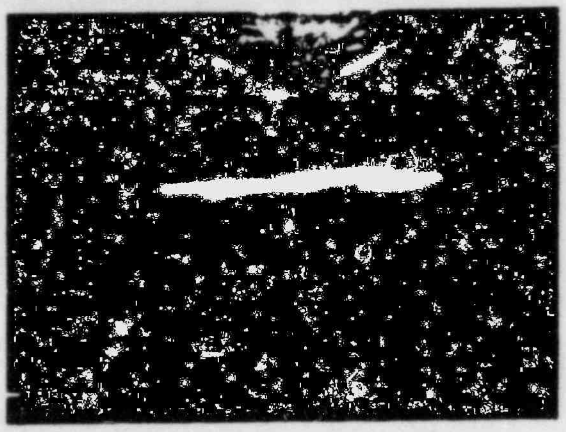
Figure 5-7

Calibration Standard Defect Information
(Continued)

Sample Number	Dimensions A B Inches	Defect Information: Position Number	Actual Depth	Cross Section	Component	% of Component Wall	% of Total Wall	Type	Comments
Tube C Sleeve A	Not Applicable	15-16	.071"	.095"φ/ .050"φ	Tube/Sleeve	100/68	88	EDM	
		15-16	.064"	.095"φ/ .050"φ	Tube/Sleeve	100/46	80	EDM	
		15-16	.059"	.187"φ/ .050"φ	Tube/Sleeve	100/32	73	EDM	
Tube F Sleeve B		17	.023"	.095"φ	Tube	46	28	EDM	
		17	.011"	.095"φ	Tube	22	13	EDM	
Tube C Sleeve B		15	.049"	.050"φ	Tube	100	60	EDM	
		15	.034"	.095"φ	Tube	71	43	EDM	
		15	.024"	.095"φ	Tube	48	29	EDM	
Tube D Sleeve B		15	.049"	.050"φ	Tube	100	60	EDM	
		15	.040"	.080"φ	Tube	81	49	EDM	
		15	.030"	.110"φ	Tube	61	37	EDM	
		15	.019"	.175"φ	Tube	38	23	EDM	

FIGURE 5-8

SIGNALS FROM "CLEAN" BULGE



Center of Expansion

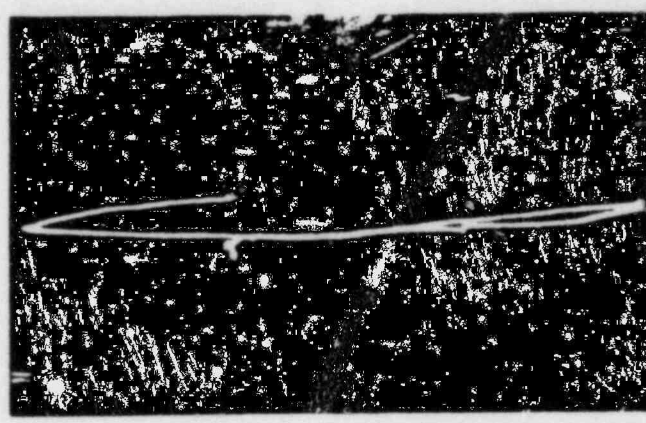
(a)

Inboard End of Expansion

(b)

Outboard End of Expansion
Best Signal

(c)



Outboard End of Expansion
Typical Signal

(d)

NOTES:

1. All defect signals recorded with EM 3300 sensitivity at 70, and vertical and horizontal settings at 1 volt/division, unless indicated.

2. Signals are produced from the axial wound probe operating at 200 KHz.

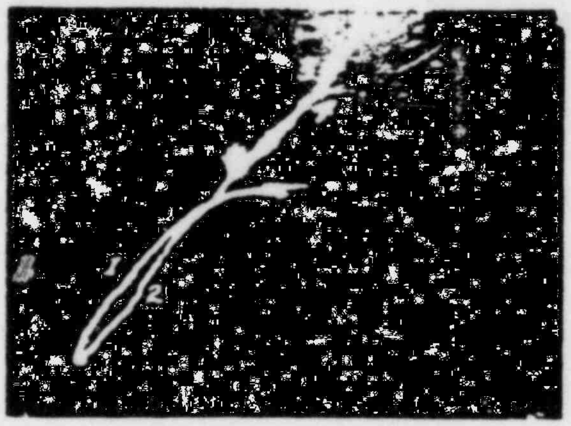
FIGURE 5-9

EXPANDED REGION

SIGNALS FROM TUBE OUTER SURFACE DEFECTS - NO SLEEVE DEGRADATION

100% Through Tube Wall
0% Sleeve Wall
60% Combined Wall

(a)

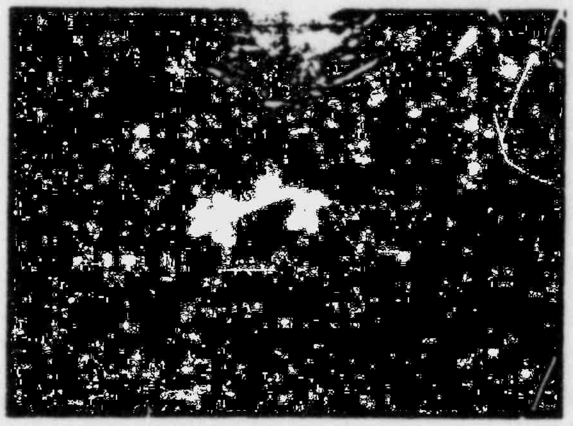


67% Tube Wall
0% Sleeve Wall
41% Combined Wall

(b)

53% Tube Wall
0% Sleeve Wall
32% Combined Wall

(c)



39% Tube Wall
0% Sleeve Wall
25% Combined Wall

(d)

NOTES:

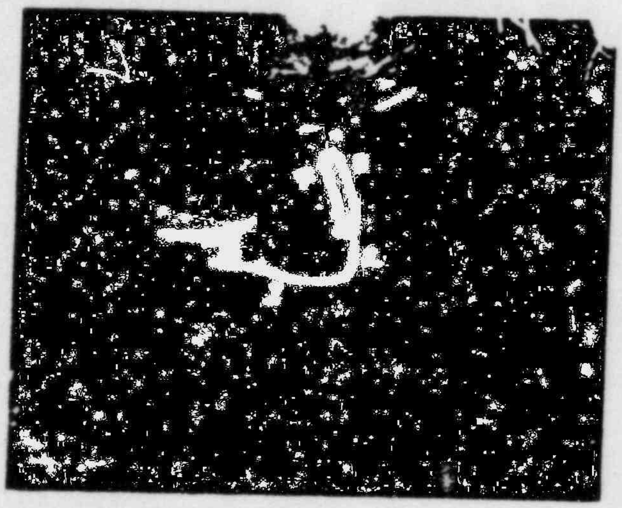
1. All defect signals recorded with EM 3300 sensitivity at 7[illegible], and vertical and horizontal settings at 1 volt/division, unless indicated.

2. Signals are produced from the axial wound probe operating at 200 KHz.

FIGURE 5-16

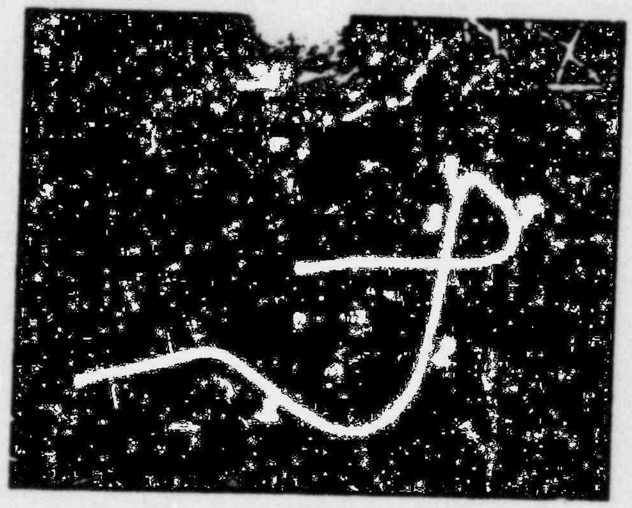
EXPANDED REGION

SIGNALS FROM TUBE INNER SURFACE DEFECTS - NO SLEEVE DEGRADATION



47% Tube Wall (I.D.)
0% Sleeve Wall
28% Combined Wall

(a)



39% Tube Wall (I.D.)
0% Sleeve Wall
23% Combined Wall

(b)

NOTES:

1. All defect signals recorded with EM 3300 sensitivity at 70, and vertical and horizontal settings at 1 volt/division, unless indicated.

2. Signals are produced from the axial wound probe operating at 200 KHz.

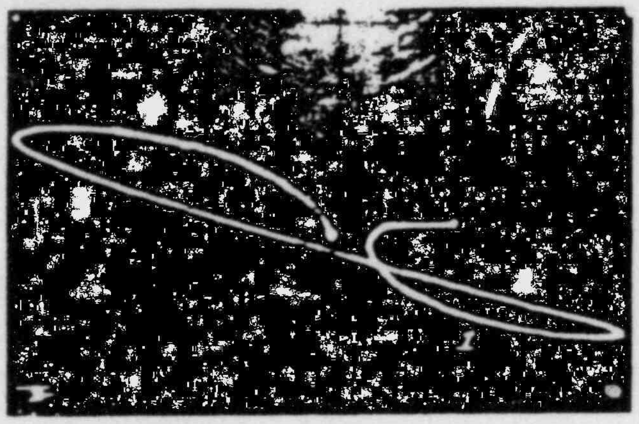
FIGURE 5-11

EXPANDED REGION

SIGNALS FROM TUBE THROUGH WALL PLUS SLEEVE DEFECTS

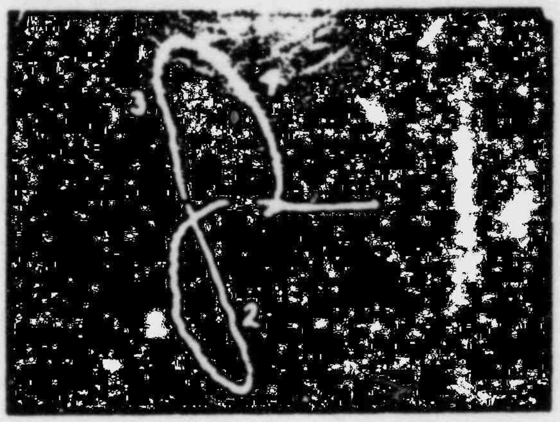
AND

SIGNALS FROM SLEEVE OUTER SURFACE DEFECTS, TUBE CLEAN



100% Tube Wall
100% Sleeve Wall
100% Combined Wall

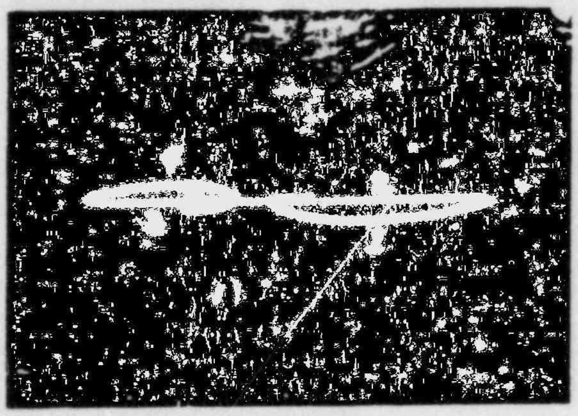
(a)



100% Tube Wall
53% Sleeve Wall
81% Combined Wall

(b)

Tube Through Wall Plus Sleeve Defect Signals



0% Tube Wall
100% Sleeve Wall
40% Total Wall
2 volts/div, horizontal & vertical

(c)

0% Tube Wall
34% Sleeve Wall
15% Total Wall

(d)

Sleeve Only Defect Signals

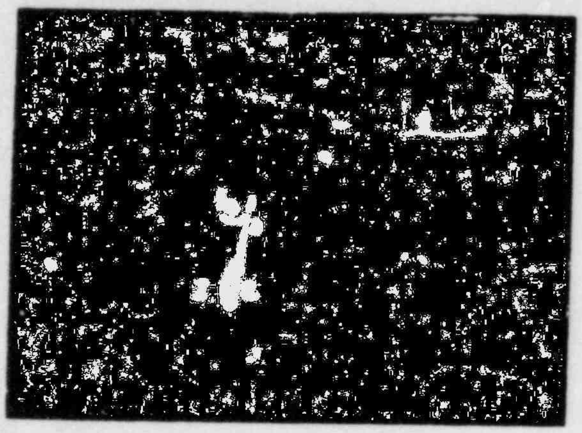
NOTES:

1. All defect signals recorded with EM 3300 sensitivity at 70, and vertical and horizontal settings at 1 volt/division, unless indicated.
2. Signals are produced from the axial wound probe operating at 2[illegible] KHz.

FIGURE 5-12

UNEXPANDED REGION

SIGNALS FROM TUBE OUTER SURFACE DEFECTS - NO SLEEVE DEGRADATION



100% Tube Wall
0% Sleeve Wall
60% Combined Wall

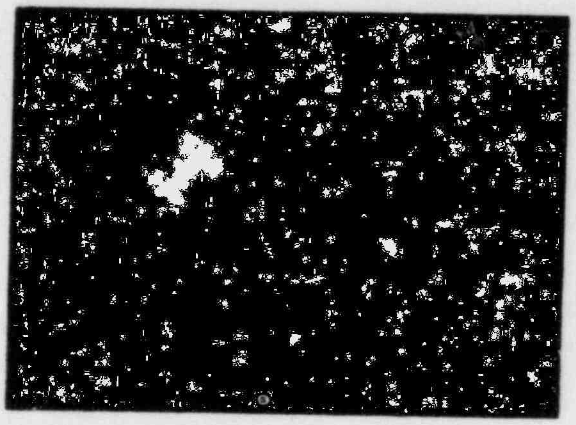
(a)

81% Tube Wall
0% Sleeve Wall
49% Combined Wall

(b)

61% Tube Wall
0% Sleeve Wall
37% Combined Wall

(c)



48% Tube Wall
0% Sleeve Wall
29% Combined Wall

(d)

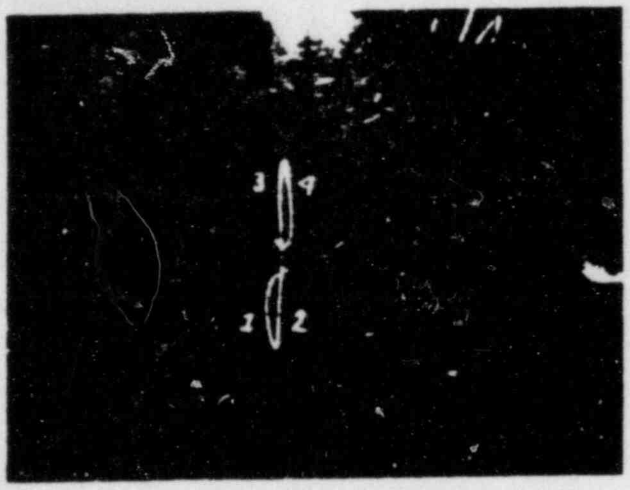
NOTES:

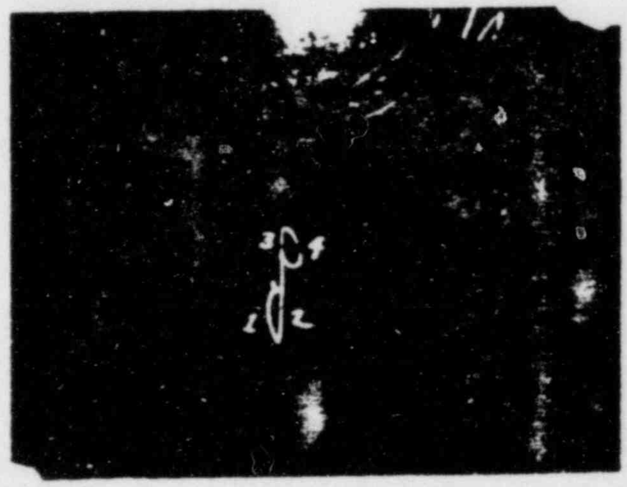
1. All defect signals recorded with EM 3300 sensitivity at 7[illegible], and vertical and horizontal settings at 1 volt/division, unless indicated.
2. Signals are produced from the axial wound probe operating at 2[illegible] KHz.

FIGURE 3-13

UNEXPANDED REGION

SIGNALS FROM [illegible] TUBE SURFACE DEFECTS - NO SLEEVE EXPANSION





46% Tube Wall (I.D.)
[illegible] Sleeve Wall
28% Combined Wall
2 volts/div horizontal & vertical

(a)

22% Tube Wall (I.D.)
0% Sleeve Wall
15% Combined Wall

(b)

NOTES:

1. All defect signals recorded with EM 3300 sensitivity at [illegible], and vertical and horizontal settings at 1 volt/division, unless indicated.

2. Signals are produced from the axial wound probe operating at [illegible] KHz.

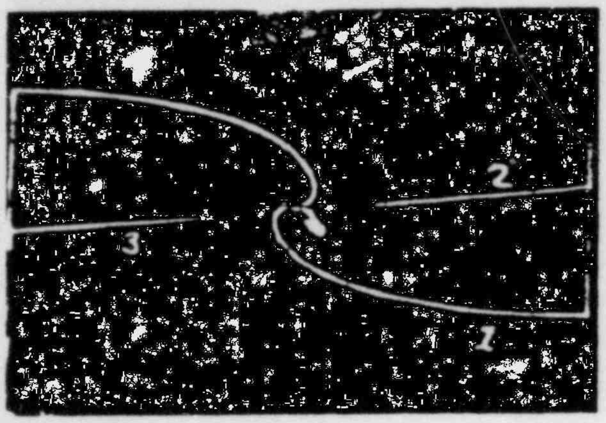
FIGURE 5-14

UNEXPANDED REGION

SIGNALS FROM TUBE THROUGH WALL PLUS SLEEVE DEFECTS

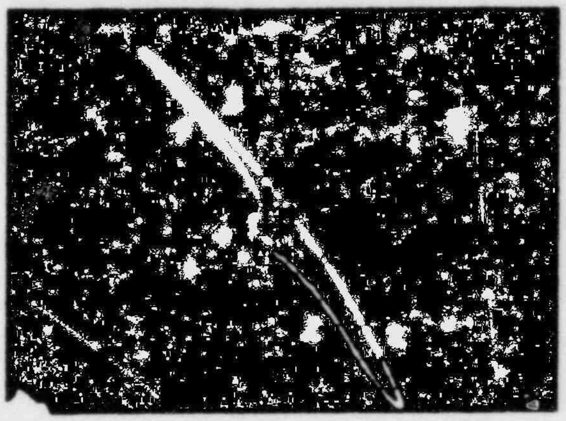
AND

SIGNALS FROM SLEEVE OUTER SURFACE DEFECTS - TUBE CLEAN



100% Tube Wall
100% Sleeve Wall
100% Combined Wall

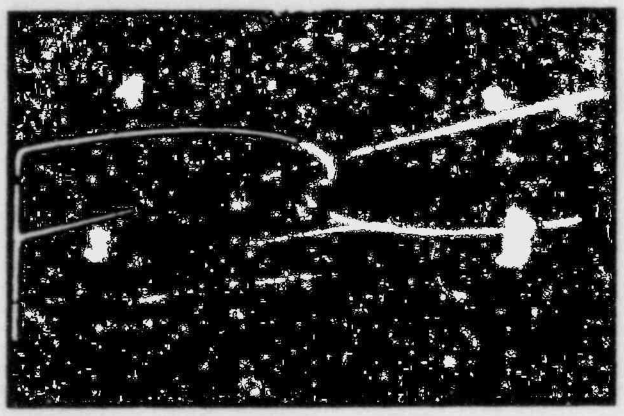
(a)



100% Tube Wall
32% Sleeve Wall
73% Combined Wall

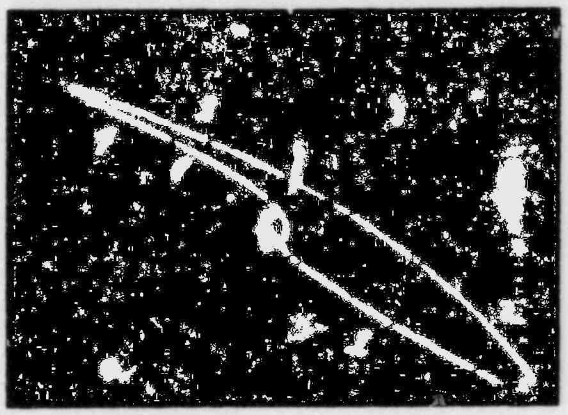
(b)

Tube Through Wall Hole Plus Sleeve Defect Signals



0% Tube Wall
100% Sleeve Wall
40% Combined Wall

(c)



0% Tube Wall
32% Sleeve Wall
13% Combined Wall

(d)

Sleeve Only Defect Signals

NOTES:

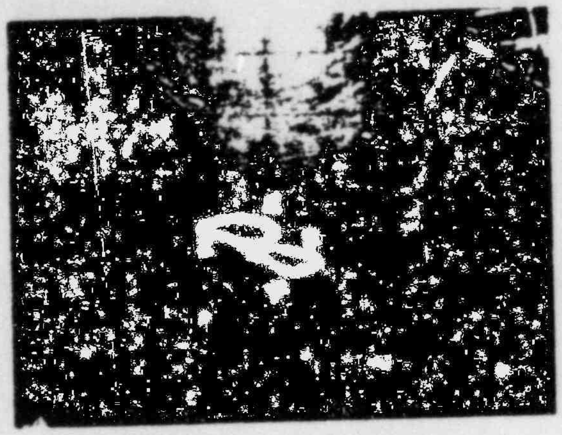
1. All defect signals recorded with EM 3300 sensitivity at 70, and vertical and horizontal settings at 2 volt/division, unless indicated.

2. Signals are produced from the axial wound probe operating at 200 KHz.

FIGURE 5-15

UNEXPANDED REGION

SIGNALS FROM TUBE OUTER SURFACE DEFECTS - NO SLEEVE DEGRADATION



100% Tube Wall
0% Sleeve Wall
60% Combined Wall

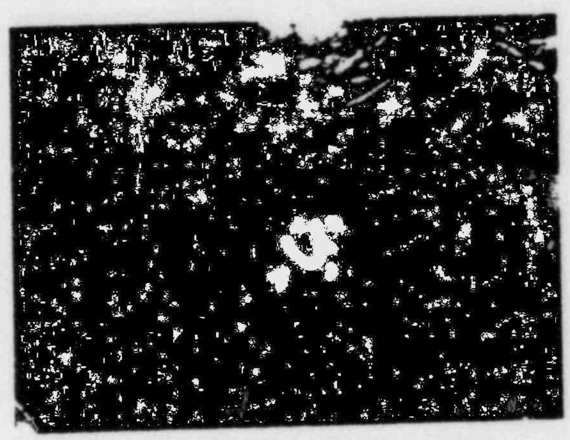
(a)

81% Tube Wall
0% Sleeve Wall
49% Combined Wall

(b)

61% Tube Wall
0% Sleeve Wall
37% Combined Wall

(c)



48% Tube Wall
0% Sleeve Wall
29% Combined Wall

(d)

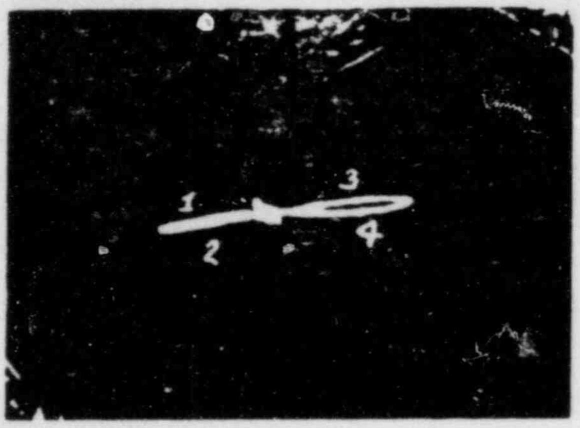
NOTES:

1. All defect signals recorded with EM 3300 sensitivity at 50, and vertical and horizontal settings at .5 volt/division, unless indicated.
2. Signals are produced from the .540" flex probe operating at 400 KHz.

FIGURE 5-16

UNEXPANDED REGION

SIGNALS FROM TUBE INNER SURFACE DEFECTS - NO SLEEVE DEGRADATION



46% Tube Wall (I.D.)
0% Sleeve Wall
28% Combined Wall

(a)

22% Tube Wall (I.D.)
0% Sleeve Wall
13% Combined Wall

(b)

NOTES:

1. All defect signals recorded with EM 3300 sensitivity at 50, and vertical and horizontal settings at 1 volt/division, unless indicated.
2. Signals are produced from the .540" flex probe operating at 400 KHz.

FIGURE 5-17

UNEXPANDED REGION

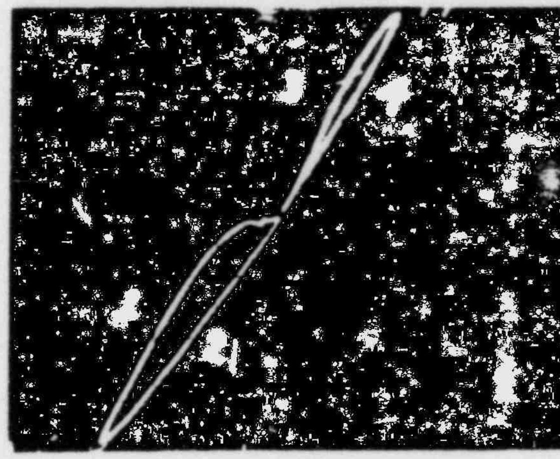
SIGNALS FROM TUBE THROUGH WALL PLUS SLEEVE DEFECTS

AND

SIGNALS FROM SLEEVE OUTER SURFACE DEFECTS, TUBE CLEAN

100% Tube Wall
100% Sleeve Wall
100% Combined Wall

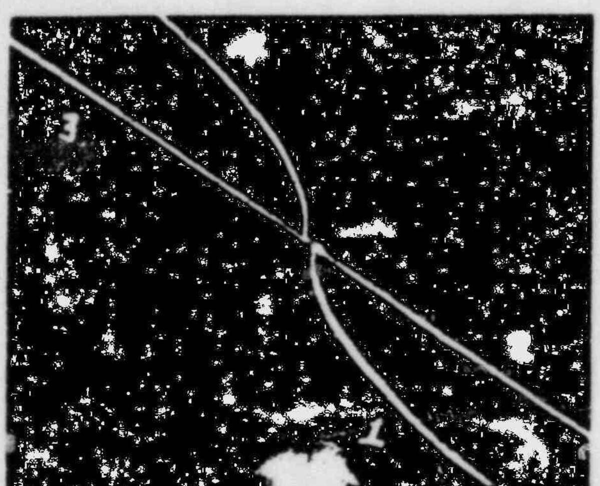
(a)



100% Tube Wall
32% Sleeve Wall
73% Combined Wall

(b)

Tube Through Wall Hole Plus Sleeve Defects



0% Tube Wall
100% Sleeve Wall
40% Combined Wall

(c)

0% Tube Wall
32% Sleeve Wall
13% Combined Wall

(d)

Sleeve Only Defect Signals

NOTES:

1. All defect signals recorded with EM 3300 sensitivity at 50, and vertical and horizontal settings at 2 volt/division, unless indicated.
2. Signals are produced from the .540" flex probe operating at 400 KHz.

6.0 TUBE SLEEVE CORROSION RESISTANCE

Utilizing primary and secondary water chemistries representative of typical conditions in the Palisades steam generators, tube/sleeve corrosion evaluation tests were performed. Tube/sleeve assemblies tested included normal, wasted tubes and simulated intergranular attack to the steam generator tube. The objective of this program was to demonstrate that the sleeving process does not aggravate the corrosion of steam generator tubes, nor cause tube/sleeve crevice corrosion.

6.1 SUMMARY AND CONCLUSIONS

Corrosion tests of sleeved steam generator tubes are in progress to confirm that installation of a sleeve does not lead to corrosion problems. The test conditions include a variety of normal and faulted secondary side chemistry conditions and nominal primary side conditions. These tests are conducted in pot boilers which provide the capability of determining susceptibility to corrosion in the presence of heat transfer and two-phase secondary side conditions. Results of the planned tube and sleeve examinations will be included in a report after these tests are completed; however, no detrimental effects of sleeving have been noted to date during the conduct of these tests.

Beginning in 1975, several sleeves were installed in a pot boiler like the ones used for the corrosion tests. This boiler operated for several hundred hours under transient and steady-state conditions with normal volatile secondary chemistry and primary chemistry conditions. Visual and metallographic examinations following this test showed no tendency for the sleeve installation to promote corrosive attack from either the primary or secondary side. The results of these examinations are detailed below.

6.2 TEST FACILITY

Corrosion evaluation tests are conducted in the Combustion Engineering Nuclear Laboratory, utilizing a high temperature, high pressure facility capable of supplying primary coolant at 600°F, 2200 psig. Boilers simulating steam generators in an NSSS, contain the secondary chemistry being investigated. Sleeves are installed in the straight portion of short U-bend sections of steam generator tubes and primary chemistry similar to that at Palisades is passed through the tube/sleeve assembly. By means

of heat transfer through the tubes, secondary coolant is raised from approximately 200°F to 540°F at saturation pressure. Secondary pressure and temperature are maintained by allowing the steam to flow through a condenser and returning the condensate to the boiler at a point beneath the water line. The tubes are kept covered with a minimum of six inches of secondary water at all times. Samples of the secondary chemistry are taken three times weekly with chemical additions as necessary. Due to the small volume essentially closed loop system and the steady state nature of the test, little fluctuation in chemistry conditions is evidenced.

Primary chemistry is sampled weekly. Again little necessity for chemical additions is found due to the sealed nature of the test loop. Figure 6-1 presents a schematic of the steam generator simulation test system. A flow rate of 2 to 4 gpm per four tube test boiler is maintained for primary coolant.

The tubes in the boilers are as configured in Figure 6-2. Each boiler houses four U-bend steam generator tubes with two sleeves installed per tube, one in each leg. The sleeves installed are eight inches in length, but otherwise identical to that pictured in Figure 1-1. One virgin tube and three partially laboratory degraded tubes are studied under each chemistry. These samples represent the range of defects anticipated for sleeving. The samples are present in each of the four chemistry tests. One tube defect is a 70 percent of wall circumferential phosphate wastage midway between the two expansion joints. This simulates a tube which would require plugging by current technical specifications. A second tube with 90 percent elliptical wastage at center span is studied. The final tube defect is a 13 percent of wall intergranular attack (IGA) located in the expanded joint region. The IGA is introduced prior to tube/sleeve expansion processes. This defect is representative of expanding a sleeve in an area where a tube defect is not detected by non-destructive eddy current examination. Each of the defects is encouraged to propagate by means of an umbrella concentrating device affixed to the tube just above the defect. These concentrators, coupled with the severe phosphate chemistry, provide a simulation of the Palisades corrosion characteristics in a much shorter time (typically one month) than is expected or has been found in the Palisades generators.

6.3 TEST CONDITIONS

As mentioned, the tube/sleeve samples are exposed to several secondary and a single primary water chemistry. The secondary chemistries are representative of past, present and proposed Palisades steam generator conditions. A primary system chemistry is used which is representative of that in all PWR steam generator primary coolant systems.

The first secondary chemistry sequence explored is described in Table 6-1. A one month period of phosphate chemistry of the intense nature described is believed adequate to simulate early steam generator conditions, particularly with the umbrella concentrators on the tubes. These conditions provide corrosion propagation and deposits equal to those at Palisades in one month. The test samples are subjected to a transition to volatile for a four month operating period. Over this length of time, any corrosion tendencies are expected to become evident. Finally, the tube/sleeve samples experience a wet layup chemistry to simulate Palisades down periods when the secondary side was left filled.

The second generation Palisades chemistry described in Table 6-2 adds condenser in leakage to the sequence to represent that phase of plant operation. Concentration and pH levels are in accord with Palisades technical specification levels. Attempts are made to match actual plant conditions where information is available. These first two chemistries utilize Lake Michigan water in phosphate and volatile chemistries, respectively.

The third test (Table 6-3) simulates the volatile secondary chemistry control with cooling tower water. Phosphate chemistries are run to introduce corrosive deposits on the test samples. A pre- and post-volatile wet layup again simulates filled steam generator down periods.

An investigation of corrosive effects of one possible future Palisades chemistry on the tube/sleeve assembly is being made. Introduction of sodium representative of levels expected from a condensate demineralization system (CDS) is being made during the transition to volatile (Table 6-4).

The primary system chemistry employed in all tests is that shown in Table 6-5.

6.4 RESULTS

The tests of various tube/sleeve assemblies under four different secondary chemistries were designed to show the effect of the sleeving operation on tube corrosion and to determine whether tube to sleeve crevice corrosion might occur. Preliminary results of a virgin tube tested for over 700 hours under volatile type chemistry conditions indicated no corrosion in the tube as a result of the sleeve installation. Further post-test metallographic sectioning showed no evidence of crevice corrosion nor stress corrosion cracking. The expanded regions of the tube were surrounded with the umbrella style concentrators to accelerate corrosion effects. No signs of localized or other corrosion were found after examination. This evidence indicates the acceptability of the expansion joint employed from a corrosion resistance standpoint. Final acceptability will be verified by corrosion tests still in progress.

Longitudinal and transverse sections of the tube and sleeve were examined microscopically for signs of corrosion. Examinations focused on the expansion areas. Figures 6-3 and 6-4 present typical microstructure from the tube and sleeve in the expansion area after 700 hours of test. No evidence of pitting or cracking is seen.

Axial looseness testing of the assembly after this test showed no change from the pretest values of one to three mils movement with 25 pounds force applied. Leakage rates of 1-10 cc/minute were determined for post test samples of the tube/sleeve assembly by drilling a leak hole at midspan in the tube. This is comparable to the rate determined for samples which have not been corrosion tested.

Table 6-1

Initial Palisades Secondary Chemistry

Chemistry		Duration
PO_4 Chemistry Control		1 Month
pH (@ 25°C)	9.0-10.2	
Phosphate	30-60 ppm	
Sulfite	10-30 ppm	
Additions of Lake Michigan condenser cooling water	To the extent necessary to maintain a pH of 9.8-10.2	
Transition to Volatile		4 Months
pH (@ 25°C)	8.2-9.2	
Hydrazine addition for oxygen control		
Morphaline for pH control		
Wet Layup		1 Month
pH (@ 25°C)	9.8-10.2	
Hydrazine	150-250 ppm	
Ammonia	<10 ppm	
Inert Gas Overpressure		

Table 6-2

Second Generation Palisades Secondary Chemistry

Chemistry		Duration
Wet Layup		1 Month
pH (@ 25°C)	9.8-10.2	
Hydrazine	150-250 ppm	
Ammonia	<10 ppm	
Inert Gas Overpressure		
PO_4 Chemistry Control		1 Month
pH (@ 25°C)	9.5-10.0	
Phosphate	30-60 ppm	
Sulfite	5-10 ppm	
Transition to Volatile		1 Month
pH (@ 25°C)	8.2-9.2	
Hydrazine addition for pH and oxygen control		
Volatile plus Condenser In-Leakage		3 Months
pH (@ 25°C)	8.2-9.2	
Hydrazine addition for oxygen control		
Additions of Lake Michigan water to maintain conductivity (Specific @ 25°C approx. 15 μmhos/cm		
Morphaline for pH control		

Table 6-3

Third Generation Palisades Secondary Chemistry

		Duration
PH_4 Chemistry Control		1 Month
pH (@ 25^{o}C)	9.5-10.0	
Phosphate	30-60 ppm	
Sulfite	5-10 ppm	
Wet Layup		1 Month
pH (@ 25^{o}C)	9.8-10.2	
Hydrazine	150-250 ppm	
Ammonia	<10 ppm	
Inert Gas Overpressure		
Transition to Volatile		3 Months
pH (@ 25^{o}C	8.2-9.2	
Hydrazine addition for oxygen control		
Morphaline for pH control		
Additions of Palisades cooling tower water	To the extent necessary to maintain pH of 8.2-8.6	
Wet Layup		1 Month
pH (@ 25^{o}C)	9.8-10.2	
Hydrazine	150-250 ppm	
Ammonia	<10 ppm	
Inert Gas Overpressure		

Table 6-4

Palisades Secondary Chemistry with Condensate Polishers

Chemistry		Duration
PO_4 Chemistry Control		1 Month
pH (@ 25°C)	9.5-10.0	
Phosphate	30-60 ppm	
Sulfite	5-10	
Transition to Volatile w/Sodium Concentration from CDS		4 Months
pH (@ 25°C)	8.2-9.2	
Feed and vent of CDS effluent to concentrate sodium in the bulk water to approximately 400 ppb		
Hydrazine addition for oxygen control		
Morphaline for pH control		
Wet Layup		1 Month
pH (@ 25°C)	9.8-10.2	
Hydrazine	150-250 ppm	
Ammonia	<10 ppm	
Inert Gas Overpressure		

Table 6-5

Palisades Primary Chemistry

Controlled Variable	Limits
pH (@ 25°C)	4.5-10.2
Hydrazine	1.5 x (O_2), max. 20 ppm
Ammonia	<0.5 ppm
Oxygen	<0.100 ppm
Chloride	<0.15 ppm
Fluoride	<0.10 ppm
Boron	500-4400 ppm
Lithium	0.2-1.0 ppm

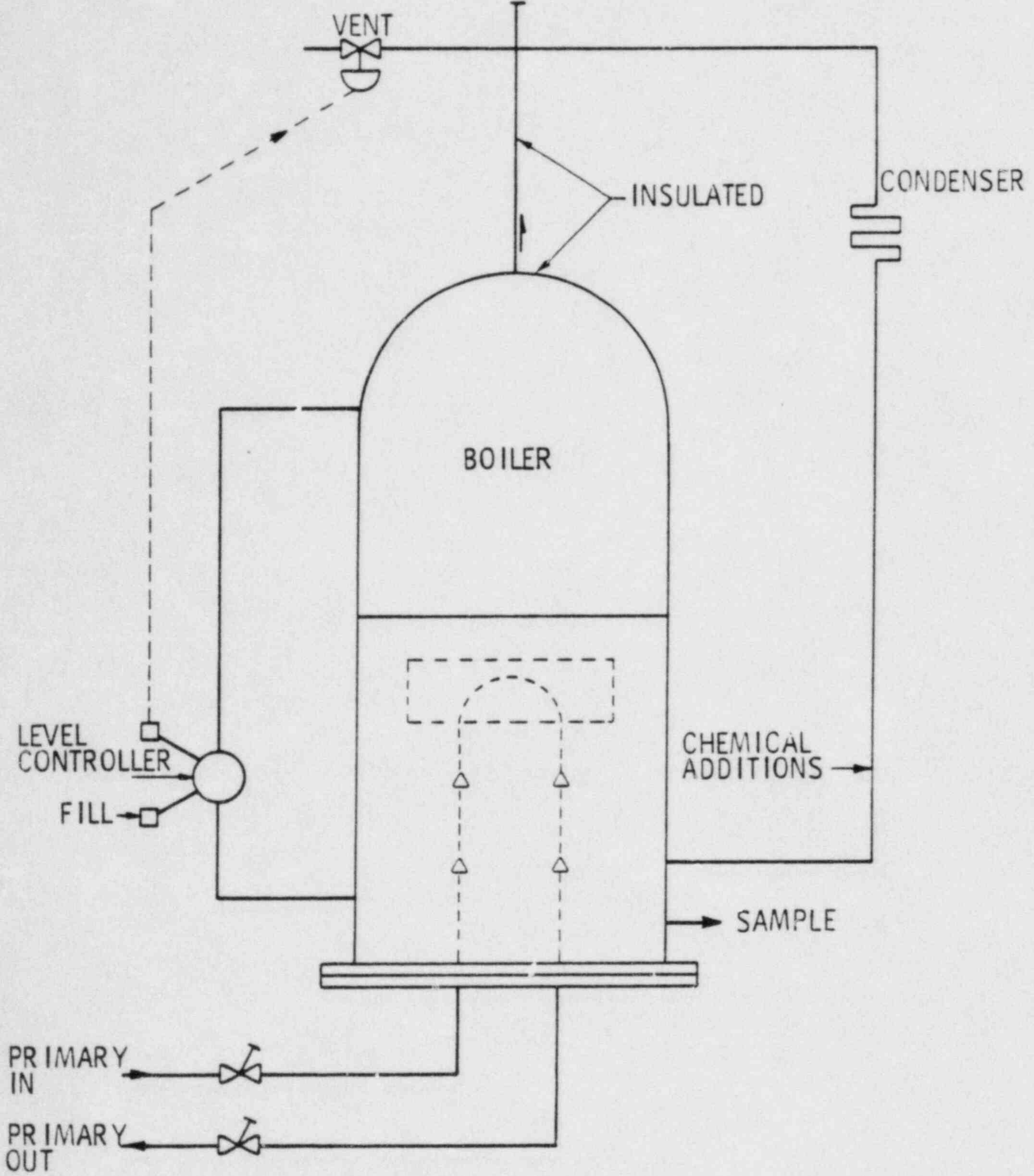


Figure 6-1
TEST BOILER SCHEMATIC

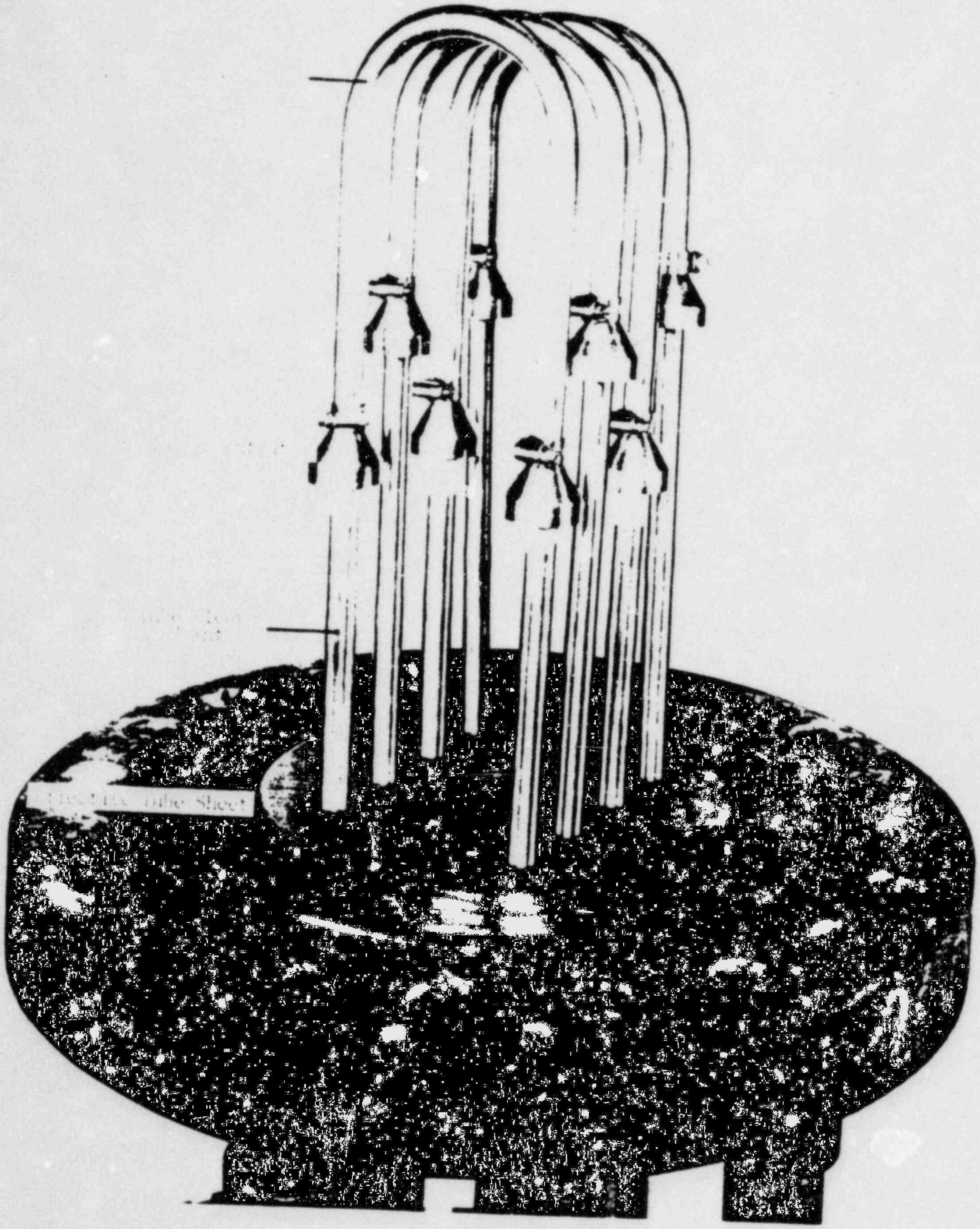
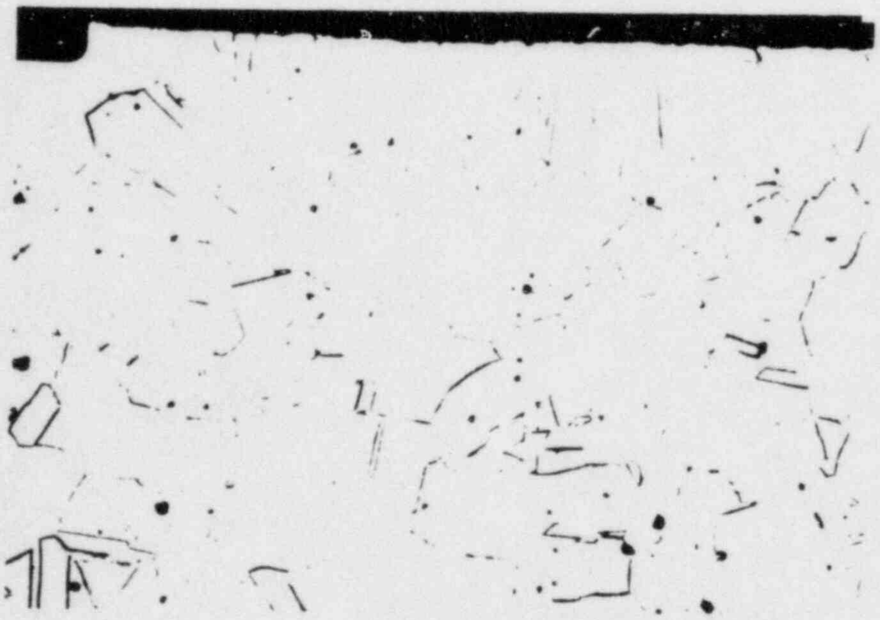

Tube Sheet

Figure 6-3

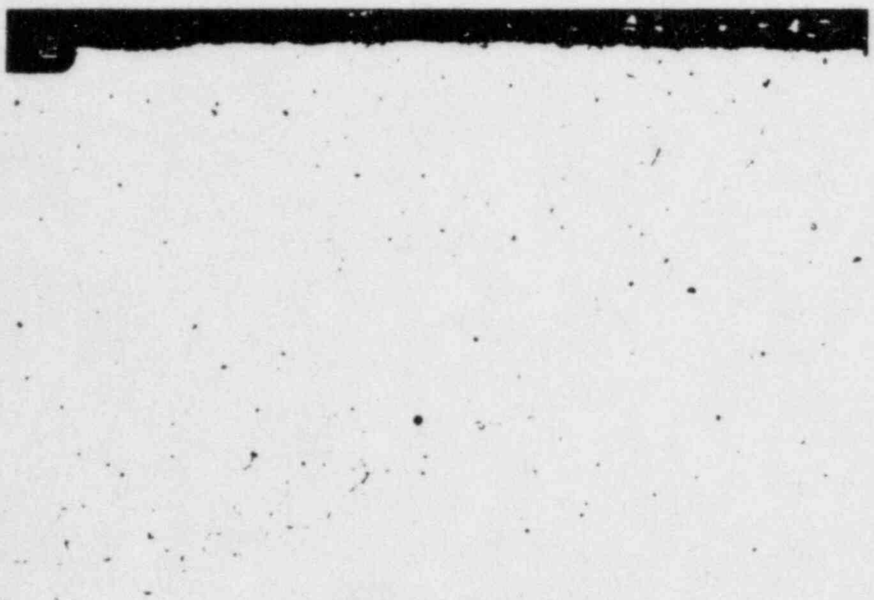
Typical Tube Material Microstructure After Preliminary Corrosion Test



Typical microstructure of the Inconel 600 tube in the expansion area. The edge (black area) is that edge of the tube to tube sleeve mating surface in the crevice area. No signs of corrosion are evident. 200X. Etched

Figure 6-4

Typical Sleeve Material Microstructure
After Preliminary Corrosion Test



Typical microstructure of the tube sleeving in the expansion/crevice area. The black edge is the sleeve to tube mating surface. No signs of corrosion were evident. 200X. Etched

7.0 STRUCTURAL ANALYSIS OF TUBE-SLEEVE ASSEMBLY

It is the intention of this analysis to establish the structural integrity of the tube-sleeve assembly for postulated worst case accident conditions. The accident conditions considered are main steam line break and loss of coolant.

7.1 Summary and Conclusions

A qualification analysis is performed to insure the structural integrity of the tube-sleeve assembly during a main steam line break accident. There exists a radial gap in the expansion joint of the sleeved tube. This results in an axial gap which allows the parent tube to separate a finite amount before the sleeve comes in contact with both ends of the parent tube. The geometry of the expansion joint is determined from an optical comparator plot of a typical expansion joint. The rate at which the sleeve engages the parent tube is extracted from axial pull test results. This amount of tube separation is then incorporated into a simplified dynamic analysis of the tube-sleeve assembly. From this dynamic analysis, a maximum, equivalent static, axial load on the sleeve is determined. This maximum axial load on the sleeve is compared with the experimentally determined load required to pull apart a severed tube-sleeve assembly, and a factor of safety of 2.4 for sleeve disengagement is calculated.

Next, the mode of failure for sleeve disengagement is analytically determined and compared to experimental test results. A strain energy analysis is used to determine the force required to pull the sleeve out of the parent tube. This force was determined to be 4522 lb. which agrees closely with the experimentally determined failure load of 3795 lb. The stress in the sleeve due to a static axial load indicates that the mode of failure for the tube-sleeve assembly will be a neck down of the sleeve if sufficient force and freedom for the tube to separate axially were available. This agrees with the experimental test results.

Next, the effect of a tube-sleeve assembly with 100% degraded tube on previous analytical assessments of postulated loadings is looked at.

The NRC Staff Criteria gives a maximum sleeve wall degradation of 53%. The LOCA + SSE accident loading is the limiting criteria and indicates that the maximum sleeve wall degradation permitted should be 34%.

A vibration response test will be conducted on 64% and 100% degraded sleeved tubes in order to obtain a qualitative assessment of the presence of sleeved tubes from the standpoint of dynamic tube response. Information with regard to the natural frequency and damping of the sleeved tubes will also be obtained. These measured natural frequencies will be compared with the frequencies of virgin tubes in order to assess the effect of the presence of sleeves. The predominant vibratory forcing function in the secondary fluid bundle entrance region is fluid elastic coupling. For Palisades steam generator virgin tubes, no vibration problem due to fluid elastic vibration is anticipated. Unless there is a large divergence in dynamic response or natural frequency between virgin tubes and sleeved tubes, no vibration problems are expected for sleeved tubes.

Pressures considered in this analysis are those originally specified for operating conditions. Higher primary and secondary pressures corresponding to the "stretch rating" will be considered at a later time. A dynamic analysis of Main Steam Line Break plus Safe Shutdown Earthquake will be performed and the results provided at a later time.

7.2 TUBE-SLEEVE ASSEMBLY QUALIFICATION ANALYSIS

Assuming an instantaneous circumferential failure of a sleeved tube due to main steam line break, the behavior of the sleeved tube is characterized.

The amount of tube separation before the sleeve comes in contact with both ends of the parent tube is conservatively determined. The rate at which the sleeve engages the tube is extracted from axial pull test results.

A dynamic analysis of the sleeved tube assembly is performed and a maximum,equivalent static, axial load on the sleeve is determined.

The maximum axial load is compared with the load required to pull apart a severed tube-sleeve assembly, which has been determined by a pull test. The comparison of the failure load with the maximum applied load (from dynamic analysis) represents a factor of safety for sleeve disengagement.

7.2.1 Radial Gap in Expansion Joint

The unpressurized radial gap in the expansion joint is calculated using an inelastic analysis with a plane strain assumption.

A plane strain model is used to approximate the hydraulic expansion of the sleeve into the tube. A thin section of tube-sleeve assembly at the center of the expansion joint is modeled.

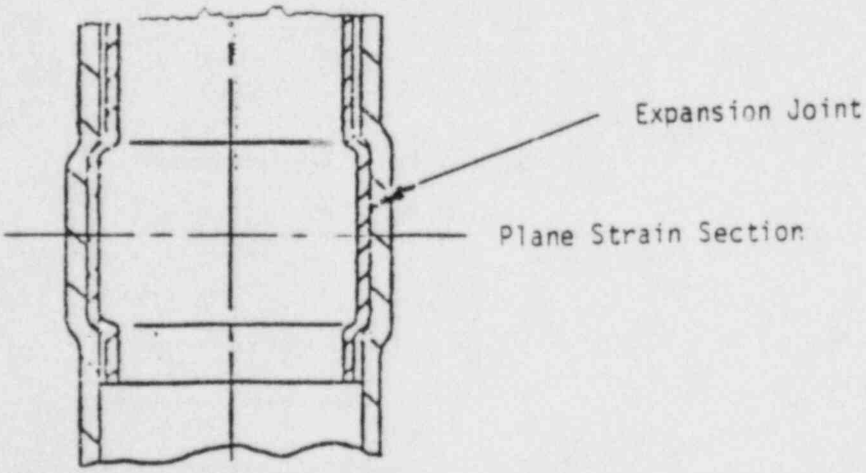


FIGURE 7-1

The pressurized radial gap between the sleeve and tube is determined from theoretical radial deflection equations and the unpressurized radial gap.

Plane Strain Model

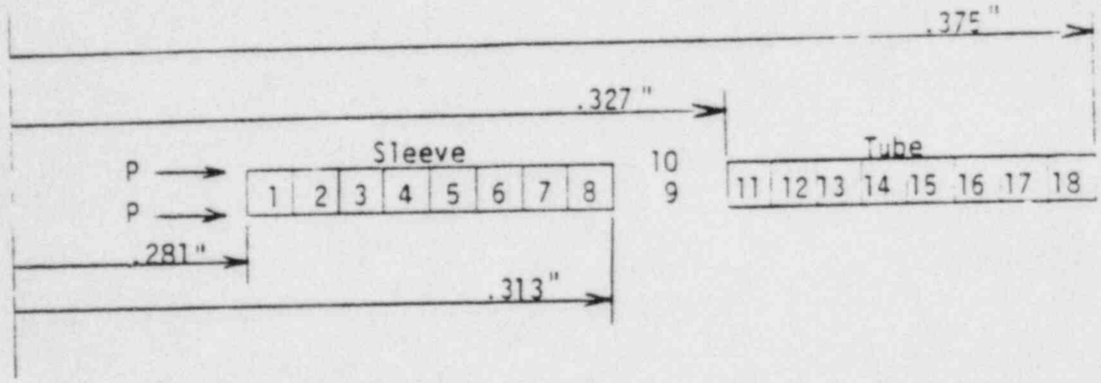


FIGURE 7-2

The above dimensions are dimensions before any hydraulic pressure is applied to sleeve.

An inelastic analysis of the plane strain section is performed using the "ANSYS" Computer Program (Reference 7.3). The sleeve and tube are modeled with the isoparametric element STIF42 using the axisymmetric option. Eight elements were used to model the sleeve and tube wall thickness so as to provide better representation of the inelastic propagation. The initial radial gap between the sleeve and tube is modeled with the interface element STIF12. Plane strain is assumed as the sleeve is expanded into the tube.

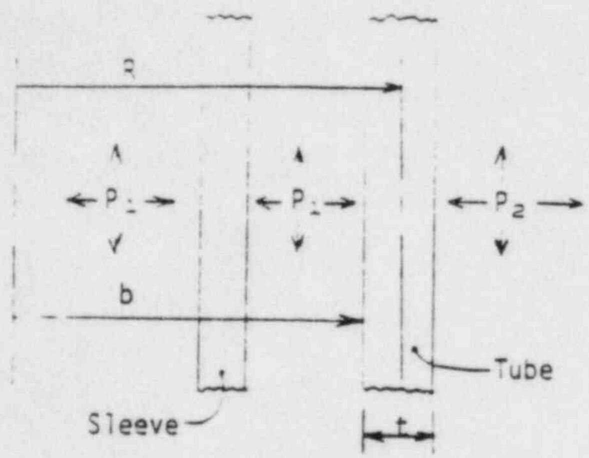
After the sleeve has been hydraulically expanded into the tube and the pressure removed, an unpressurized radial gap exists.

From inelastic analysis: $GAP_{unpressurized} = .00004$ in.

Pressurized Radial Gap

The pressurized radial gap is determined by adding the radial deflection of the tube under pressure to the unpressurized radial gap.

FIGURE 7-3



$$\Delta p = \frac{b^2}{Et}\left(\frac{R}{b} - \frac{\nu}{2}\right) P = \text{Pressurized Radial Gap}$$

b = Expanded inside radius of tube = [ ] 2, 3

t = Tube wall thickness = .048 in

R = [ ] 2, 3

E = Elastic modulus of Inconel = 29.4×10^6 psi, 600°F

ν = Poisson's Ratio = .3

P = Pressure = $P_1 - P_2$ = 2150 psi - 770 psi = 1380 psi

$GAP_{pressurized} = \Delta p$ = .0001041 in

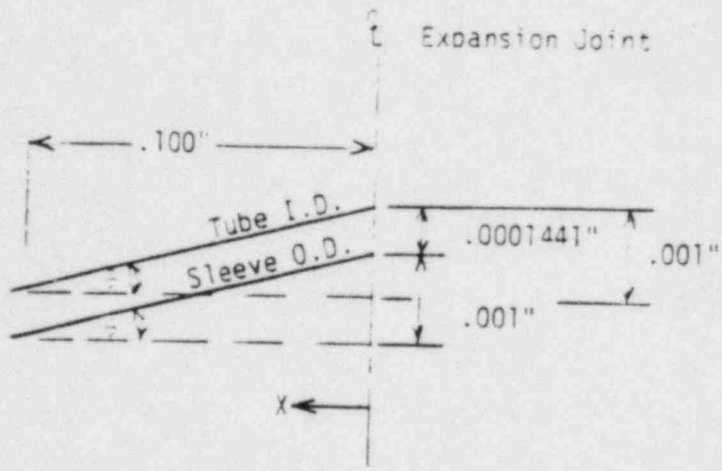
GAP_{radial} = .00004 in + .0001041 in = <u>.0001441 in</u>

7.2.2 Amount of Tube Separation

Now determine the maximum amount of tube separation before the sleeve comes in contact with both ends of the parent tube.

Figure 7-14 is an optical comparator plot for the expansion joint of a tube-sleeve assembly, from which the geometry of the expansion joint is determined.

FIGURE 7-4



$$\tan \theta = \frac{.001"}{.100"} = .01$$

Let X = axial gap of which there are two between the sleeve and tube

$$\tan \theta = .01 = \frac{.0001441}{X}$$

$$X = .01441 \text{ in}$$

Let d = maximum amount of tube separation

$$d = 2X = 2(.01441 \text{ in}) = .02882 \text{ in}$$

For conservatism, multiply d by 1.5:

$$d = 1.5\ (.02882 \text{ in}) = .043 \text{ in}$$

∴ The tube separates a maximum distance of .043 inches before the sleeve engages the parent tube.

7.2.3 Maximum Equivalent Static Load on Sleeve

The maximum axial load on the sleeve is determined from a simplified dynamic analysis of a severed tube-sleeve assembly.

The tube-sleeve assembly is modeled as a spring-mass system using the "ANSYS" computer program (Reference 7.3). The lower part of the severed tube and the tube sleeve are modeled as springs using the spring element STIF 14. The mass of the sleeve and the mass of both ends of the severed tube are modeled using the general mass element STIF21.

The distance that the upper part of the tube travels before the sleeve comes in contact with both ends of the parent tube is modeled with a gap condition. This consists of a gap and a stiffness associated with the closed gap. This stiffness is taken to be the rate at which the sleeve comes in contact with both ends of the tube. In order to simplify the dynamic analysis, the force on the spring-mass model is applied in compression rather than tension. This results in a compressive force in the sleeve whereas it should be a tensile force, but the magnitude is correct.

Spring-Mass Model of Sleeved Ruptured Tube

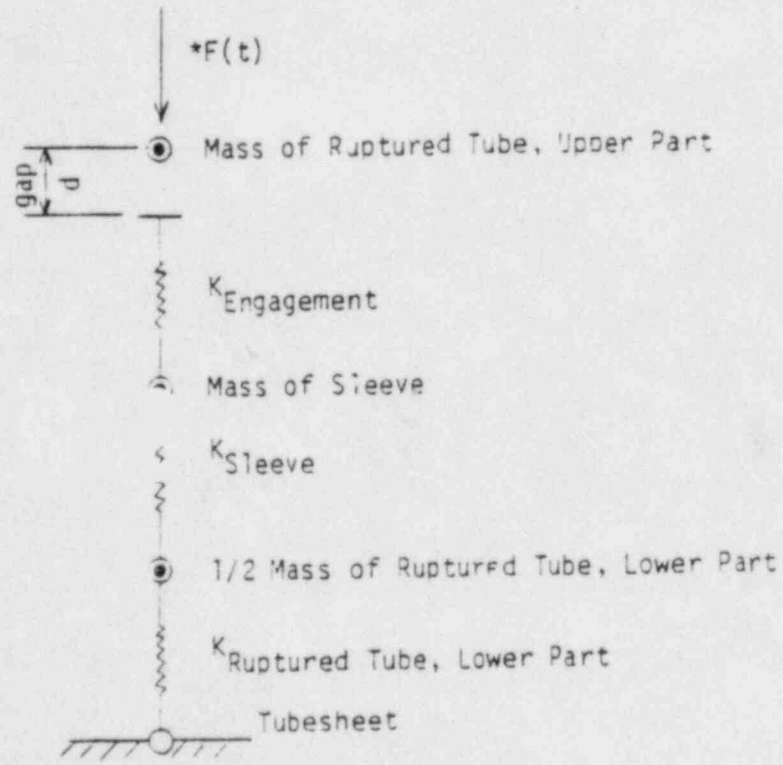


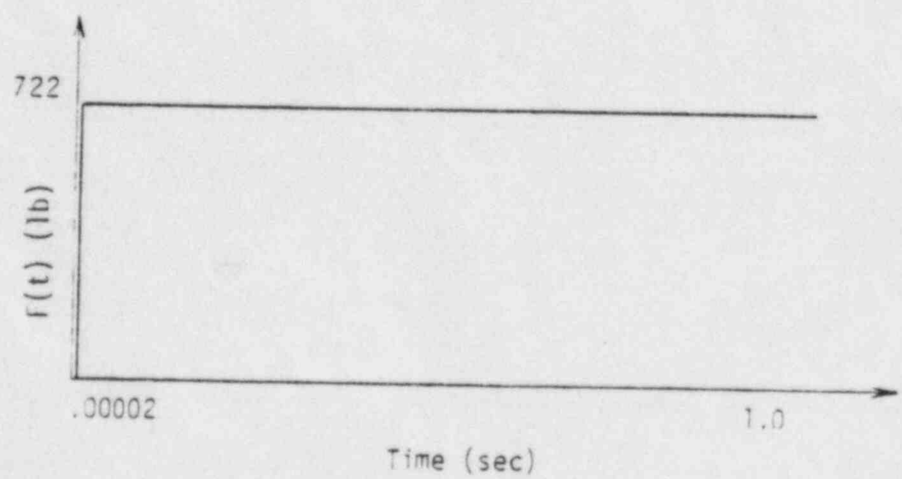
FIGURE 7-5

*F(t) is the blow-off force due to a main steam line break accident.

Using the preceeding simplified dynamic analysis, parametric studies of various tube rows and different defect locations indicate that Tube Row 1 at its uppermost support plate represents the worst case condition for a sleeved tube. This conclusion is also substantiated by examining the analytical solution to the simplified single degree of freedom problem. The above described location is 216 inches above the face of the tubesheet.

Now assume that a tube in Tube Row 1 is sleeved at this defect location and sustains an instantaneous circumferential failure at this location during an MSLB accident. A reduced linear transient analysis is performed using the spring-mass model. F(t) is the blow-off load on the severed tube. This force is conservatively assumed to be applied instantaneously to the severed tube. A force-time history is given below.

FIGURE 7-6



Blow-off Load for Main Steam Line Break

$F(t) = \text{Blow-off Load} = PA_{iT}$

$P = P_2 - P_1$

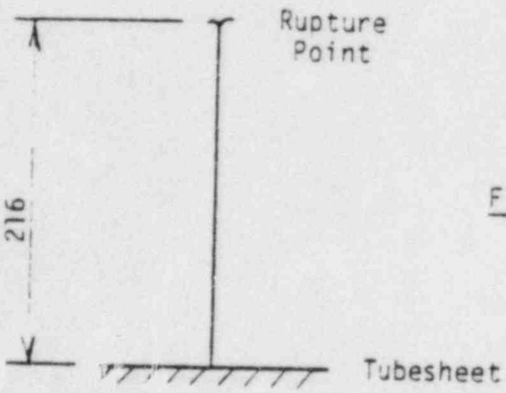
Where P_2 = Primary Pressure = 2150 psi

P_s = Secondary Pressure = 0 psi

P = 2150 psi - 0 psi = 2150 psi

$F(t)$ = 2150 psi x .336 in^2 = <u>722 lb</u>

<u>Mass of Severed Tube, Lower Part</u>



<u>FIGURE 7-7</u>

M_L = Mass of severed tube, lower part

$$M_L = (A_T\rho_T + A_{iT}\rho_i + CA_{oT}\rho_{oL})\frac{L_L}{g}$$

ρ_T = Density of tube material = .305 lb/in^3

ρ_i = Density of water in tube = .026 lb/in^3

ρ_{oL} = Density of water displaced by lower part of tube = .014 lb/in^3

A_T = Area of tube material = .106 in^2

A_{iT} = Inside area of tube = .336 in^2

A_{oT} = Outside area of tube = .442 in^2

C = Virtual mass coefficient = 1.0

L_L = Length of tube lower part = 216 in

g = 386 in/sec^2

M_L = .026 lb-sec^2/in

Mass of Severed Tube, Upper Part

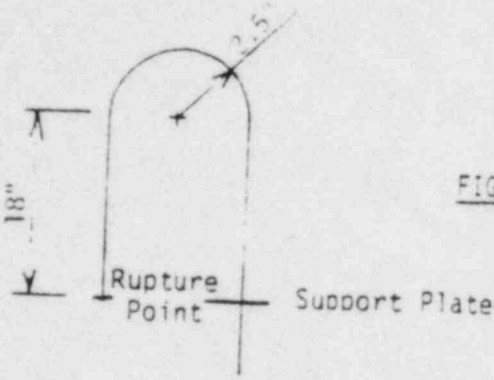


FIGURE 7-8

L_u = Length of tube, upper part

$L_u = 18 \text{ in} + \frac{2.5}{2} \pi \text{ in} = 21.9 \text{ in}$

M_u = Mass of severed tube, upper part

$M_u = (A_T \rho_T + A_{iT} \rho_i + C A_{oT} \rho_{ou}) \frac{L_u}{g}$

ρ_{ou} = Density of water displaced by upper part of tube = .008 lb/in^3

M_u = .0025 lb-sec^2/in

Mass of Sleeve

M_S = Mass of Sleeve

$M_S = (A_S \rho_S + A_{iS} \rho_i + C A_{oS} \rho_o) \frac{L_S}{g}$

ρ_S = Density of sleeve material = .305 lb/in^3

ρ_i = Density of water in sleeve = .026 lb/in^3

ρ_o = Density of water displaced by sleeve = .026 lb/in^3

A_S = Area of sleeve material = .059 in^2

A_{iS} = Inside area of sleeve = .248 in^2

A_{oS} = Outside area of sleeve = .308 in^2

C = Virtual mass coefficient = 1.0

L_S = Length of sleeve = 12.0 in

g = 386 in/sec^2

M_S = .001 lb-sec^2/in

Tube-Sleeve Assembly Parameters

R_{iS} = Inside radius of sleeve = .281 in

R_{oS} = Outside radius of sleeve = .313 in

t_S = Sleeve wall thickness = .032 in

L_S = Length of sleeve = 12.0 in

A_S = Area of sleeve material = .059 in^2

R_{iT} = Inside radius of tube = .327 in

R_{oT} = Outside radius of tube = .375 in

t_T = Tube wall thickness = .048 in

L_T = Length of tube from face of tubesheet to defect = 216.0 in

A_T = Area of tube material = .106 in^2

E = Elastic modulus = 29.4 X 10^6 psi, 600°F

K_S = Sleeve stiffness

K_T = Lower part of severed tube stiffness

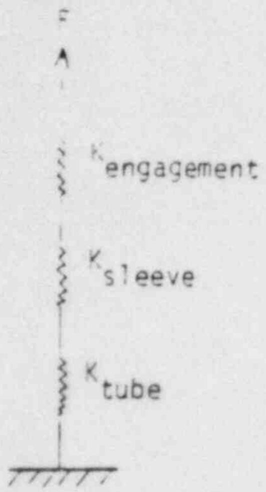
$$K_S = \frac{A_S E}{L_S} = 144550 \text{ lb/in}$$

$$K_T = \frac{A_T E}{L_T} = 14428 \text{ lb/in}$$

Rate of Sleeve Engagement

Now the rate at which the sleeve comes in contact with both ends of the parent tube will be determined using Figure 8-2. Figure 8-2 gives a load-displacement history for a tube-sleeve assembly as determined from a tensile pull test.

Tensile Pull Test



$$K = \frac{1}{\frac{1}{K_E} + \frac{1}{K_S} + \frac{1}{K_T}}$$

K_E = Rate of sleeve engagement

K_S = Sleeve stiffness as tested

K_T = Tube stiffness as tested

FIGURE 7-9

From Figure 8-2: $K = \frac{F}{\Delta} = \frac{2100 \text{ lb}}{0.25 \text{ in}} = 8400$ lb/in

(A conservatively stiff spring coefficient for the tube-sleeve assembly is chosen.)

$$K_S = \frac{A_S E}{L_S} = 144550 \text{ lb/in}$$

$$K_T = \frac{A_T E}{L_T} = 173133 \text{ lb/in}$$

A_S = Area of sleeve material = .059 in^2

L_S = Length of sleeve used in tensile test = 12.0 in

E = Elastic modulus = 29.4 X 10 lb/in^2

A_T = Area of tube material = .106 in^2

L_T = Length of tube used in tensile test = 18.0 in

$$K = \frac{1}{\frac{1}{K_E} + \frac{1}{K_S} + \frac{1}{K_T}}$$

$$\frac{1}{K_E} + \frac{1}{K_S} + \frac{1}{K_T} = \frac{1}{K}$$

$$\frac{1}{K_E} = \frac{1}{K} - \frac{1}{K_S} - \frac{1}{K_T} = .0001064$$

$$K_E = 9400 \text{ lb/in}$$

Coefficient of Viscous Damping

C = Coefficient of viscous damping

$C = 2\, M\, \zeta\, \omega_N$

M = Total mass of spring-mass system

ζ = Viscous damping factor = 1% = .01 (Ref. 7.6)

ω_N = Natural frequency of spring-mass system

$$\omega_N = \sqrt{\frac{K}{M}} = 775 \text{ rad/sec}$$

$$K = 8400 \text{ lb/in}$$

$$M = \frac{.026}{2} \frac{\text{lb-sec}^2}{\text{in}} + .001 \frac{\text{lb-sec}^2}{\text{in}} = .014 \frac{\text{lb-sec}^2}{\text{in}}$$

$$C = 2\left(.014 \frac{\text{lb-sec}^2}{\text{in}}\right)(.01)\left(775 \frac{\text{rad}}{\text{sec}}\right)$$

$$C = .22 \frac{\text{lb-sec}}{\text{in}}$$

Maximum Equivalent Static Load on Sleeve

The results of the dynamic analysis of the spring-mass system are shown in Figure 7-15. The peak force in the sleeve is taken to represent the maximum equivalent static load on the sleeve.

$$F_{Peak} = 1560 \text{ lb} = F_{Sleeve}$$

This maximum axial load will now be compared with the load required to pull apart a severed tube-sleeve assembly, and a factor of safety for sleeve disengagement will be determined. This failure load was determined from unpressurized experimental tensile pull tests.

$\underline{F_{Failure} > 3795 \text{ lb}}$

$$\text{Factor of Safety} = \frac{F_{Failure}}{F_{sleeve}} = \frac{3795}{1560} = 2.4$$

This factor of safety shows that there is a large margin of safety for sleeve disengagement.

7.3 FAILURE MODE DETERMINATION

In this section, a comparison is made between the calculated modes of failure of the tube-sleeve expansion joint and experimental test results. Sample severed tube-sleeve assemblies which have been experimentally pulled apart are studied to determine the mode of failure.

Figure 7-17 shows a tube-sleeve assembly that has been pulled apart.

This specimen indicates that the sleeve yielded and the tube did not. The specimen also indicates that the sleeve necks down when the assembly is pulled apart. This neck-down at the tube-sleeve expansion joint reduces the normal force between the sleeve and tube, thus lowering the friction force and allowing the sleeve to be pulled out of the tube.

Now a mode of failure is analytically determined.

7.3.1 Stress in Tube Sleeve

The stress in the sleeve is determined assuming an instantaneous circumferential failure of the parent tube during a MSLB accident. The stress is calculated for the static case using the maximum equivalent static load on the sleeve as determined in Section 7.2.3.

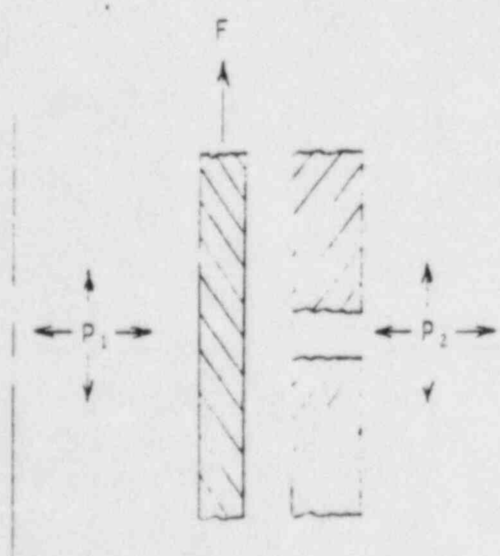


FIGURE 7-10

$F = F_{sleeve} = 1660$ lbs (Section 7.2.3)

R_{oS} = Outside radius of sleeve = .313 in

R_{iS} = Inside radius of sleeve = .281 in

t_S = Sleeve wall thickness = .032 in

A_S = Area of sleeve material = $\pi (R_{oS}^2 - R_{iS}^2)$ = .059 in^2

$P = P_1 - P_2$ = 2150 psi - 0 = 2150 psi

$$\sigma_x = \frac{F}{A_S} = 26.4 \text{ ksi}$$

$$\sigma_\theta = \frac{PR}{t_S} = 19.9 \text{ ksi}$$

Where $R = (R_{oS} + R_{iS}) / 2 = .295$ in

$$\sigma_r = -\frac{P}{2} = -1.1 \text{ ksi}$$

$S.I._{max} = \sigma_x - \sigma_r$ = 26.4 ksi + 1.1 ksi

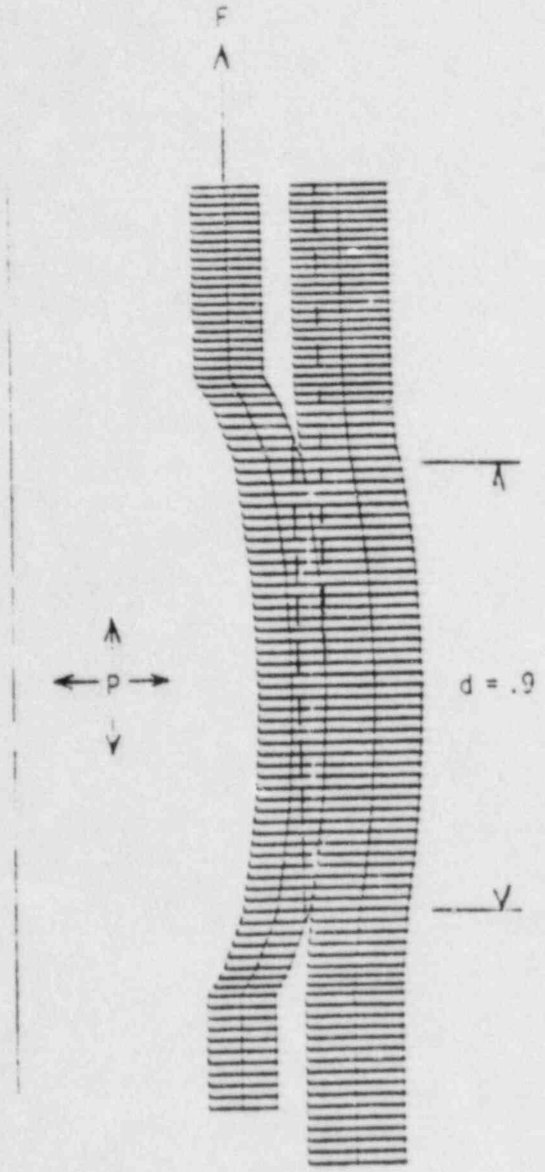
$S.I._{max}$ = 27.5 ksi < $^*\sigma_{allow} = 0.7\ \sigma_{ultimate}$ = 56.0 ksi

Note: $S.I._{max}$ = 27.5 ksi < σ_{yield} = 27.9 ksi

* From Appendix F of Ref. 7.1.

7.3.2 Strain Energy Analysis

Assume that an instantaneous circumferential failure has occurred in a sleeved tube. The force required to pull the sleeve out of the parent tube is determined.



F is the force required to pull the sleeve a distance of d = .9".

Note:

(1) The effect of P is ignored in order to conform with the axial pull tests.

(2) d is the distance over which the sleeve and tube are in contact.

FIGURE 7-11

R_{oT} = Outside radius of tube = .375 in

R_{iT} = Inside radius of tube = .327 in

R'_{oT} = Expanded outside radius of tube = [ ] 2, 3

R'_{iT} = Expanded inside radius of tube = [ ] 2, 3

t_T = Tube wall thickness = .048 in

R_{oS} = Outside radius of sleeve = .313 in

R_{iS} = Inside radius of sleeve = .281 in

R'_{oS} = Expanded outside radius of sleeve = [ ] 2, 3

R'_{iS} = Expanded inside radius of sleeve = [ ] 2, 3

t_S = Sleeve wall thickness = .032 in

<u>Hoop Stress</u>

$$\sigma_{sleeve} = -\frac{P'R'_{oS}}{t_S} = -\frac{.340}{.032}\ P' = -10.6\ P'$$

$$\sigma_{tube} = \frac{P'R'_{iT}}{t_T} = \frac{.340}{.048}\ P' = 7.1\ P'$$

Where P' is contact pressure between the sleeve and tube.

$\sigma_{tube} = -2/3\ \sigma_{sleeve}$.

σ_{yield} = 31.5 ksi at 600F (see Figure 7-16).

∴ σ_{sleeve} may attain a maximum value of 47.3 ksi before the tube yields.

∴ <u>The sleeve will deform plastically and not the tube.*</u>

* <u>Note</u>: This assumes that the sleeve and tube have the same yield strength.

The work done in deforming the sleeve is equal to the change in strain energy of the sleeve material.

$$W = \Delta U$$

Where W = work

ΔU = change in strain energy

$$\Delta U = V \int_{\varepsilon_1}^{\varepsilon_2} \sigma \, d\varepsilon$$

Where: V = Volume of deformed material

$$V = \pi \, (R_{oS}^2 - R_{iS}^2) \, (.9) = .053 \text{ in}^3$$

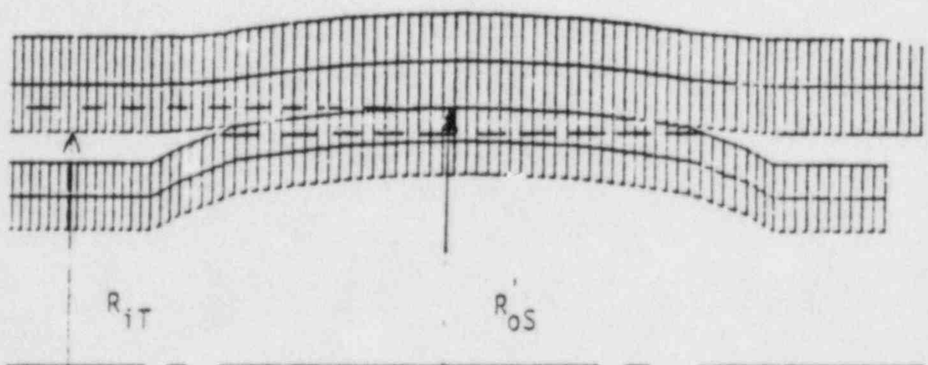


FIGURE 7-12

$$\varepsilon = \frac{\delta}{R'_{oS}} = \frac{R'_{oS} - R_{iT}}{R'_{oS}} = .038 = 3.8\%$$

Assume that the material exists in a virgin state: $\varepsilon_1 = 0$. This is conservative since it yields a lower strain energy.

Assume that $\varepsilon_2 = \frac{1}{2}\varepsilon = .019 = 1.9\%$.

(In being pulled thru the tube, the sleeve experiences 3.8% strain only at the peak of the expansion joint.)

From Figure 7-16: $\int_0^{1.9\%} \sigma d\varepsilon = A = 644$ psi

$\Delta U = (.053\ in^3)(644\ lb/in^2) = \underline{34\ in\text{-}lb}$

$\therefore$ The energy required to deform the sleeve is ΔU = 34 in-lbs.

Two types of work are done by pulling the sleeve a distance d - positive work by the force F and negative friction work.

W = total work done on sleeve = $W_F - W_f$

W_F = work done by force on sleeve = $F \cdot d = 0.9\ F$

W_f = friction work = $\mu N \cdot d$

$$\sigma_{yield} = 31500\ psi = \frac{P' R_{iT}}{t_s}$$

$$P' = \frac{\sigma_y \times t_s}{R_{iT}} = \frac{31500 \times .032}{.327} = 3082\ psi$$

N = Normal force between sleeve and tube

$N = 2\pi R_{iT} \times d \times P = 5700$ lb

μ = Coefficient of friction between sleeve and tube

μ = .8 (from experimental pull test results)

$$W_f = \mu N d = .8 \times 5700 \times .9 = 4104\ in\text{-}lb$$

$$W = W_F - W_f = \Delta U$$

$$W = 0.9\ F - 4104\ in\text{-}lb = 34\ in\text{-}lb$$

$$0.9\ F = 4070\ in\text{-}lb$$

$$F = 4522\ lb$$

Where F is force required to deform the sleeve and move it the distance d.

From Section 7.2.3, the maximum applied load on the sleeve during a main steam line break is 1560 lbs.

Comparing the force required to pull the sleeve out of the tube and the maximum applied load on the sleeve gives a factor of safety for sleeve disengagement.

$$\text{Factor of safety} = \frac{4522 \text{ lb}}{1560 \text{ lb}} = 2.9$$

Again this factor of safety indicates a large margin of safety. In fact, sufficient room is not available within the tube bundle for the tube to separate axially even if sufficient force was available. This adds to the already large margin of safety against sleeve disengagement.

In summary, the mode of failure for the tube-sleeve assembly will be a neck-down of the sleeve if sufficient force and freedom for the tube to separate axially were available, which agrees with the experimental test results.

7.4 ALLOWABLE SLEEVE DEGRADATION

This analysis is intended to determine the effect of a tube-sleeve assembly with 100% degraded tube on previous analytical assessments of postulated loadings and safety margins (Reference 7.2).

Healthy Sleeve: R_{os} = .313 in

R_{is} = .281 in

t = .032 in

I = .0026 in^4

Z = .0084 in^3

7.4.1 NRC Staff Criteria (Reference 7.8)

Determination of minimum required thickness t_R.

i. Normal Operation

Tubes with defects will not be stressed beyond the elastic range of the tube material.

S_y < 27.9 ksi, 600 F

$$t_R = \frac{\Delta P\, R_{is}}{S_y - 0.5\,(P_1 + P_2)}$$

P_1 = 2150 psi

P_2 = 770 psi

ΔP = 1380 psi

$$t_R = \frac{1.38\,(.281)}{27.9 - 0.5\,(2.92)}$$

t_R = .015

% Allowable degradation of sleeve

$$\% = \frac{.032 - .015}{.032} \times 100$$

= 53

ii. Normal Operation

The factor of safety against failure by bursting is not less than three at any tube location where defects have been detected.

$3\sigma < S_u = 80.0$ ksi, 600F

$$t_R = \frac{3\Delta P\ R_{is}}{S_u - 0.5\ (P_1 + P_2)}$$

$P_1 = 2150$ psi

$P_2 = 770$ psi

$\Delta P = 1380$ psi

$$t_R = \frac{3(1.38)(.281)}{80.0 - 0.5\ (2.92)}$$

$t_R = .015$

% Allowable degradation of sleeve

$$\% = \frac{.032 - .015}{.032} \times 100$$

<u>% = 53</u>

iii. Main Steam Line Break

Defects that could lead to rupture during a main steam line break accident condition would not be acceptable.

$\sigma < .7\ S_u = 56.0$ ksi, 600 F

$$t_R = \frac{\Delta P\ R_{is}}{.7\ S_u - 0.5\ (P_1 + P_2)}$$

$P_1 = 2150$ psi

$P_2 = 0$

$\Delta P = 2150$ psi

$$t_R = \frac{2.15\ (.281)}{56.0 - 0.5\ (2.15)}$$

$t_R = .011$

Allowable degradation of sleeve

$$= \frac{.032 - .011}{.032} \times 100$$

$\underline{\% = 65}$

Of the three criteria, the first and second one are the most restrictive. For these criteria, the allowable sleeve wall degradation is 53%.

7.4.2 Combined LOCA + SSE Analysis

The LOCA + SSE analysis considers stresses produced by various hydraulic phenomena associated with rapid flow through the tubes, the dynamic responses due to the impulsive load occurring at the pipe break opening, safe shutdown earthquake induced accelerations, and differential pressure. Stresses resulting from these loadings are combined elastically in a conservative manner and evaluated against an allowable for faulted conditions, determined from Appendix F, Section III of the ASME Code.

The elastic analysis is intended to provide justification for establishing the allowable sleeve wall degradation. At some later time, a plastic analysis will be performed to provide additional evidence in support of the conclusions drawn from the elastic results. A static plastic analysis will be performed on a degraded sleeve using the ANSYS computer program. Experimental work will be performed to demonstrate the conservatism and accuracy of the ANSYS computer program.

From Reference 2:

(i) Tube Row 110 exhibits the most severe moment due to the lateral LOCA + SSE loading.

(ii) The value of this moment is 402.5 in-lb.

(iii) $P_i = 0$

$P_o = 770$ psi

Combined Stress Intensity

FIGURE 7-13

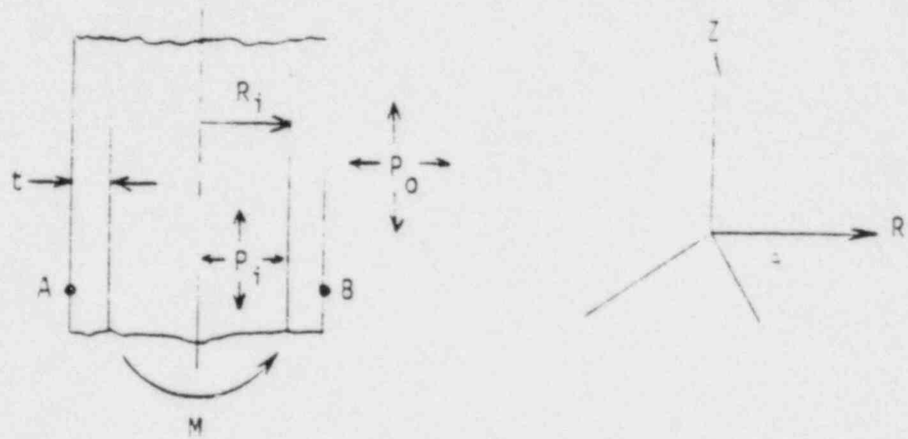


TABLE 7-1

Healthy Sleeve t_s = .032 in
R_{is} = .281 in
Z = .0084 in³

Loading	Type of Stress	Stress (ksi) A	Stress (ksi) B
LOCA + SSE	$\sigma_z = \pm \frac{M}{Z}$	+47.9	-47.9
	$\sigma_z = \frac{(Pi - Po)Ris}{2t_s}$	+ 3.4	+ 3.4
Pressure	$\sigma_\theta = \frac{(Pi - Po)Ris}{t_s}$	+ 6.3	+ 6.8
	$\sigma_r = - P_o$	- 0.8	- 0.8

Stress Intensity = (47.9 + 3.4 + 0.8)

Point A = 52.1 ksi < allowable = 80.6 ksi

Stress Intensity = (-47.9 + 3.4 - 6.8)

Point B = 51.3 ksi < allowable = 80.6 ksi

Now solve for the required sleeve wall thickness of a degraded sleeve by an iterative solution.

TABLE 7-2

Degraded Sleeve t_s
R_{is} = .281 in
Z

Loading	Type of Stress	Stress (ksi) A	Stress (ksi) B
LOCA + SSE	$\sigma_z = \pm \frac{M}{Z}$	$+\frac{.4025}{Z}$	$-\frac{.4025}{Z}$
	$\sigma_z = \frac{(P_i - P_o)R_{is}}{2t_s}$	$+\frac{.108}{t}$	$+\frac{.108}{t}$
Pressure	$\sigma_\theta = \frac{(P_i - P_o)R_i}{t_s}$	$+\frac{.216}{t}$	$+\frac{.216}{t}$
	$\sigma_r = -P_o$	-0.8	-0.8

Stress Intensity Point A = $\left[\frac{.4025}{Z} + \frac{.108}{t} + 0.8\right] < 80.6$ ksi

$$\left[\frac{.4025 \times R_{os}}{\frac{\pi}{4}(R_{os}^4 - .281^4)} + \frac{.108}{(R_{os} - .281)} + 0.8\right] < 80.6 \text{ ksi}$$

R_{os} = .302

74.3 ksi + 5.1 ksi = 79.4 ksi < 79.8 ksi

t_s = .302 in - .281 in = .021 in

Allowable degradation of sleeve

$$\% = \frac{.032 - .021}{.032}$$

% = 34

7.4.3 Summary of Allowable Sleeve Degradation

(i) NRC Staff's Criteria

% Allowable sleeve degradation = 53

(ii) LOCA + SSE

% Allowable sleeve degradation = 34

Based on these results, the maximum sleeve wall degradation permitted should be 34%.

7.5 SLEEVED TUBE VIBRATION ANALYSIS

7.5.1 Vibration Response Test

A test will be conducted which models a cluster of seven tubes with Palisades plate and "eggcrate" tube supports. The vertical straight tube region from the tube sheet to the highest "eggcrate" support will be represented. Several tubes will be sleeved in a probable sleeving location. Circumferential defects of 64% and 100% degradation will be simulated in the sleeved tubes. The tests will be conducted with shell-side water at room temperature. Using secondary side water at room temperature (ρ = 62.4 lb/ft^3) is conservative since the operating secondary coolant is less dense (ρ = 49.3 lb/ft^3 maximum) and thereby decreases the virtual mass. Primary coolant is omitted from the test but a compensating density correction will be made to the test data. At the completion of these tests, an examination of the tube/sleeve joints will be made to ensure that vibration has not caused wear of metal surfaces or loosening of the joints.

A mechanical shaker will input a lateral acceleration of 1 G into the base plate, which is connected to the tubesheet, sweeping from 20 H_z to 200 H_z. The 1 G base plate acceleration is a more severe forcing function than that anticipated in service. The selection of 1 G is predicated on control of test equipment and accuracy in the interpretation of response data. Tube responses will be measured at several locations in each tube span as well as at support locations for four of the seven tubes in the cluster (see Figure 7-18). Even numbered support plates are used in the test bundle to provide the longest span from the tubesheet to the lowest tube support plate. It is conservative to model tubes which pass through alternate tube support plates since longer spans produce lower natural frequencies. Data from these tests would assess the effect of the presence of the tube sleeve from the standpoint of dynamic tube response. In addition information with regard to natural frequency and damping would be obtained. For virgin tubes the fundamental natural frequencies are as follows (Reference 7.10):

At the tubesheet (Fixed-Simple)

$$f_n = \frac{15.4}{2\pi}\sqrt{\frac{EI}{M_T L^3}}$$

$$= 36.9\ H_z$$

where - L = 48.0 in.
I = 0.00655 in^4
E = 29.4 x 10^6 psi
M_T = .0077 $\frac{lb\text{-}sec^2}{in.}$

Between Drilled Support Plates and "Eggcrates" (Simple-Simple)

$$f_n = \frac{9.87}{2\pi}\sqrt{\frac{EI}{M_T L^3}}$$

$$= 33.5\ H_z$$

Where L = 38.0 in (Typical)

A comparison of the measured sleeved tube natural frequencies with the frequencies of virgin tubes will provide a qualitative assessment of the presence of the sleeved tubes.

7.5.2 Shellside Flow Vibration Test

A test which models the bundle entrance region of secondary fluid (at the tubesheet) has been completed and is generic to all CE steam generators. The test was run at room temperature with a maximum flow rate of 4500 GPM. Tube motion was recorded with internally mounted strain gages and accelerometers. In addition pressure drop, velocity profiles and water temperatures were recorded. Several tubes in the array were monitored simultaneously to determine the relationship of one tube's movement with regard to another. All data was viewed in a real time mode as well as being recorded on tape. This test enabled a quantitative appraisal of tube vibration in water cross flow (see Figure 7-19). Since the tube external geometry is only slightly affected by the presence of a sleeve, this test data is valid for predicting forcing functions on a sleeved tube.

7.6.3 Tube Vibration Design Criteria

Testing and findings in Reference 7.9, indicate the predominant vibratory forcing function in the secondary fluid bundle entrance region was fluid elastic coupling. Fluid elastic coupling occurs when sufficient flow velocity exists to put the tube in a motion which leads to the establishment of a feedback mechanism. This causes ever increasing amplitude of vibration until either a balance is reached between fluid energy absorbed and energy dissipated through damping by the tube or impacting ensues. The pertinent relationship is as follows:

$$V_{critical} = \frac{K}{LF} f_n \, d \sqrt{m_o \delta_o / \rho \, d^2}$$

Where:

K - Experimental Constant = [ ]

LF - Length Factor - 16/48 = 0.33

f_n - Tube Span Natural Frequency = 36.9 H_z

d - Tube Outside Diameter - 0.75 in = .0625 ft

m_o - Tube Virtual Mass = 0.745 lb/ft

δ_o - Logarithmic Decrement = 0.157 ($\delta_o = 2\pi\zeta$)

ζ - Damping Ratio = 2.5%

ρ - Fluid Density = 49.3 lb/ft^3

For Palisades the secondary fluid bundle entrance velocity in the tube gap was calculated to be 11.0 feet/second at 100% power.

7.6 REFERENCES FOR SECTION 7

7.1 ASME Boiler and Pressure Vessel Code, Section III for Nuclear Vessels.

7.2 Letter from David A. Bixel, Consumers Power Company, to the Director of Nuclear Reactor Regulation, Operating Reactor Branch No. 1, U.S. Nuclear Regulatory Commission, dated February 12, 1976, Concerning Docket 50-255, License DPR-20, Palisades Plant, Steam Generator Tube Plugging Criteria - "Analysis to Determine Allowable Tube Wall Degradation for Palisades Steam Generator," January 29, 1976, and Revision 1, March 15, 1976, Revision 2, March 20, 1976.

7.3 ANSYS, Engineering Analysis System, User's Manual, John A. Swanson. 1971.

7.4 CENC-1120 (Palisades Steam Generator Final Report).

7.5 Engineering Specification for a Steam Generator Assembly, Spec. No. 70P-002 (Palisades).

7.6 Regulatory Guide 1.61, Damping Values for Seismic Design of Nuclear Power Plants.

7.7 "Hydrodynamic Inertia Coefficients for a Tube Surrounded by Rigid Tubes," Moretti and Lowery, June 23, 1975, ASME Publication 75-PVP-47.

7.8 Testimony of James Knight before the Atomic Safety and Licensing Board in the Matter of Northern States Power Company (Paririe Island Nuclear Generating Plant, Units 1 and 2). Docket Nos. 50-282, 50-306.

7.9 "Fluidelastic Vibration of Tube Arrays Excited by Cross Flow," H. J. Connors, Jr., Westinghouse Research and Development Center.

7.10 <u>Mechanical Vibrations</u> (Fourth Edition), by J. P. Den Hartog; Mcgraw-Hill Book Company, New York, N. Y.

$V_{critical}$ = [ ] ft/sec.

Testing results indicate that tube movement and subsequent stress are at low levels until the threshold of instability is reached. Since V < $V_{critical}$, no vibration problems are anticipated for virgin tubes. Similarly, unless there is large divergence in dynamic response or natural frequency between virgin tubes and sleeved tubes, no vibration problems are anticipated for sleeved tubes. The sleeved tube parameters measured in the "Vibration Response Test" will be evaluated for critical velocity.

7.5.4 Axial Flow Region

The 1-1/2 MWt steam generator model duplicates flow induced vibration in the axial flow region. The model is a minature steam generator with 21 active U-bend tubes, having an average length of approximately 25.5 feet. Control features enable the parameteric operation of the model in all ranges of steam quality, mass flow rate and steam pressure which are experienced in CE steam generators. Vibration data was taken with high temperature strain gages mounted 90° apart circumferentially at a given elevation. From the raw output data, the resultant vibration amplitude as a function of frequency was plotted and evaluated. Final data reduction is in progress but preliminary results are now available.

Results from the 1-1/2 MWt Steam Generator Model Test (see Figure 7-20) indicate a low level of tube vibration in this region. The maximum amplitudes measured did not exceed 0.005 inches. Thus no vibratory problems are anticipated in this region which extends the length of the vertically straight tubes. Based on the dynamic response data obtained from the "Vibration Response Test" for sleeved tubes, an evaluation of the maximum expected amplitude of vibration will be made for sleeved tubes in the axial flow region.

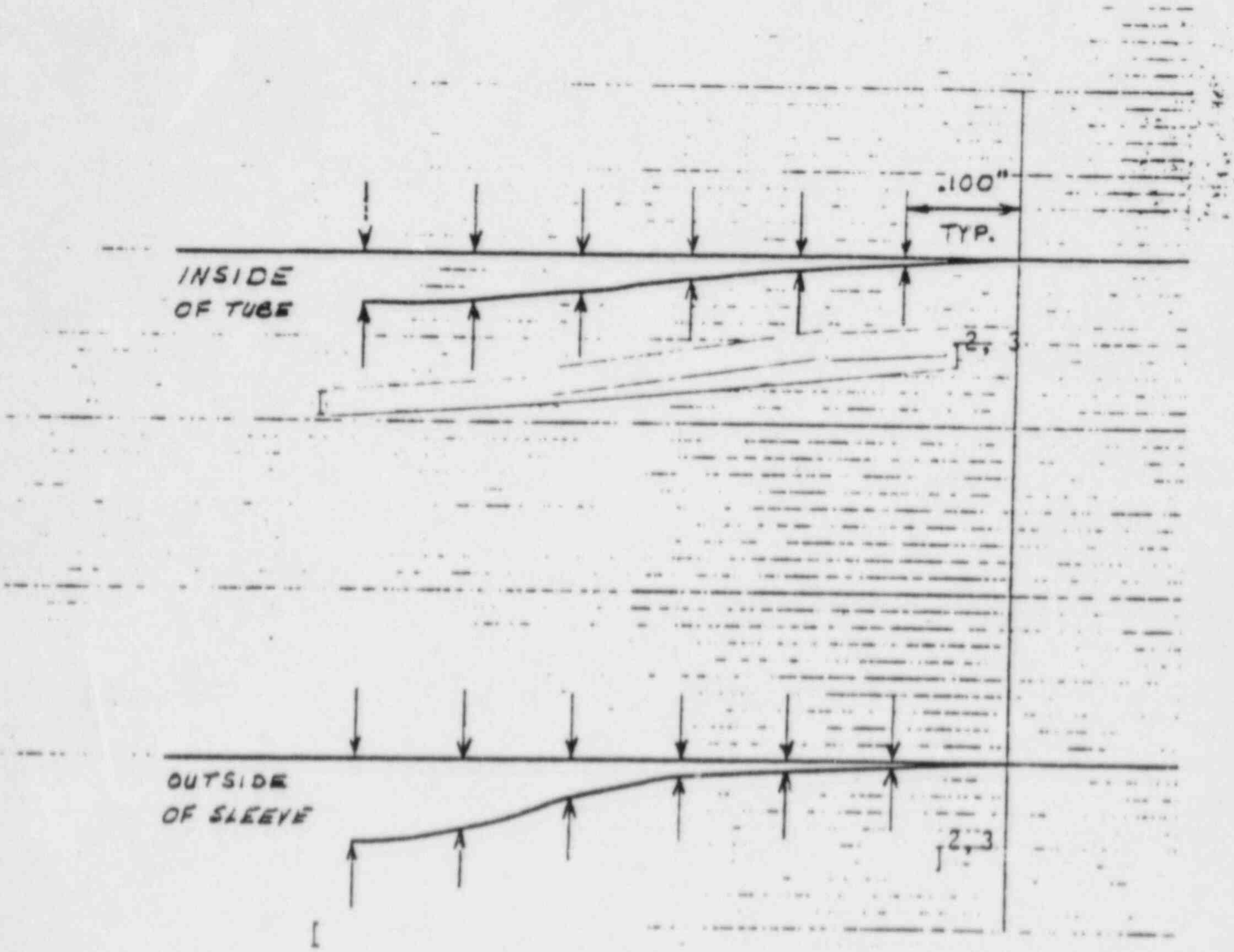


FIGURE 7-14

OPTICAL COMPARATOR PLOT FOR PROFILE
TUBE - SLEEVE ASSEMBLY EXPANSION JOINT

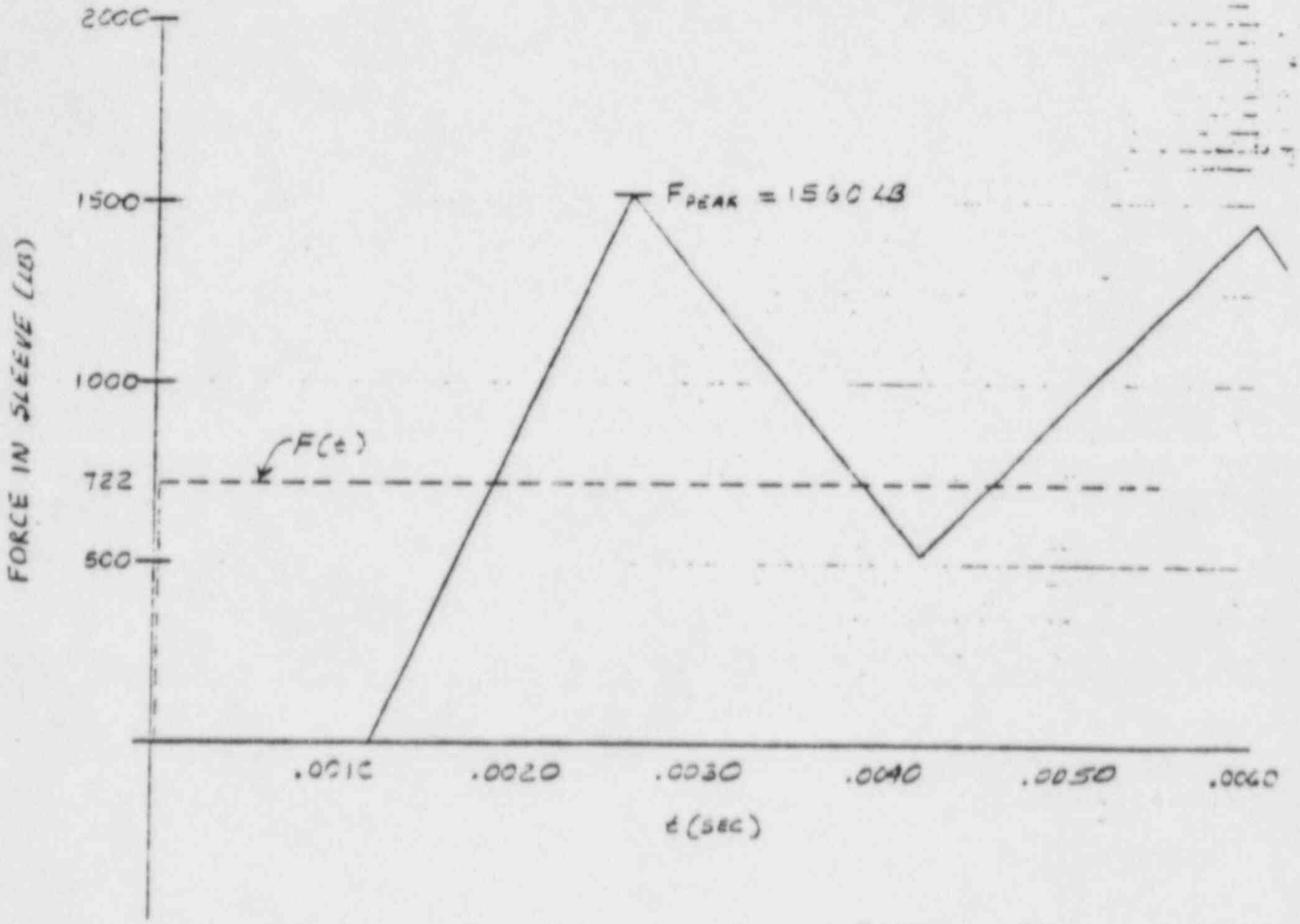


FIGURE 7-15

TUBE - SLEEVE RESPONSE HISTORY

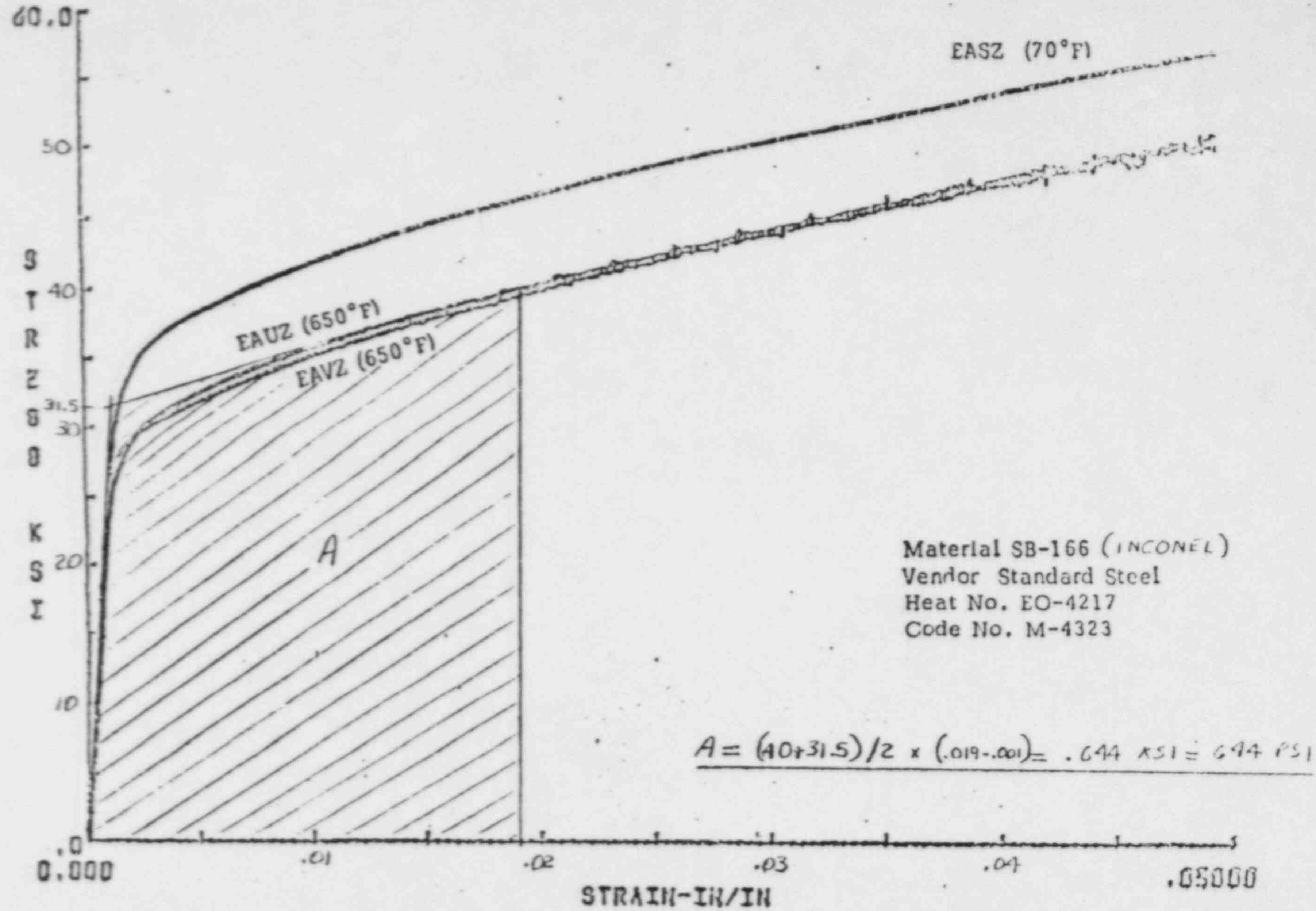


FIGURE 7-16 Stress-Strain Curves to 0.05 In/in Strain

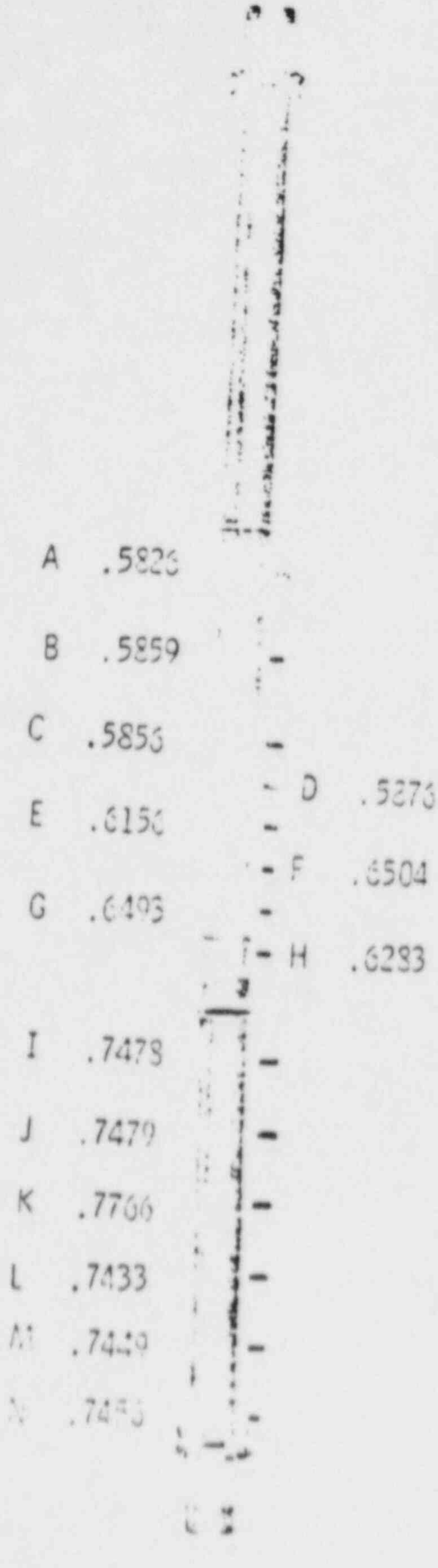


FIGURE 7-17

AMPOULE NO. A-HG-1[illegible]

[illegible] TO FULL SEPARATION

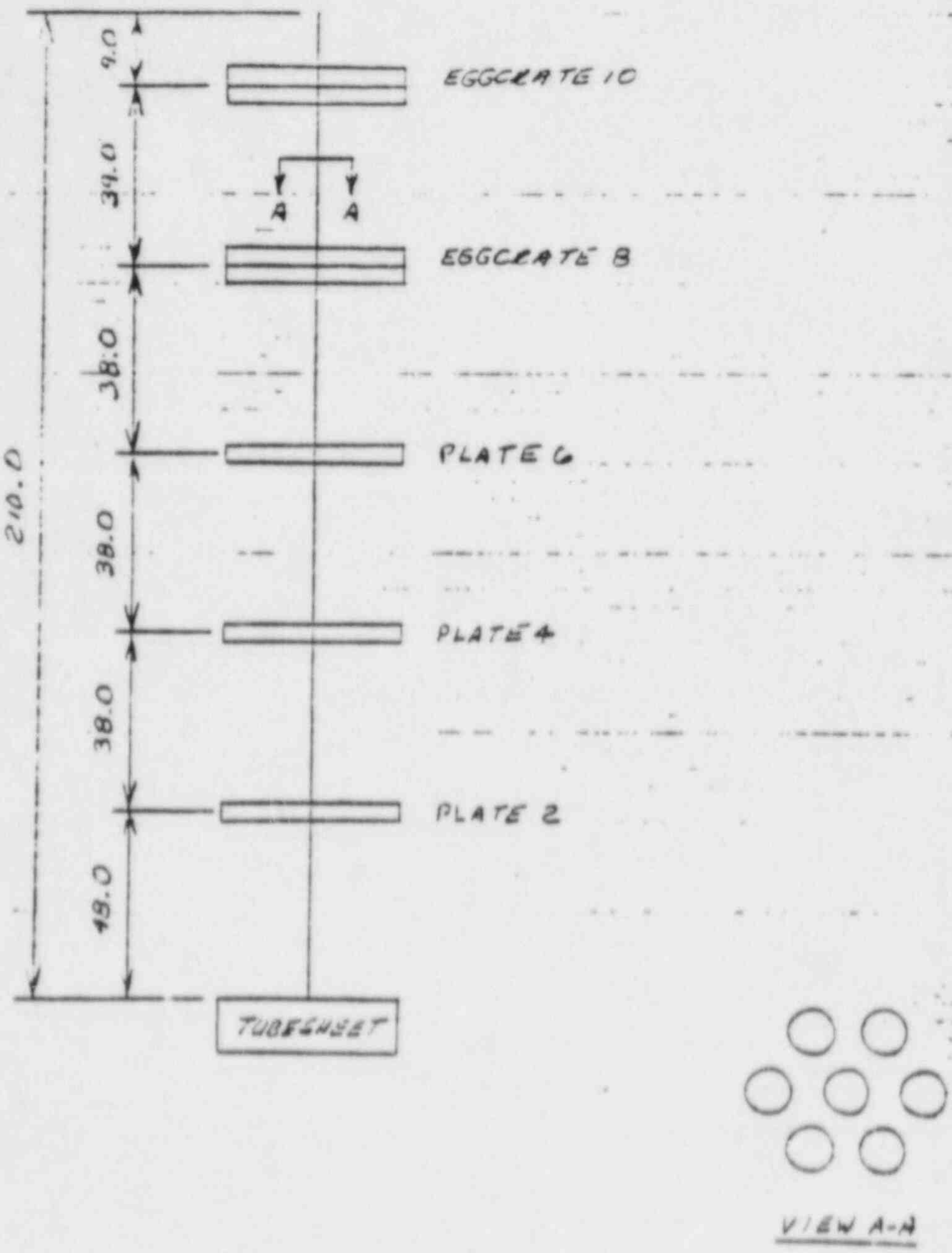
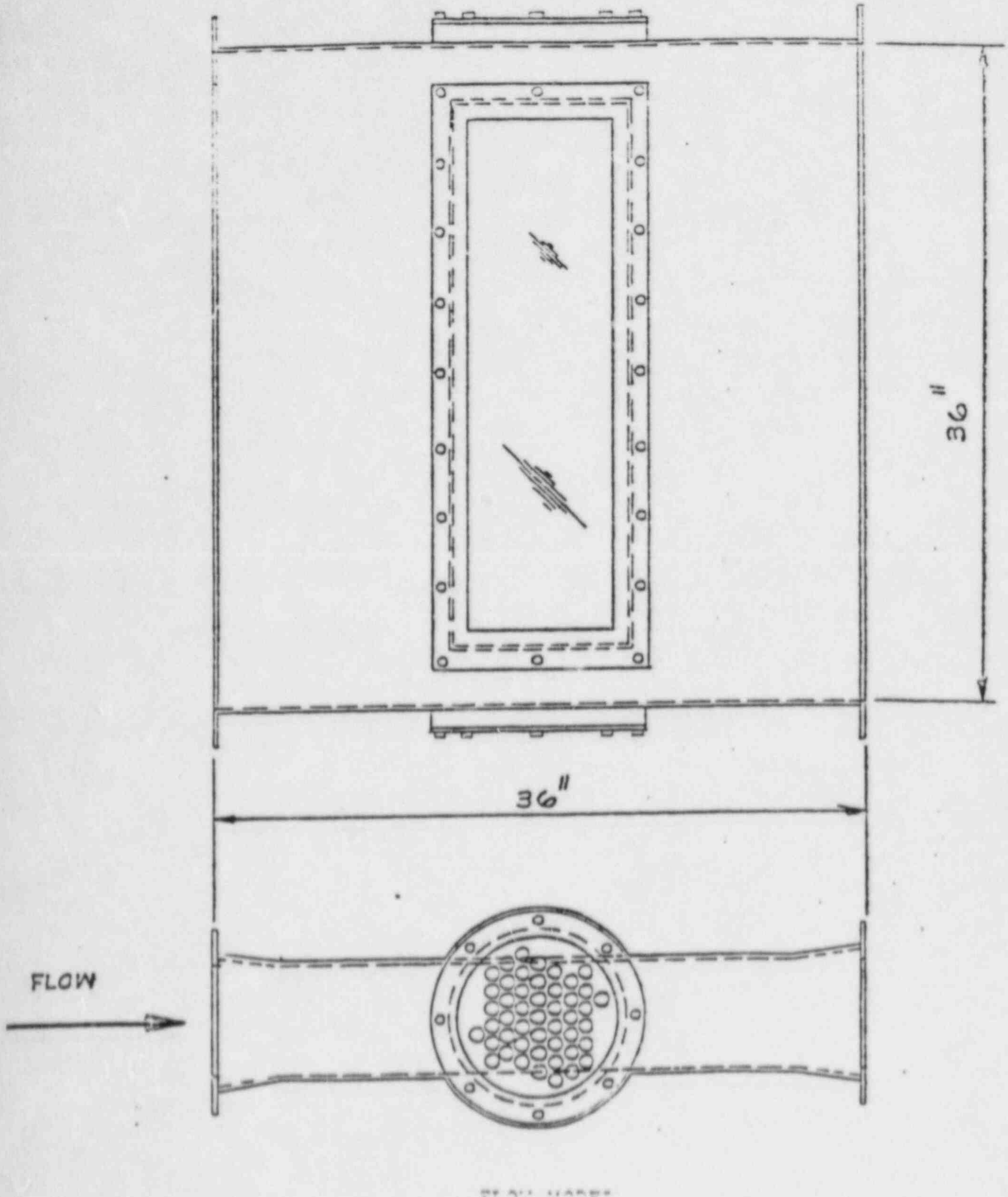


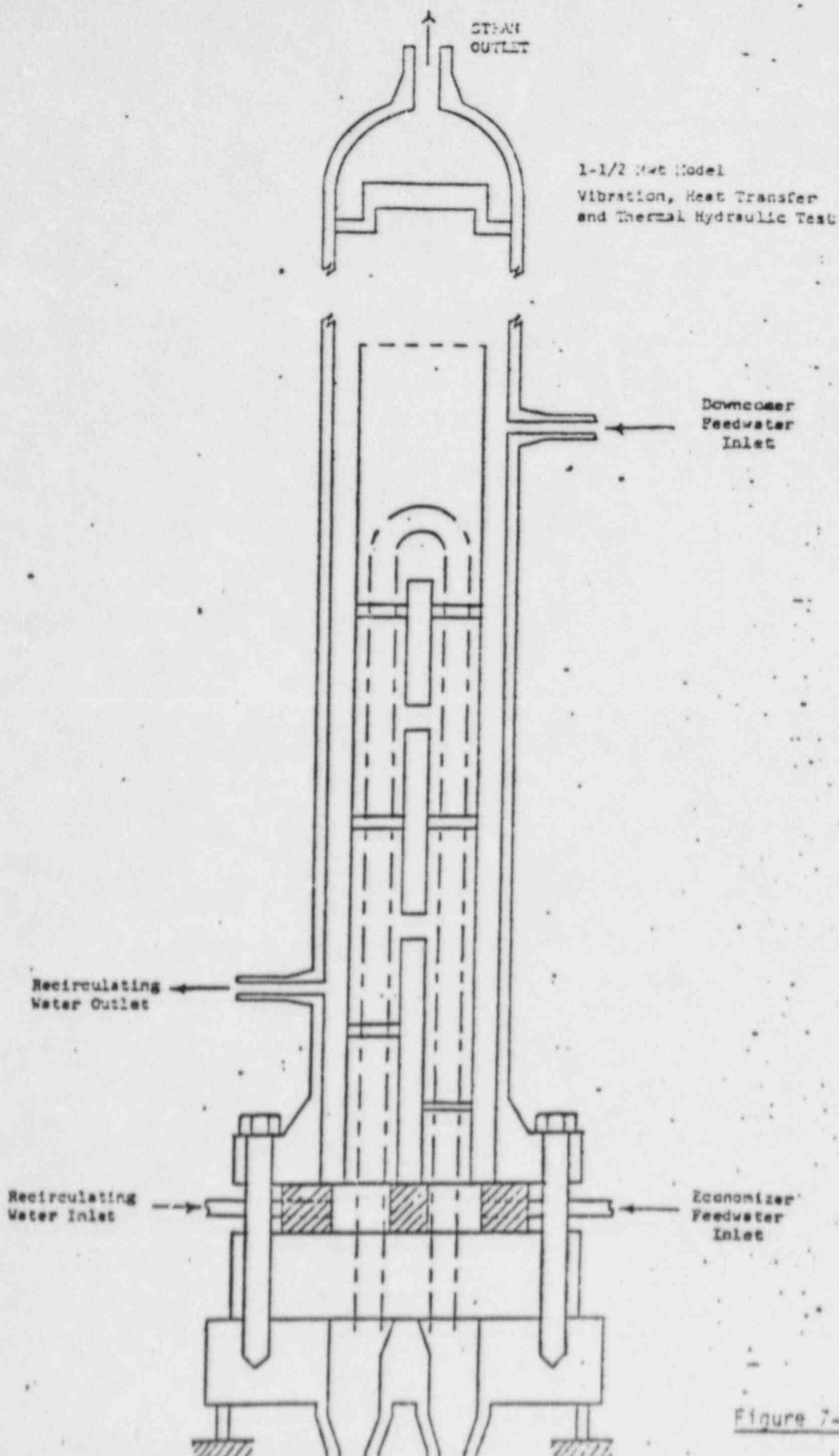
FIGURE 7-13

PALISADES SUPPORT ARRANGEMENT



FLOW MODEL

Figure 7-19



STEAM OUTLET
1-1/2 Mwt Model
Vibration, Heat Transfer and Thermal Hydraulic Test
Downcomer Feedwater Inlet
Recirculating Water Outlet
Recirculating Water Inlet
Economizer Feedwater Inlet

Figure 7-20

8.0 MECHANICAL TESTS OF TUBE/SLEEVE ASSEMBLY

Mechanical testing of the tube/sleeve assembly was performed to provide a characterization of its performance under a range of normal and postulated accident steam generator operating conditions.

8.1 SUMMARY AND CONCLUSIONS

The looseness, leakage and reaction to thermal/pressure cyling properties of the tube/sleeve assembly were characterized. The capability of the assembly to withstand postulated conditions of loss of coolant and main steam line break were demonstrated. Preliminary tests indicate potential axial movement of the sleeve in the unpressurized tube of 0.001 to 0.003 inches end to end, with application of a 25 pound load. Leakage rates of 1 to 10 cc/minute were evident in early internal pressure tests. The preliminary thermal cycling tests indicate no change in joint characteristics (leakage or looseness) resulting from that environment. Uniaxial tensile testing of a sleeved steam generator tube with a through wall circumferential defect, indicated that more than three times the axial load resulting from the internal pressure effective during a main steam line break is required to separate the tube from the sleeve. Pressurization of a sleeve sample inside diameter resulted in material yielding at greater than 185 percent of the normal operating pressure differential (Criteria 1, Table 8-3) and burst at greater than four times the normal Palisades reactor operating pressure differential (Criteria 2, Table 8-3). While all of these results are preliminary in nature (results of final testing will be reported later), all indications are that the repair sleeve is an acceptable technique for reestablishing the structural integrity of a degraded steam generator tube.

8.2 CONDITIONS TESTED

Mechanical tests are of both a characterizing and a qualification nature. Initially parameters of tube/sleeve mechanical and leak tightness are measured at room temperature and pressure. This information provides a standard against which tubes tested under accident conditions can

be compared. Additionally, the axial strength of the tube/sleeve joint in resisting separation is determined. These three parameters, then, characterize the tube/sleeve joint.

Tube/sleeve samples are exposed to loss of coolant accident (LOCA), main steam line break (MSLB), repeated startup/shutdown and primary flow induced vibration conditions. The intent of these tests is to demonstrate the integrity of the tube/sleeve joint under simulated normal operation and accident environments. Post test examinations are made to demonstrate that the characteristics of the joint do not vary significantly and the primary pressure boundary is not violated.

Looseness testing is conducted in a fixture which applies ± 25 pounds axial force to a sleeve which has been installed into a steam generator tube sample. The tests are performed at room temperature and pressure. Temperature effects can be ignored since sleeve and tube materials are identical. Pressure was not included in the screening test for ease in handling. Motion is approximately linear up to a force of 25 pounds. At 25 pounds, a large increase in force is required for additional sleeve motion.

Leakage testing, for screening purposes, is conducted at 1550 and 2500 psig internal, 1550 psig external and a repeat of the 1550 psig internal. The two internal pressures are representative of effective maximum normal operating and accident pressures. The external pressure is in excess of the maximum anticipated pressure of 1300 psi for a secondary hydrostatic test and is used to provide for ease in testing. The internal pressure test is repeated at one condition to verify that pressure cycling of the assembly does not alter leakage rates. All tests are done at room temperature due to tube/sleeve material identity.

Uniaxial tensile separation tests are performed at room temperature and 600°F for unpressurized tube/sleeve assemblies. The assemblies are mounted in a test fixture and pulled to separation. Recordings of load versus separation are made. The test is performed to demonstrate that under operating conditions, a tube degraded 100 percent circumferentially at its center will

not slip on the sleeve far enough to permit contact with the adjacent tube which is more than three eighths of an inch away. Application of the maximum possible internal pressure of 2500 psig results in an axial load of 830 pounds.

Simulation of a MSLB is performed by internally pressurizing a tube/sleeve. The test demonstrates that the assembly will not fail at the maximum anticipated pressure and that a safety margin of more than a factor of three exists against burst at the normal operating pressure differential. The maximum internal pressure of 3125 psig was used. This corresponds to 2500 psi at 600°F when ratioing SB-163 yield stengths (See Table I-2.2, Reference 8-1). Burst testing is also conducted to demonstrate no failure below 5610 psig. This corresponds to three times a differential pressure of 1870 psi at room temperature (70°F), which is equivalent to 1700 psi at 600°F when ratioing ultimate strengths of SB-163 (See Table 8-1). Testing is conducted on a variety of tube center wastage levels including 100 percent.

LOCA simulation testing is conducted by externally pressurizing a tube/sleeve assembly. A collapse pressure in excess of 1300 psig at 70°F is sought as this represents the maximum anticipated secondary hydrostatic leak test and is greater than the maximum secondary pressure of 1000 psi following a LOCA. Tests are conducted on assemblies with four inches of the steam generator tube missing from the center of the tube/sleeve assembly. This prevents the tube from adding to sleeve collapse strength.

Thermal and pressure cycling tests are conducted to demonstrate that plant startup and shutdown cycling does not significantly affect tube/sleeve joint characteristics. An assembly is cycled from cold (200°F), low pressure, startup conditions to normal operating conditions (600°F/2200 psig) and back a total of 100 times.

Tube sleeve assemblies are exposed to a primary flow of 25 gpm at 600°F/2200 psig for 1000 hours. This test is performed to investigate the likelihood of fretting at the tube/sleeve joint region as a result of primary flow induced vibrations. A test period of 1000 hours is adequate for the investigation of fretting.

8.3 RESULTS

The results presented in this section are the initial ones or incomplete due to the fact that many of the tests were performed for development reasons. They are presented for information and will be supplemented with controlled condition tests, later. All tests discussed, herein, will be repeated. The results found substantiate the capabilities of the sleeve as an acceptable repair structure for a degraded steam generator tube. While these results are preliminary, the trends shown and the magnitude of the results presented are expected to be repeated in final tube/sleeve assembly testing.

Testing for axial looseness has shown a zero to .003 inch axial motion under a reversing load of approximately 25 pounds for all of the 11 tube/sleeve assembly samples tested to date. Free floating looseness, as such, has not been found. The 25 pound applied load greatly exceeds service conditions. Figure 8-1 presents looseness test information for two representative sample assemblies. In addition to providing a characterization of tube/sleeve joint properties, the tight nature of the joint indicates that sleeve freeplay is minimal. This is beneficial in preventing any tube to sleeve wear or fretting problems.

Leakage rates across the tube/sleeve joint were characterized. For internal pressures of 1000 to 2500 psig, leakage rates of 1 to 10 cubic centimeters per minute (cc/min.) of ambient temperature water were found with most samples at about 1 cc/min. For external pressures of 500 to 1550 psig, leakage rates of 0 to 20 cc/min. were found. After the external pressure leakage tests, a second internal pressure test at 1000 to 1550 psig was conducted.

Leakage rates of 1 to 10 cc/min. again resulted. Additional tests are being performed to characterize the nature of the scatter in leak rates. The data indicate rates well below the steam generator acceptable operating rate of 1136 cc/min. (.3 gallons/min.). Thus, in addition to its strength characteristics, the sleeve provides a significant barrier to leakage.

Uniaxial tensile separation testing of sleeved tube assemblies has shown full separation loads in excess of 3700 pounds force. Separation of tube ends by 1/4 inch required a minimum of 1350 pounds force which is in excess of the 1000 pound level established in Section 3.0 criteria. All tests were performed on sleeved tube assemblies with a 100 percent circumferential defect at the tube mid-span. This indicates that even under worst degradation conditions, the maximum anticipated pressure loads will not result in an axial force sufficient to elongate a sleeved steam generator tube far enough to contact its nearest neighbor, which is 3/8 inches away.

The mode of tube/sleeve failure in the separation tests was either the sleeve necking down plastically then sliding through the undeformed tube; or the sleeve necking down and the tube expanding slightly as the two were pulled apart. Figure 8-2 shows the applied load versus axial tube separation. Table 8-2 presents diametrical measurements of separated tube/sleeve assemblies. This information provides the basis for establishing the potential assembly failure mode.

A single sleeve has been internally pressurized to failure in an MSLB simulation. This too provides preliminary information on sleeve burst pressure margin in satisfaction of Reference 3-1 criteria. The tube indicated yielding, by visual observation, at approximately 4000 psig internal. This exceeds the Reference 3-1 criteria (the first in Table 8-3) of 3125 psig. Burst of this sample occurred at 8250 psig. Since these tests were conducted at 70°F, a burst pressure in excess of 5610 psig shows a safety margin of greater than three for the Reference 3-1 second criteria of Table 8-3.

Preliminary thermal cycling tests have been completed with more detailed temperatures and pressure cycling tests scheduled. The boiler discussed

in Section 6.0 was used for 706 hours of steady state operation and 42 startup/shutdown cycles. A typical Palisades primary chemistry was maintained at 600°F, 2200 psig. Volatile secondary chemistry conditions were held at 535°F and saturation pressure. Post test leakage tests at 1550 and 2500 psig internal, 1550 psig external, and a second internal test at 1550 psig revealed leak rates in the same 1-10 cc/min. range shown in baseline tests. (All leak tests were conducted using a leak hole drilled at the tube mid-span.) This indicates that thermal cycling has little or no effect on tube/sleeve leak rates across the joint.

8.4 REFERENCES FOR SECTION 8.0

8-1 ASME Boiler & Pressure Vessel Code, Section III, Nuclear Power Plant Components, 1974

Table 8-1

SB-163 Ultimate Strength

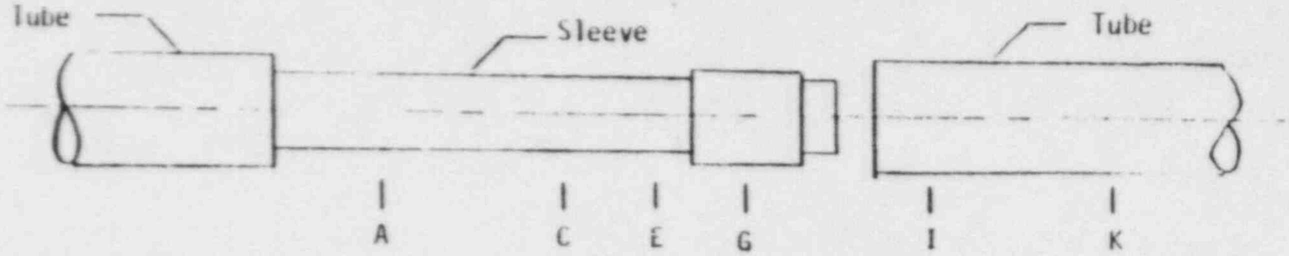
Based on 881 tube samples:

Mill reports lists minimum ultimate tensile strength (S_u) as 87.5 ksi at room temperature.

An ultimate tensile strength (S_u) of 80.0 ksi at an operating temperature of 600^{o}F is found based upon the curves from Nuclear Systems Materials Handbook, TID-26666, Hanford Engineering Development Laboratory, 1975

Table 8-2

Diameters of Separated Samples



Assembly No.	Separation Load at 1/4 Inch (lbs.)	Total Separation Load (lbs.)	Nominal Sleeve OD (inches)	Nominal Tube OD (inches)	Diameter (Inches) A	C	E	G (max)	I	K (max)
1	1350	4293	.628	.746	.5932	.5943	.5955	.6490	.7457	.7760
2	1800	4512	.628	.746	.5826	.5856	.6156	.6493	.7478	.7766
3	--	4387	.628	.746	.6005	.5987	.5992	.6501	.7463	.7717
4	--	3795	.628	.747	.6131	.6131	.6148	.6526	.7495	.7604

Note: Assemblies 1 and 3 separated due to plastic sleeve neckdown.

Assemblies 2 and 4 separated due to plastic sleeve neckdown and minor tube expansion.

Table 3-3

Criteria for Minimum Acceptable Wall Thickness

(Reference 3-1)

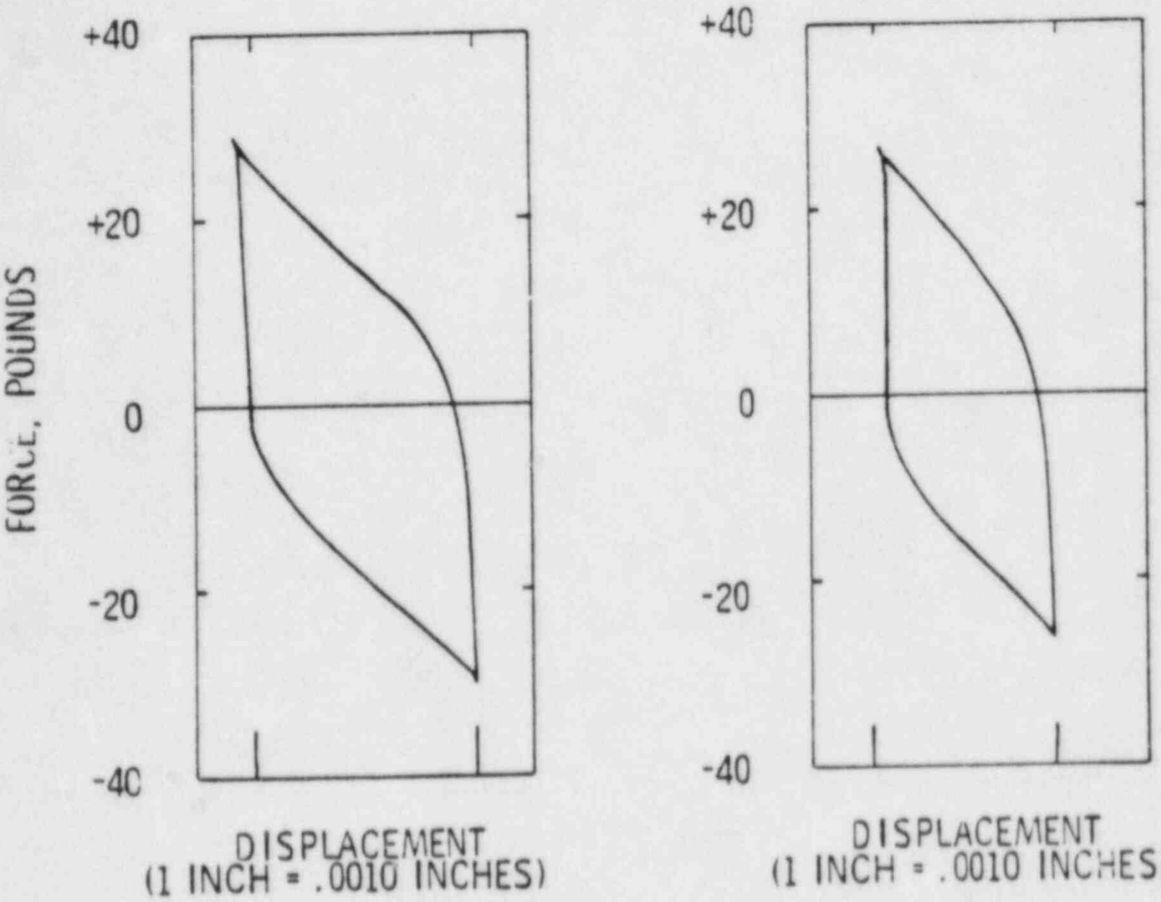
1) Tubes with detected defects will not be stressed during the full range of normal reactor operation beyond the elastic range of tube material.

2) The factor of safety against failure by bursting under normal operating conditions is not less than three at any tube location where defects have been detected.

3) Crack-type defects that could lead to tube rupture either during normal operation or under postulated accident conditions will not be acceptable.

Figure 8-1

TUBE/SLEEVE MOTION UNDER REVERSING LOAD



ASSEMBLY A

ASSEMBLY B

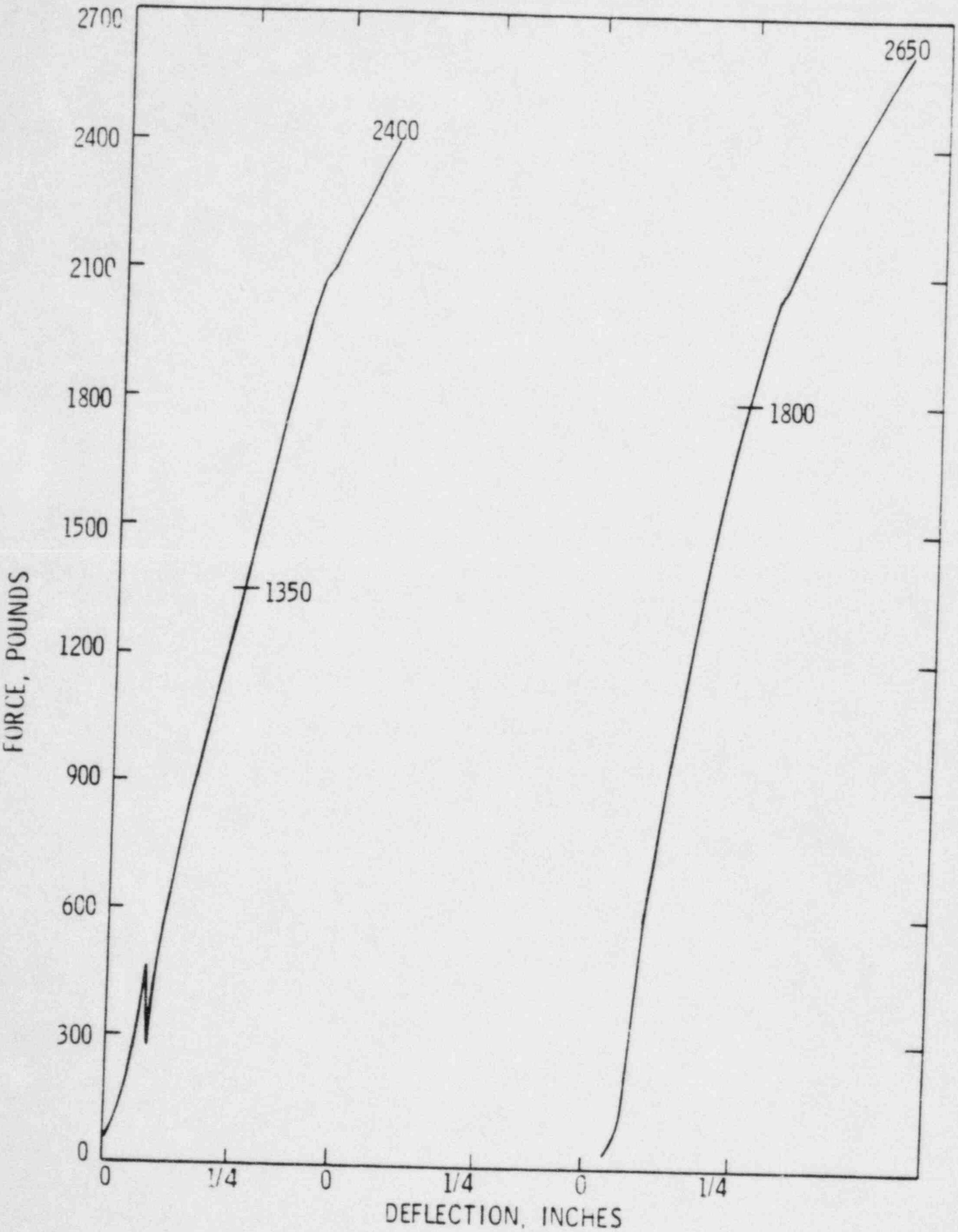


Figure 8-2
UNIAXIAL TENSILE SEPARATION

AFFIDAVIT PURSUANT

TO 10 CFR 2.790

Combustion Engineering, Inc.)
State of Connecticut)
County of Hartford) SS.:

I, A. E. Scherer, depose and say that I am the Manager, Licensing of Combustion Engineering, Inc., duly authorized to make this affidavit, and have reviewed or caused to have reviewed the information which is identified as proprietary in the enclosure document referenced below; that the identified information includes trade secret and commercial or financial information belonging to Combustion Engineering, Inc., which we believe to be privileged or confidential; that the identified information has been maintained as privileged or confidential by Combustion Engineering, Inc. and cannot be obtained from public sources without the expenditure of significant amounts of time and effort and is information the release of which would be likely to cause substantial harm to the competitive position of Combustion Engineering, Inc.; and that this information is of a type customarily held in confidence or transmitted in confidence by Combustion Engineering, Inc.

Enclosure: Palisades Steam Generator Tube Repair Sleeving; CEN-42(P)P, December 10, 1976.

Sworn to before me this
10th day of December, 1976

A. E. Scherer
Manager, Licensing

Notary Public