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Laser Welded Repair of Hybrid Expansion Joint Sleeves for Kewaunee Nuclear Power Plant

Westinghouse Energy Systems



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LASER WELDED REPAIR OF HYBRID EXPANSION JOINT SLEEVES
FOR
KEWAUNEE NUCLEAR POWER PLANT

August 1996

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ABSTRACT

This report provides the technical basis for the use of the Westinghouse Laser Welded Sleeve (LWS) technique to repair hybrid expansion joint (HEJ) sleeved tubes at the Kewaunee Nuclear Power Plant. This report summarizes and/or references the results of design and materials evaluations, structural and thermal/hydraulic analyses, as well as corrosion, inspection and mechanical testing, and reviews the Laser Weld Repair (LWR) process for HEJ sleeves.

In-service inspections of the HEJ sleeves installed in Kewaunee have detected indications in the sleeved region of the parent tubing. The majority of the parent tube indications are in, or below the region of the lower transition of the HEJ upper hardroll. To date, all sleeved tubes with indications within the lower transition of the upper hardroll region have been plugged.

Because of the location of the parent tube indications, it is possible to use the LWS technique to perform a Laser Welded Repair (LWR). The LWR will form a new pressure boundary attachment point above the indications, thus effectively removing the degraded tube region from the pressure boundary. The repair allows the sleeved tube to remain in service with no additional penalty on the operational characteristics of the HEJ sleeved tube.

This report concludes that LWR is an acceptable means for repair of HEJ sleeves at the Kewaunee Nuclear Power Plant.

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1.0 INTRODUCTION AND SUMMARY

1.1 Scope and Definition

This report provides the technical basis for use of the Westinghouse Laser Welded Sleeve (LWS) method to perform a Laser Welded Repair (LWR) of hybrid expansion joint (HEJ) sleeves at the Kewaunee Nuclear Power Plant. This report replaces the Interim Report on Laser Welded Repair of HEJ Sleeves (Reference 1-1), and supplements the evaluations in the generic laser welded sleeving (LWS) report for application in 7/8-inch tubes, WCAP-I3088 Rev. 3 (Reference 1-2), as well as the November 1988 HEJ sleeving report for Kewaunee, WCAP-11643 Rev. 1 (Reference 1-3). The principal additional information includes a description of the LWR process as applied to HEJ sleeves, the results of a structural analysis of the LWR joint, and corrosion testing results of HEJ LWR joints fabricated with tube/sleeve interfaces "pre-conditioned" to simulate Kewaunee HEJs exposed to primary water. References are provided for applicable design and materials evaluations, structural and thermal/hydraulic analyses, as well as corrosion, inspection and mechanical testing.

Unless otherwise specified, use of the term *HEJ* will be meant to include only the upper, hydraulically expanded plus roll expanded joint in an HEJ sleeved tube. The lower joint in the HEJ sleeve is unaffected by the LWR. The term *LWR* is meant to indicate the joint weld including its subsequent stress relief.

1.2 Degradation Locations

Inspection information is useful in illustrating the potential benefit of LWR in addressing HEJ degradation patterns, and in reviewing the condition of the tube/sleeve juncture at the weld prior to welding. In-service inspections (Reference 1-4) of the HEJ sleeved tubes at Kewaunee have detected indications in the upper HEJ region of the parent tubing. The first parent tube indications at Kewaunee were detected in the Spring of 1994. The majority of the parent tube indications (PTIs) are in or below the region of the lower transition of the HEJ upper hardroll. Figure 1-1 provides a definition of the HEJ expansion transitions. Figure 1-2 illustrates the combined degradation location results for the 1994 and 1995 Kewaunee inspections.

Three HEJ-sleeved tube samples were removed from Kewaunee in 1995 for laboratory inspection and testing. During NDE and visual inspection, no cracks were found at the upper transitions

of the two destructively examined Kewaunee HEJ samples. In addition, no cracking was detected in the straight portion of the HEJ hardroll, which corresponds to the intended laser weld location.

1.3 HEJ Sleeved Tube Structural Integrity Criteria

The LWR technique is intended to repair HEJ sleeved tubes with parent tube indications that do not satisfy the criteria discussed in Reference 1-5, "HEJ Sleeved Tube Structural Integrity Criteria: ' ΔD ' Diametral Interference at PTIs". The ΔD criterion supports the conclusion that with a minimum diametral interference of 0.003" (plus an allowance for NDE uncertainty) between the maximum sleeve ID in the roll expansion transition and the sleeve ID adjacent to the parent tube indication (PTI), structural integrity will be provided for all plant conditions. In addition, leakage resistance will be provided with the ΔD criterion such that offsite doses following a postulated main steam line break outside of containment will remain within 10% of the Part 100 guidelines when all leakage sources are considered. Figure 1-3 illustrates the ΔD criterion for Kewaunee HEJ sleeves.

Laser weld repair will not be performed in HEJ sleeves which are known to have indications in the upper hardroll region above the proposed weld location; such sleeved tubes would be removed from service.

1.4 Pressure Boundary Considerations

Laser welding repair of the HEJs will form a new pressure boundary in the tube/sleeve assembly. By welding the tube and sleeve with the autogenous laser welding process at the location illustrated in Figure 1-4, the parent tube length between the laser weld and the lower hydraulic expansion transition of the (upper) HEJ is excluded as pressure boundary. The revised pressure boundary definition is consistent with that of a laser welded sleeve (Reference 1-2).

1.5 Laser Welding With Contaminated Sleeve/Tube Interface

The repair technique being proposed is a laser weld within the upper hardrolled zone of a HEJ. The integrity of the weld between the tube and sleeve will be verified by ultrasonic (UT) examination. The weld will then be stress relieved by heat treatment, and a baseline eddy current examination will be performed. This approach, which is based on the very successful proven technology of the laser welded sleeve, can be applied with no additional modification to the

existing HEJ sleeve geometry. Therefore, there are no changes to the flow or heat transfer characteristics of the sleeved tube or the RCS.

Evaluation of two HEJ samples removed from Kewaunee (neither of which had throughwall parent tube cracks), as described in Reference 1-6, suggests that primary water had passed through the sleeve-to-tube interface at the HEJ region, and there is the possibility of oxides and contaminants being present in the hardroll region. One of the concerns examined in the evaluation of laser welding as a repair process was the effect of contaminants on the weld integrity. To address this issue, as described in Sections 2.5 and 5.2, testing was performed on tube and sleeve samples which were "pre-conditioned" prior to HEJ formation by exposure to an oxidizing environment, immersion in a contaminant solution developed from examination of the removed sleeve/tube crevice contaminants, and air drying. The HEJ joints were then fabricated in the same manner as they were fabricated in the field, and LWR was performed. The welds were sound, with no cracking, demonstrating that the [

]c.e

1.6 Summary of Report Sections

A summary of each of the following sections is provided below:

Section 2 - The LWR for Kewaunee uses the same weld process parameters as 7/8" laser welded sleeves, and employs the same ASME Code qualification program. The pressure boundary after LWR is the same as after LWS.

Section 3 - The LWR meets all primary stress limits, maximum range of stress intensity limits, and satisfies all ASME Code fatigue limits. The plugging limit for the sleeve, in percent of undegraded minimum wall thickness, is []b.c.e.

Section 4 - It is found that a.) the laser weld is leak tight to pressures greater than 3100 psi at 600°F, b.) the load carrying capability of the laser weld exceeds the end cap loadings associated with a safety factor of 3 applied to the normal operating primary-to-secondary pressure differential, and c.) the LWS test results are directly applicable to the LWR.

Section 5 - Corrosion testing has indicated that the []^{c,e}

Section 6 - The LWR process steps are essentially identical to those for LWS, including welding and stress relief.

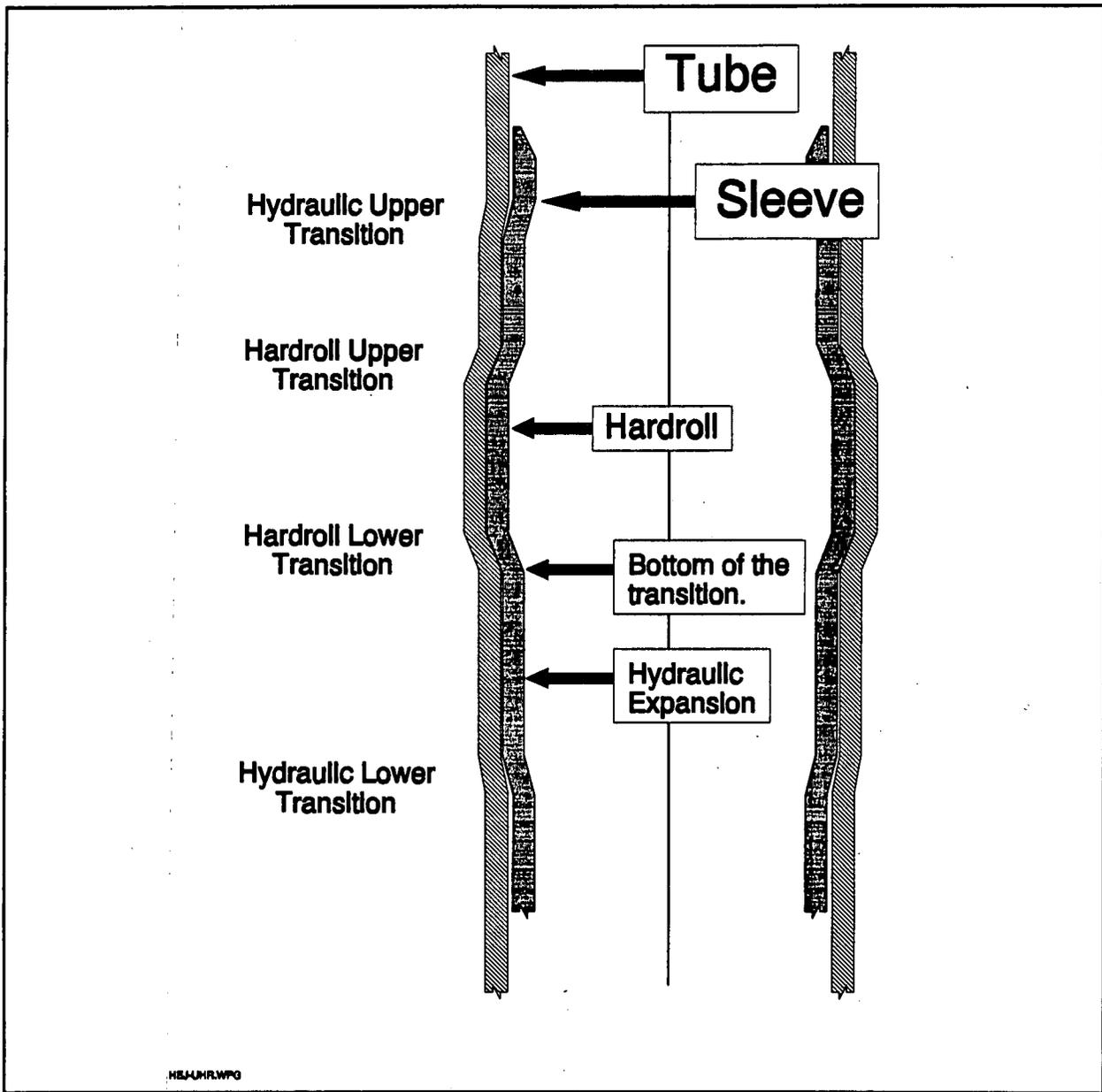
Section 7 - Inspection techniques and criteria are essentially identical to those used for LWS.

It is concluded that the evaluation and qualification testing programs demonstrate that LWR is an acceptable means to repair HEJ sleeved tubes.

1.7 References for Section 1

- 1-1 SGO-ATD-96-13, "Interim Report on Laser Weld Repair of Hybrid Expansion Joint Sleeves", W Nuclear Services Division, April 4, 1996. (Westinghouse Proprietary Class 2C). Transmitted to USNRC by Wisconsin Public Service Corporation cover letter dated April 18, 1996.
- 1-2 WCAP-13088 Rev. 3, "Westinghouse Series 44 and 51 Steam Generator Generic Sleeving Report, Laser Welded Sleeves", W Nuclear Services Division, January 1994. (Westinghouse Proprietary Class 2).
- 1-3 WCAP-11643 Rev. 1, "Kewaunee Steam Generator Sleeving Report (Mechanical Sleeves)", W Nuclear Service Division, November 1988. (Westinghouse Proprietary Class 2).
- I-4 Letter Dated 12/13/95, R. J. Laufer (Project Manager, NRC NRR), "Summary of December 8, 1995, Meeting on WPSC's Proposed License Amendment on Steam Generator Tube Repair Criteria", Docket No. 50-305.
- 1-5 WCAP-14641 Rev. 0, "HEJ Sleeved Tube Structural Integrity Criteria: 'AD' Diametral Interference at PTIs", W Nuclear Services Division, April 1996. (Westinghouse Non-Proprietary Class 3).

- 1-6 WCAP-14513, "Presentation Materials for the August 10th, 1995, Meeting with American Electric Power Service Corporation, USNRC, and Westinghouse Concerning Application of the Revised Pressure Boundary Limit for HEJ Sleeved Tubes", November 1995. (Westinghouse Proprietary Class 2C).



HEJ/HR/WPG

Figure 1-1
Definitions of HEJ Upper Expansion Transitions

a,c

Figure 1-2
Cumulative Degradation Location Results for Kewauuee Upper Expansions

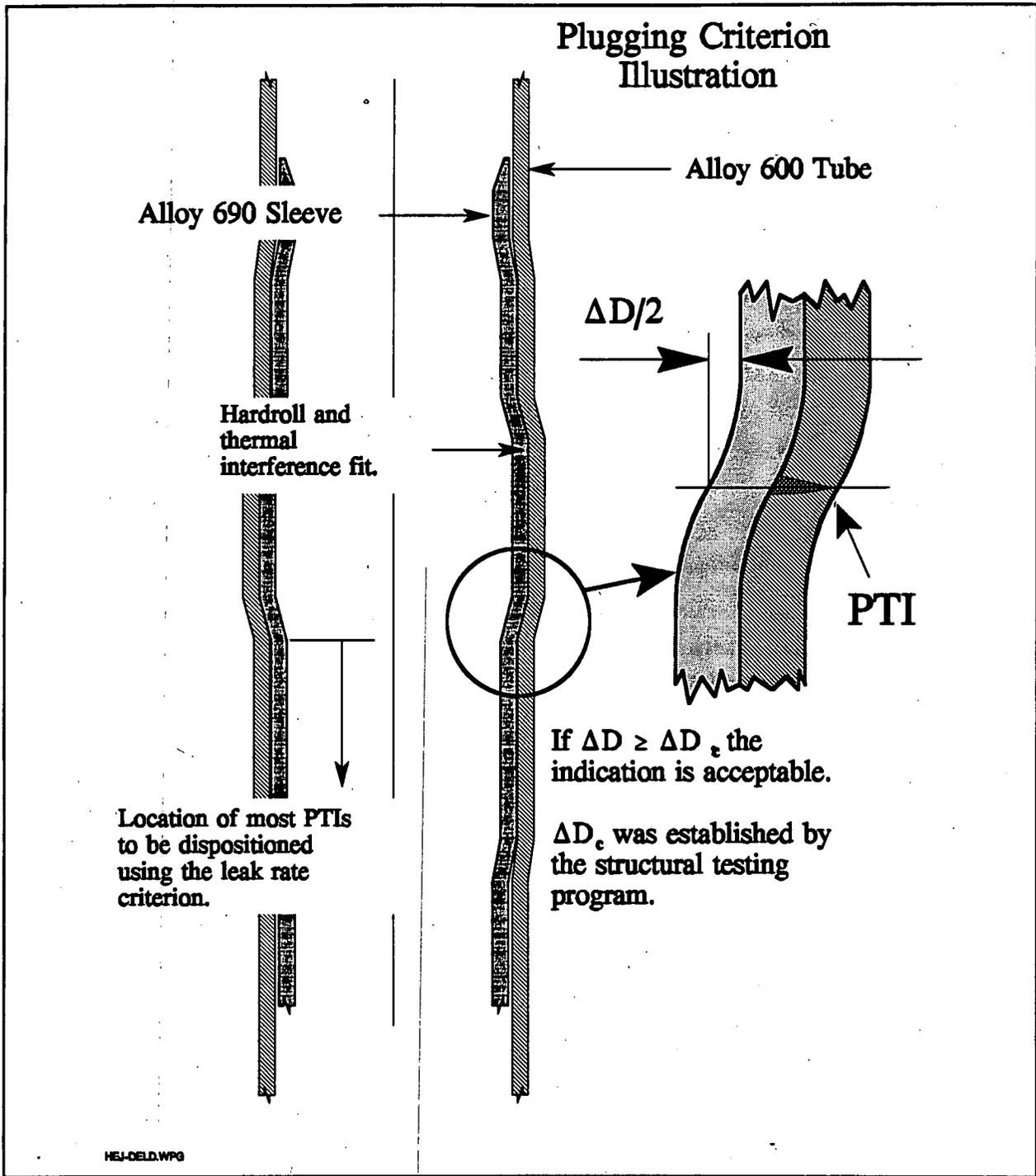


Figure 1-3
 ΔD Criterion for Repair of HEJ Indications

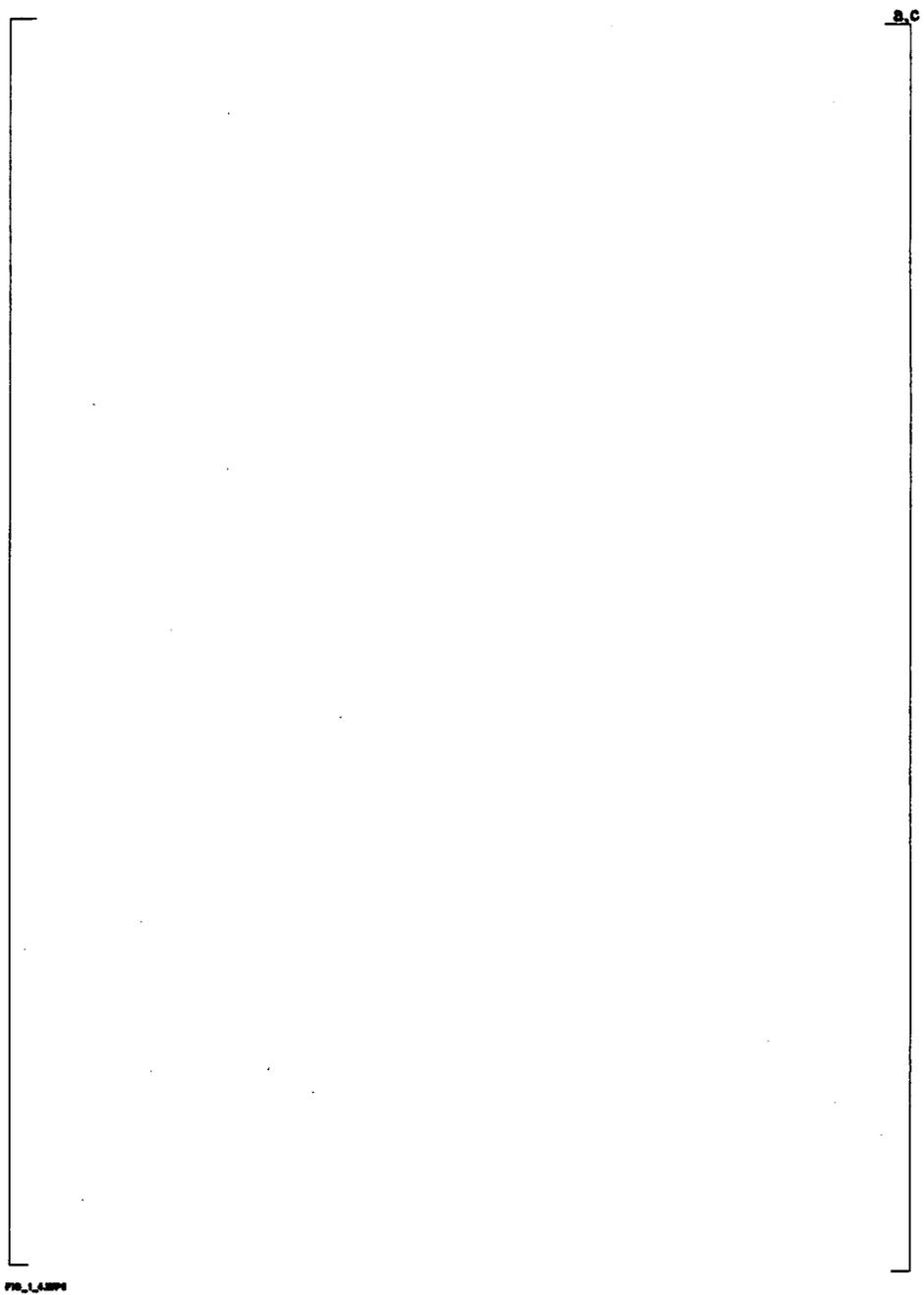


Figure 1-4
Illustration of Laser Weld Repair in Kewauuee HEJ Upper Joint

2.0 REPAIR DESIGN DESCRIPTION AND WELD QUALIFICATION

This section describes the laser weld repair geometry and the laboratory weld qualification program. Related sections are Section 6.0, which describes the LWR process, and Section 5.0, which describes the corrosion test program.

2.1 Hybrid Expansion Joint Configuration

The HEJ sleeve is used to bridge regions of degradation observed in Alloy 600 steam generator tubes in the tubesheet crevice and top of tubesheet region. The HEJ sleeve design, illustrated in Figure 2-1, consists of two mechanical joints. The lower joint is located within the tubesheet region and consists of a [

] ^{a,c,e} The upper joint, located in the free span above the top of the tubesheet, also consists of a [

] ^{a,c,e} Complete information on the design, qualification, and testing of the HEJ sleeve for Kewaunee is included in Reference 1-3.

2.2 LWR Design Configuration

The repair technique is a laser weld within the HEJ upper hardrolled zone. The 360° weld is axially positioned at the approximate centerline of the rolled region as shown in Figure 1-5.

The production of a laser weld in the upper HEJ hardroll region [

] ^{a,c} A discussion of fabrication stresses is included in the discussion of the corrosion test specimen preparation in Section 5.0.

2.3 Weld Process Development

Some initial laser welds were made on sleeved tube geometries consistent with those of the HEJ in 7/8-inch tubes. The welds were made in the hardrolled region with the current 7/8 inch laser

weld head and weld parameters within the currently qualified 7/8 inch tube sleeve laser weld process. After welding was completed the welds were metallographically sectioned and evaluated. The welds exceeded the minimum width requirements described in Section 3.1.1. The welds were sound with no cracking, porosity, or indications on the weld ID when subject to liquid dye penetrant inspection.

2.4 Interim Operational Effects and Testing

HEJ sleeves were installed in Kewaunee in 1988, 1989, and 1991. As noted in section 1.5, examination of the HEJ samples removed from Kewaunee indicated that primary water had passed through the sleeve-to-tube interface at the HEJ region, and the possibility exists for oxides and contaminants to be present in the hardroll region. In addition to the testing described in section 1.5, a comparison of the Kewaunee HEJs to similar welded sleeve configurations is useful in evaluating the effects of interim operation on welding, inspection, and heat treatment of the LWR.

In defining the condition of the Kewaunee HEJs, it is first noted that the Kewaunee HEJ tube IDs were wet honed prior to HEJ sleeve installation. In this clean condition, the HEJ hydraulic expansion and upper and lower hardrolls were performed providing a tight, metal-to-metal contact between the tube and sleeve. [

]a,c,e

Laser welding has also been performed successfully where the tube/sleeve interface could not be cleaned. Westinghouse performed HEJ laser welding repair [

]a,c The crevices between the tube and sleeve at this unit had been exposed to primary fluid for several operating cycles, and access was not available to clean the tube/sleeve crevice prior to hydraulic expansion. Laser weld repair of about []a,c

Information on types of contaminants present in the joint region was obtained through analyses performed on HEJ sleeved tubes removed from the Kewaunee generators (Reference 1-6). These analyses revealed the contaminants to consist of those summarized in Table 2-1.

To determine the effects of a representative, "pre-conditioned" tube/sleeve interface on LWR, four HEJ specimens were prepared in which both the sleeves and tubes were [

]a,c HEJ joints were then fabricated in the same manner as they were fabricated in the field. LWR was performed with weld parameters in the middle of the qualified ranges. The widths of the welds were approximately []a,c Examination showed that welds were sound with no cracking. The test demonstrated that the [

]c

Subsequent to the above test, as described in Section 5.0, a matrix of [

]a,c

2.5 Weld Qualification Program

The HEJ LWR weld process is essentially the same as the process for LWS of 7/8" tubes (Reference 1-1). The LWS weld process has been used in numerous []a,c sleeves for 7/8 inch OD tubes, and was qualified per the guidelines of the ASME Code. The

qualification included the generation of a procedure qualification record and welding procedure specification.

For the LWS weld qualification program, representative field processes were used to assemble the specimens to provide similitude between the specimens and the actual installed welds. The laser welded joints are representative in length and diametral expansion of the expansion zones. The sleeve and tube materials were consistent with the materials and dimensional conditions representative of the field application. Essential welding variables, defined in ASME Code Section IX, Code Case N-395 and Section XI, IWB-4300 were used to develop the weld process.

[

]a.c.e

The LWS procedure qualification was reviewed to determine if the HEJ LWR weld procedure remained within prescribed essential variables limits. The reference power level and other variables for the HEJ LWR remained within allowable ranges, so requalification of the LWR HEJ weld procedure was not required.

Table 2-1
Crevice Simulant for HEJ Sleeve Testiug

Anions or Cations Compounds Used	Test Simulant Initial Cation Concentration (µg/ml)	Test Simulant Initial Anion Concentration (µg/ml)	Pulled HEJ Cation Conc. (Note 1) (µg/ml)	Pulled HEJ Cation Conc. (Note 1) (µg/ml)
K as K ₂ CO ₃			21	
Ca as CaCO ₃			21	
Na as Na ₂ CO ₃			97	
Na and SO ₃ as Na ₂ SO ₃				10
Mg as Mg(OH) ₂			25	
Li as LiOH			10	
Oxalate as Oxalic Acid				10
Acetate as Acetic Acid				37
Formate as Formic Acid				70
Cl as HCl				28
SO ₄ as H ₂ SO ₄				171
B as H ₃ BO ₃				
pH of Solution				

Note 1: Concentration estimated from leachate of pulled Kewaunee HEJs, per Reference 1-6.

3.0 ANALYTICAL VERIFICATION

3.1 Structural Analysis

This section provides the structural basis for the laser welded repair of the HEJ mechanical sleeves in the Series 51 steam generators used in Kewaunee. Reference 3-1 documents the initial structural evaluation of the HEJ sleeve and tube assembly with sleeve material TT Alloy 690, tube material MA Alloy 600, and a []^{a,c} in accordance with the criteria of the 1983 Edition of the ASME Code, Reference 3-6. Subsequent evaluations were performed for []^{a,c} sleeve lengths, which were also installed at Kewaunee; these analyses showed that the maximum range of stress intensity []

[]^{a,c} sleeve length is the limiting analysis case. The initial evaluation showed that the HEJ mechanical sleeve configuration satisfied the Code limits for primary stress intensity, maximum range of stress intensity, and cumulative fatigue usage for the Kewaunee loading conditions specified in Reference 3-2. The initial HEJ structural evaluation of Reference 3-1 also gives minimum wall thicknesses for the HEJ sleeve that are based on lower bound tolerance limit strength data.

Eddy-current (EC) inspections of the Kewaunee HEJ sleeves have detected indications in the sleeved region of the parent tube, Reference 1-4. Most of these indications are within the currently-defined pressure boundary for an HEJ sleeve (see paragraph 1.4), but would not be included in the pressure boundary subsequent to laser weld repair (see Figure 1-4); the HEJ LWR pressure boundary is consistent with the pressure boundary defined for a laser welded sleeve (Reference 1-2).

The structural evaluation of the repaired HEJ joint is based on finite element calculations that extend the existing generic LWS evaluation to the similar laser weld repair of the HEJ sleeves in Kewaunee, thereby structurally qualifying the laser weld repair for use in Kewaunee. The existing generic structural analyses, qualifying the LWS sleeves for 7/8 inch tubes in Series 44 and 51 steam generators, are documented in Reference 3-4. These existing generic LWS analyses were performed for a generic set of loading conditions given in Reference 3-5, which umbrella most of the Kewaunee loads specified in Reference 3-2. Throughout the discussions of this section, it is assumed that the LWR has been stress relieved. Stress relief parameters are discussed in Section 6.0.

In addition, the minimum sleeve wall thicknesses for normal, maximum upset, and maximum faulted conditions have been re-calculated for the increased Kewaunee pressure differential loading using the more conservative minimum strength data from the ASME Code rather than the lower bound tolerance limit strength data used in Reference 3-1. The revised overall limiting wall thickness for the Kewaunee sleeve is used to define the sleeve plugging limit based on the tube plugging criteria of Reg. Guide 1.121, Reference 3-7.

3.1.1 Geometry

Finite element models of both the HEJ sleeve (with the laser weld repair) and the generic laser welded sleeve were performed as discussed later in Section 3.1.5. The models used were developed using the most structurally conservative dimensions for pressure stresses (i.e., minimum wall thicknesses, maximum unexpanded and maximum acceptable expanded diameters). Based on previous experience at the upper joint, [

]^{a,c}. Again, based on experience with previous laser welded joints in Reference 3-4, the nominal interfacial axial extent of engagement of the laser weld joining the tube and sleeve is expected to be about []^{a,c}. However, qualification tests for the weld process show that the weld engagement may be as small as []^{a,c}, as conservatively assumed in Reference 3-4. Therefore, the stress and fatigue results for the Kewaunee laser weld repair, which are based on the generic results in Reference 3-4, also implicitly and conservatively assume the limiting minimum weld engagement length of []^{a,c}.

3.1.2 Materials

The material of construction for the 7/8 inch tubes in the Kewaunee Series 51 steam generators is Alloy 600 in the mill annealed (MA) condition. Therefore, the tube strength data used in this evaluation are for the 35 ksi minimum yield mill annealed material. All of the Kewaunee HEJ sleeves are thermally treated (TT) Alloy 690 which has a 40 ksi minimum yield. Since the laser weld process joins the sleeve and tube autogenously by direct fusion, without using a filler metal, the weld section was conservatively assumed to have at least the lower strength properties of the weaker MA Alloy 600 material. The sleeve, tube, and weld materials in the generic LWS

analyses of Reference 3-4 are identical to the Kewaunee sleeve, tube, and weld materials. Structural and thermal properties are taken from the appropriate tables of Appendix I of the 1989 Edition of the ASME Code, Reference 3-6. Likewise, the cumulative fatigue calculations are based on the design fatigue curves for austenitic steels and nickel-chromium-iron alloys (600 and 690) given in Figures I-9.2.1 and I-9.2.2 of Appendix I.

3.1.3 Loading Conditions

The generic structural evaluation of the LWS sleeves, documented in Reference 3-4, was performed for a generic set of loading conditions given in Reference 3-5, which umbrella most of the Kewaunee loads specified in Reference 3-2. Table 3-1 lists the generic operating conditions and the current Kewaunee operating conditions. Table 3-2 lists the generic umbrella pressure loads for design, faulted, and test conditions, taken from Reference 3-5 for the Series 51 steam generator. Table 3-3 lists the applicable normal, upset, and test transient conditions and their frequency, as specified in Reference 3-5. These cyclic loads cover all specified relevant design transients for the primary reactor coolant and secondary steam side of the generic Series 44 and 51 steam generators in standard two, three or four-loop plants for a 40 year fatigue operating period and were used in both the maximum stress intensity range and cumulative fatigue usage evaluations, conducted for the generic LWS in Reference 3-4.

[

]° load factor does not apply to the design, faulted, and test condition pressure differentials listed in Tables 3-2 and 3-3 which remain unchanged for Kewaunee.

At the location of the HEJ upper joint just above the tubesheet, the seismic loads (both OBE and SSE) result in negligible stresses in the tube and sleeve. Also, the fatigue usage due to the OBE

is negligible. Therefore, seismic loads are not listed in either Table 3-2 or Table 3-3.

3.1.4 Acceptance Criteria

References 3-1 and 3-4 employ the same structural design criteria for evaluating the sleeve and tube as defined in Subsection NB of the ASME Code, Reference 3-6, 1986 and 1989 Editions, respectively. The weld, connecting the TT Alloy 690 sleeve to the MA Alloy 600 tube, was included in the generic analysis of Reference 3-4 and is evaluated to the ASME Code criteria as a structural weld conservatively assuming the smaller strength properties of the MA Alloy 600 tube. Summaries of the applicable stress and fatigue limits for the sleeve, tube, and weld are given in Tables 3-4 through 3-7. It will be shown later, by comparative analyses, that these limits are satisfied for the laser weld repair of the Kewaunee HEJ sleeves. In establishing minimum wall requirements for sleeve plugging limits, the ASME Code minimum values for the material properties for TT Alloy 690 are used.

3.1.5 Analysis Models and Methods

The structural evaluation of the weld repair of the Kewaunee HEJ upper sleeve to tube joint is of interest here. At this joint, the primary difference between the laser weld repaired HEJ sleeve and the generic laser welded sleeve (LWS) is the additional hard rolled expanded region where the repair weld is made. [

] ^{a,c}

The analyses of both the HEJ and generic laser welded sleeves utilize the finite element models shown in Figures 3-2, 3-3, and 3-4. Figure 3-2 is the "HEJLWR" finite element model, simulating the laser welded repair of the HEJ sleeve, and Figure 3-3 is the "GENLWS" finite element model, simulating the generic laser welded sleeve. [

] ^{a,c}

The analysis considers both intact tubes, as well as postulated fully severed tubes. In the repaired HEJ model, shown in Figure 3-2, the severed section is assumed to occur [

] ^{a,c}. Intact or hypothetical severed tube conditions are simulated by enabling or disabling, respectively, the nodal displacement couplings between the tube segments in the model. In the generic LWS model, shown in Figure 3-3, the severed section is assumed to occur [

] ^{a,c}.

Since the tube can be either fixed or free at the first tube support plate (TSP), both possibilities are considered. Therefore, four independent combinations of tube status (intact or severed) and boundary condition constraints at the TSP (fixed or free) are considered in the evaluation as follows:

Combo # 1:	Tube Status: INTACT	B.C. @ TSP: FREE,
Combo # 2:	Tube Status: INTACT	B.C. @ TSP: FIXED,
Combo # 3:	Tube Status: SEVERED	B.C. @ TSP: FREE,
Combo # 4:	Tube Status: SEVERED	B.C. @ TSP: FIXED.

In Table 3-2, the highest limiting load conditions have the primary pressure greater than the secondary ($P_p > P_s$), which results in the maximum ΔP loading on the welded connection that serves as the pressure boundary, where $\Delta P = P_p - P_s$. Therefore, the comparative stress evaluation is performed for a primary to secondary pressure differential unit load of 1000 psi, applied in the

same manner to both models, as shown in Figures 3-5 and 3-6. Unit pressure load cases were run for each of the four independent combinations of tube status (intact or severed) and constraints at the TSP (fixed or free) listed above. A tensile end cap axial load is applied to the tube for Combos 1 and 3, when the boundary condition at the TSP is free. In all finite element solutions, [

] ^{a,c}. See Figures 3-5 and 3-6 for the assumed unit pressure load and boundary conditions.

3.1.6 Thermal Analysis

The thermal analyses [

] ^{a,c}. These thermal stresses are superimposed on the pressure stresses and considered in the stress range and fatigue evaluations of the generic LWS. As discussed previously in Section 3.1.5, at the upper hard rolled region of the HEJ, which is to be laser welded, the additional diametric expansion relative to the hydraulic expansion, is [^{a,c}. Therefore, [

] ^c.

3.1.7 Stress Analysis Results

Figures 3-7 and 3-8 show the [^{a,c} selected for evaluation in the HEJ laser weld repair finite element model ("HEJLWR") and the generic laser welded sleeve finite element model ("GENLWS"), respectively. In each model, [^{a,c} as follows:

] a,c

Linearized membrane, membrane plus bending, and total surface stress components and the resulting associated stress intensities were calculated at each ASN and are listed in Tables 3-8 to 3-12 for []^{a,c}, respectively. The "membrane plus bending" and the "total surface" stress intensities listed in the tables are the maximums of either the inside or outside surfaces of the ASNs. Calculated stresses are listed for both the HEJ laser weld repair finite element model ("HEJLWR") and the generic laser welded sleeve finite element model ("GENLWS"). Results are tabulated for both models for each of the four possible combinations of tube status (intact or severed) and tube support plate conditions (free or fixed), as discussed previously in Section 3.1.5. In all cases, the listed stress results are for a primary to secondary unit ΔP load of 1000 psi, applied as shown in Figures 3-5 and 3-6.

Also listed in Tables 3-8 through 3-12, are the ratios of the HEJLWR to GENLWS stress intensities, which are [

] ^{a,c}.

The far field stresses at [

] ^{a,c}. Table 3-13 reproduces the existing calculated generic stress intensities at

these three sections for the limiting ΔP pressure load cases from Reference 3-4 for the severed tube condition and also gives the maximum stress intensity to allowable ratios, i.e., the minimum limiting stress margins. The allowables in Table 3-13 are the same as those listed in Tables 3-4 and 3-5. Since the Kewaunee design, faulted, and test ΔP loads remain the same as the generic loads, the factors in Tables 3-9, 3-10, and 3-12 may be used to extend the generic results to Kewaunee for [

] ^{a,c}

3.1.8 Pressure Stress Evaluation

From the generic pressure stress evaluation results in Table 3-13, the maximum stress to allowable ratio is [

] ^{a,c}. This load and location give the minimum structural margin in the generic LWS analysis of all pressure loads. From Table 3-12, the appropriate corresponding stress ratio factor, giving the normalized (HEJLWR to GENLWS) increase in membrane stress due to the HEJ geometry at the weld section [

] ^{a,c}. Thus, the calculated increased maximum stress to allowable ratio for primary pressure loading in the repair weld for of the Kewaunee HEJ sleeve is:

[] ^{a,c},

which remains below the limit of one, i.e., the stress intensity is less than the allowable. Therefore, it is concluded that the laser weld repair of the Kewaunee HEJ sleeve upper joint satisfies all primary stress limits with positive structural margin.

3.1.9 Primary plus Secondary Stress Intensity Range Evaluation

The minimum positive structural margin for the primary plus secondary stress intensity range [

] ^{a,c}. From Reference 3-4, this minimum margin is reported to be [

] ^{a,c} at the upper laser welded joint. It was discovered that this [] ^{a,c} minimum margin was based on an incorrect stress range and was re-calculated to give a revised maximum S.I. range of [

] ^{a,c}. (Since the margin increased and remained positive, Reference 3-4 was not revised.) The revised generic limiting maximum stress range of [

] ^{a,c}. As stated in the generic LWS design specification, Reference 3-5, the "subsequent primary pressure test" load applies only to Series 44 steam generators. Therefore, this load does not apply to Kewaunee and does not appear in Tables 3-2 and 3-3. However, the [

] ^{a,c}.

From Table 3-12, the appropriate corresponding stress factor, giving the normalized (HEJLWR to GENLWS) increase in membrane plus bending stress due to the HEJ geometry at the weld section [] ^{a,c}. The calculated increased maximum stress to allowable ratio for the maximum stress range load combination in the repair weld of the Kewaunee HEJ sleeve is:

[] ^{a,c},

which remains below the limit of one, i.e., the stress intensity range remains less than the allowable range. Therefore, it is concluded that the laser weld repair of the Kewaunee HEJ sleeve upper joint meets the maximum range of stress intensity limit with positive structural margin at all analysis sections for all specified normal, upset, and test loads.

3.1.10 Fatigue Evaluation

The maximum calculated cumulative fatigue usage factor for the generic laser welded sleeve occurs in the upper laser welded joint, which is conservatively assumed to be at its minimum engagement length of [

] ^{a,c}.

Since the fatigue evaluation considers normal and upset loads, the Kewaunee pressure differential loads for normal and upset transients are, at most, only [] ^{a,c} than the generic pressure differential loads, due to the lower steam generator operating pressures as discussed in Section 4. Thus, all stress amplitudes (including those for test loadings) in the cumulative fatigue calculations are conservatively increased by the factor:

[

] ^{a,c}.

Using the above factor [

] ^{a,c} for Kewaunee, which remains well below the limit of one. Therefore, it is concluded that the laser weld repair of the Kewaunee HEJ sleeve upper joint satisfies the ASME Code fatigue limit with positive structural margin for all specified normal, upset, and test load combinations.

3.1.11 Minimum Sleeve Wall Calculations

The minimum wall calculations and resulting plugging margins are given in Reference 3-1 for the Kewaunee HEJ sleeve and in Reference 3-4 for the generic laser welded sleeves. [

] ^{a,c}.

In establishing the safe limiting condition of a sleeve in terms of its remaining wall thickness, the effects of loadings during both the normal operation and the postulated accident conditions must be evaluated. The applicable stress criteria are given in terms of allowables for the primary membrane and membrane-plus-bending stress intensities. Hence, only the primary loads (those necessary for equilibrium) need be considered. For sleeves near the tubesheet, there are essentially no external primary bending loads and only the membrane P_m stress intensity is significant. Therefore, for computing t_{min} , the pressure stress equation NB-3324.1 of the Code, Reference 3-6, is used. That is,

$$t_{min} = \frac{\Delta P_i \times R_i}{P_m - 0.5 (P_i + P_o)},$$

where: R_i = maximum inner radius of unexpanded sleeve = [] ^{a,c},

P_i = internal pressure = P_p = primary pressure (psig),

P_o = external pressure = P_s = secondary pressure (psig),

$\Delta P_i = P_i - P_o$,

P_m = allowable maximum value of primary membrane stress intensity (psi).

Normal Operation

From Table 3-1, the load parameters for normal steady state operation are:

$$P_i = P_p = [\quad]^{a,c} \text{ psig, } P_o = P_s = [\quad]^{a,c} \text{ psig, } \Delta P_i = P_i - P_o = [\quad]^{a,c} \text{ psi, sleeve @ } 592.5^\circ\text{F,}$$

and the allowable $P_m = S_u / 3 = 80 / 3 = 26.6$ ksi for TT Alloy 690. The resulting minimum thickness is:

$$[\quad]^{a,c}$$

Maximum Upset Condition

From Reference 3-4, the maximum upset conditions occur during the loss of load transient when the primary pressure is 2736 psig and the secondary pressure is 1110 psig, based on an initial secondary (steam) pressure of 705 psig. From Table 3-1, the lowest initial Kewaunee steam pressure is 668 psig for Steam Generator B. Therefore, the generic 1110 psig steam pressure should be reduced by the difference 705 - 668 or 37 psi for Kewaunee, and the load parameters for the maximum upset condition are:

$$P_i = P_p = [\quad]^{a,c} \text{ psig, } P_o = P_s = [\quad]^{a,c} \text{ psig, } \Delta P_i = P_i - P_o = [\quad]^{a,c} \text{ psi, sleeve @ } 600^\circ\text{F,}$$

and the allowable $P_m = S_y = 31.1$ ksi for TT Alloy 690 at 600°F. The resulting minimum thickness is:

$$[\quad]^{a,c}$$

Accident Condition: LOCA + SSE

The dominant loading for LOCA and SSE loads occurs at the top tube support in the form of bending stresses in the tubes. At tube support intersections below the top support, LOCA loads drop off dramatically. Because the sleeve is located near the tubesheet, the LOCA + SSE bending stresses in the sleeve are quite small. Therefore, the governing accident condition for the sleeve is a postulated secondary side blowdown, either a feedline break (FLB) or a steamline break (SLB) as discussed below.

Accident Condition: FLB / SLB + SSE

From Table 3-2, the maximum primary-to-secondary pressure differential occurs during a postulated feedline break (FLB) accident¹. Again because of the sleeve location, the SSE bending stresses are small. Thus, the governing stress for the minimum wall thickness requirement is the pressure membrane stress. The applicable criterion for faulted loads is:

$$P_m < \text{lesser of } 0.7 S_u \text{ or } 2.4 S_m$$

From Table 3-2, the load parameters for the feedline break are:

$$P_i = P_p = [\quad]^{\text{a,c}} \text{ psig, } P_o = P_s = [\quad]^{\text{a,c}}, \Delta P_i = P_i - P_o = [\quad]^{\text{a,c}} \text{ psi, sleeve @ } 547^\circ\text{F,}$$

and the allowable $P_m = \text{lesser of } 0.7 S_u \text{ or } 2.4 S_m$. For Alloy 690 at 547°F ,

$$0.7 S_u = 0.7 (80) = 56 \text{ ksi, and } 2.4 S_m = 2.4 (26.6) = 63.84 \text{ ksi.}$$

Thus, $P_m = 56 \text{ ksi}$ and the resulting minimum thickness is:

$$[\quad]^{\text{a,c}}$$

¹ The use of 2650 psig for FLB is conservative; 2560 psig is more appropriate.

A summary of the normal, upset and accident minimum required wall thicknesses is given in Table 3-14.

3.1.12 Determination of Plugging Limits

The minimum acceptable wall thickness and other recommended practices in Regulatory Guide 1.121, Reference 3-7, are used to determine a plugging limit for the sleeve. The Regulatory Guide was written to provide guidance for the determination of a plugging limit for steam generator tubes undergoing localized tube wall loss and can be conservatively applied to sleeves. Tubes with sleeves which are determined to have indications of degradation of the sleeve in excess of the plugging limit, would have to be repaired or removed from service.

As recommended in paragraph C.2.b of the Regulatory Guide, an additional thickness degradation allowance must be added to the minimum acceptable tube wall thickness to establish the operational sleeve thickness acceptable for continued service. Paragraph C.3.f of the Regulatory Guide specifies that the basis used in setting the operational degradation allowance include the method and data used in predicting the continuing degradation and consideration of NDE measurement errors and other significant eddy current testing parameters. An NDE measurement uncertainty value of []^{a,c} of the sleeve wall thickness, Reference 3-4, is applied for use in the determination of the operational sleeve thickness acceptable for continued service in the determination of the plugging limit.

Paragraph C.3.f of the Regulatory Guide specifies that the bases used in setting the operational degradation analysis include the method and data used in predicting the continuing degradation. To develop a value for continuing degradation, sleeve experience must be reviewed. To date, [

As a conservative measure, the conventional practice of applying a value of []^{a,c} of the sleeve wall, Reference 3-4, applied as an allowance for continued degradation, is used in this evaluation.

From Table 3-14, the structural limiting minimum sleeve wall thickness is []^{a,c} undegraded minimum wall thickness of the sleeve. Therefore, as shown in Table 3-15, the plugging limit for the Kewaunee sleeve, in percent of undegraded minimum wall thickness, is:

[]^{a,c}

3.2 Thermal/Hydraulic Analysis

The thermal/hydraulic analysis results presented in the original Kewaunee sleeving report, Reference 1-2, are unaffected by LWR.

3.3 Conclusions of Analytical Verification

Conclusions of the analytical verification elements are:

- The laser weld repair of the Kewaunee HEJ sleeve upper joint satisfies all primary stress limits with positive structural margin.
- The laser weld repair of the Kewaunee HEJ sleeve upper joint meets the maximum range of stress intensity limit with positive structural margin at all analysis sections for all specified normal, upset, and test loads.
- The laser weld repair of the Kewaunee HEJ sleeve upper joint satisfies the ASME Code fatigue limit with positive structural margin for all specified normal, upset, and test load combinations.
- The plugging limit for the Kewaunee sleeve, in percent of undegraded minimum wall thickness, is []^{a,c}.

3.4 Refereuces for Section 3

- 3-1 WCAP-11643, Revision 1, "Kewaunee Steam Generator Sleeving Report (HEJ Mechanical Sleeves)," November 1988. (Westinghouse Proprietary Class 2)
- 3-2 Design Specification 677031, Revision 4, "Reactor Coolant Systems 51 Series Steam Generator for Wisconsin Public Service Kewaunee Project," March 20, 1975. (Westinghouse Proprietary)
- 3-3 WCAP-14157, Revision 0, "Technical Evaluation of Hybrid Expansion Joint (HEJ) Sleeved Tubes With Indications Within the Upper Joint Zone," August 1994. (Westinghouse Proprietary Class 2C)
- 3-4 WCAP-13088, Revision 3, "Westinghouse Series 44 and 51 Steam Generator Generic Sleeving Report (Laser Welded Sleeves)," January 1994. (Westinghouse Proprietary Class 2)
- 3-5 Design Specification 412A19, "Laser Welded Sleeves for Plants With Series 44 and 51 Steam Generators," Rev. 0, December 17, 1992. (Westinghouse Proprietary Class 2C)
- 3-6 ASME Boiler and Pressure Vessel Code, Section III, "Rules, For Construction of Nuclear Power Plant Components," The American Society of Mechanical Engineers New York, NY.
- 3-7 USNRC Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes (For Comment)," August 1976.

Table 3-1

**Comparison of Normal Operating Parameters
Generic LWS Analysis versus Current Kewaunee**

a,c

Table 3-2

**Generic Umbrella Pressnre Loads from Reference 3-5
for Design, Faulted, and Test Conditions⁽¹⁾**

a,c

NOTES:

- (1) There are no emergency conditions specified in Reference 3-5.
- (2) The Safe Shutdown Earthquake (SSE) results in negligible stresses in the sleeve, tube, and weld compared to the pressure stresses for the listed faulted events.

Table 3-3

Summary of Generic Transient Events from Reference 3-5

a,c

NOTES: (1) The Operating Basis Earthquake (OBE) results in negligible stresses in the sleeve, tube, and weld compared to the pressure and thermal stresses for the listed upset events.

Table 3-4

Criteria for Primary Stress Intensity Evaluation
Sleeve - Alloy 690

CONDITION	CRITERIA	LIMIT (KSI)
DESIGN	$P_m \leq S_m$ $P_L + P_b \leq 1.5 S_m$	$P_m \leq 26.60$ $P_L + P_b \leq 39.90$
FAULTED	$P_m \leq 0.7 S_u$ $P_L + P_b \leq 1.05 S_u$	$P_m \leq 56.00$ $P_L + P_b \leq 84.00$
TEST	$P_m \leq 0.9 S_y$ $P_L + P_b \leq 1.35 S_y$	$P_m \leq 36.00$ $P_L + P_b \leq 54.00$
ALL CONDITIONS	$S_1 + S_2 + S_3 \leq 4.0 S_m$	$S_1 + S_2 + S_3 \leq 106.4$

Table 3-5

Criteria for Primary Stress Intensity Evaluation
Tube & Weld - Alloy 600

CONDITION	CRITERIA	LIMIT (KSI)
DESIGN	$P_m \leq S_m$ $P_L + P_b \leq 1.5 S_m$	$P_m \leq 23.30$ $P_L + P_b \leq 34.95$
FAULTED	$P_m \leq 0.7 S_u$ $P_L + P_b \leq 1.05 S_u$	$P_m \leq 55.92$ $P_L + P_b \leq 83.88$
TEST	$P_m \leq 0.9 S_y$ $P_L + P_b \leq 1.35 S_y$	$P_m \leq 31.50$ $P_L + P_b \leq 47.25$
ALL CONDITIONS	$S_1 + S_2 + S_3 \leq 4.0 S_m$	$S_1 + S_2 + S_3 \leq 93.20$

Table 3-6

**Criteria for Primary Plus Secondary Stress
Intensity Evaluation
Sleeve - Alloy 690**

CONDITION	CRITERIA	LIMIT (KSI)
NORMAL, UPSET, and TEST	$[P_L + P_b + Q]_{MAX_RANGE} \leq 3 S_m$	$[P_L + P_b + Q]_{MAX_RANGE} \leq 79.8$
NORMAL, UPSET, and TEST	Cumulative Fatigue Usage	1.0

Table 3-7

**Criteria for Primary Plus Secondary Stress
Intensity Evaluation
Tube & Weld - Alloy 600**

CONDITION	CRITERIA	LIMIT (KSI)
NORMAL, UPSET, and TEST	$[P_L + P_b + Q]_{MAX_RANGE} \leq 3 S_m$	$[P_L + P_b + Q]_{MAX_RANGE} \leq 69.9$
NORMAL, UPSET, and TEST	Cumulative Fatigue Usage	1.0

Table 3-8

Calculated Stress Results At:

ASN 1 MEMBER: Tube

LOCATION: Through Tube At Far Field Above Weld

For Unit Load $\Delta P = P_P - P_S = 1000$ psi

a,c

Table 3-9

Calculated Stress Results At:

ASN 2 MEMBER: Tube

LOCATION: Through Tube At Weld

For Unit Load $\Delta P = P_p - P_s = 1000$ psi

a,c

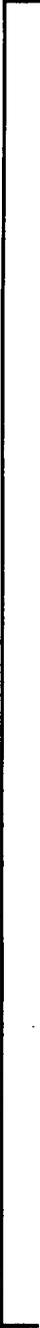
Table 3-10

Calculated Stress Results At:

ASN 3 MEMBER: Sleeve

LOCATION: Through Sleeve At Weld

For Unit Load $\Delta P = P_p - P_s = 1000$ psi



a,c

Table 3-11

Calculated Stress Results At:

ASN 4 MEMBER: Sleeve

LOCATION: Through Sleeve At Far Field Below Weld

For Unit Load $\Delta P = P_p - P_s = 1000$ psi

a,c

Table 3-12

Calculated Stress Results At:

ASN 5 MEMBER: Weld

LOCATION: Through []^o inch Engagement Length

For Unit Load $\Delta P = P_P - P_S = 1000$ psi

a,c

Table 3-13

Maximum Primary Stress Intensities (ksi) and Allowables (ksi)

From Generic LWS Evaluation for Series 51 SG, Reference 3-4

Sleeve/Tube Weld Engagement Length of []^{a,c}: Tube Severed Condition

a,c

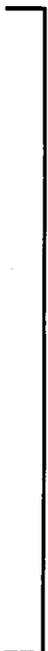
Table 3-14
Summary of Minimum Wall Thickness Calculations
Laser Weld Repair of Kewaunee HEJ Sleeves

a,c



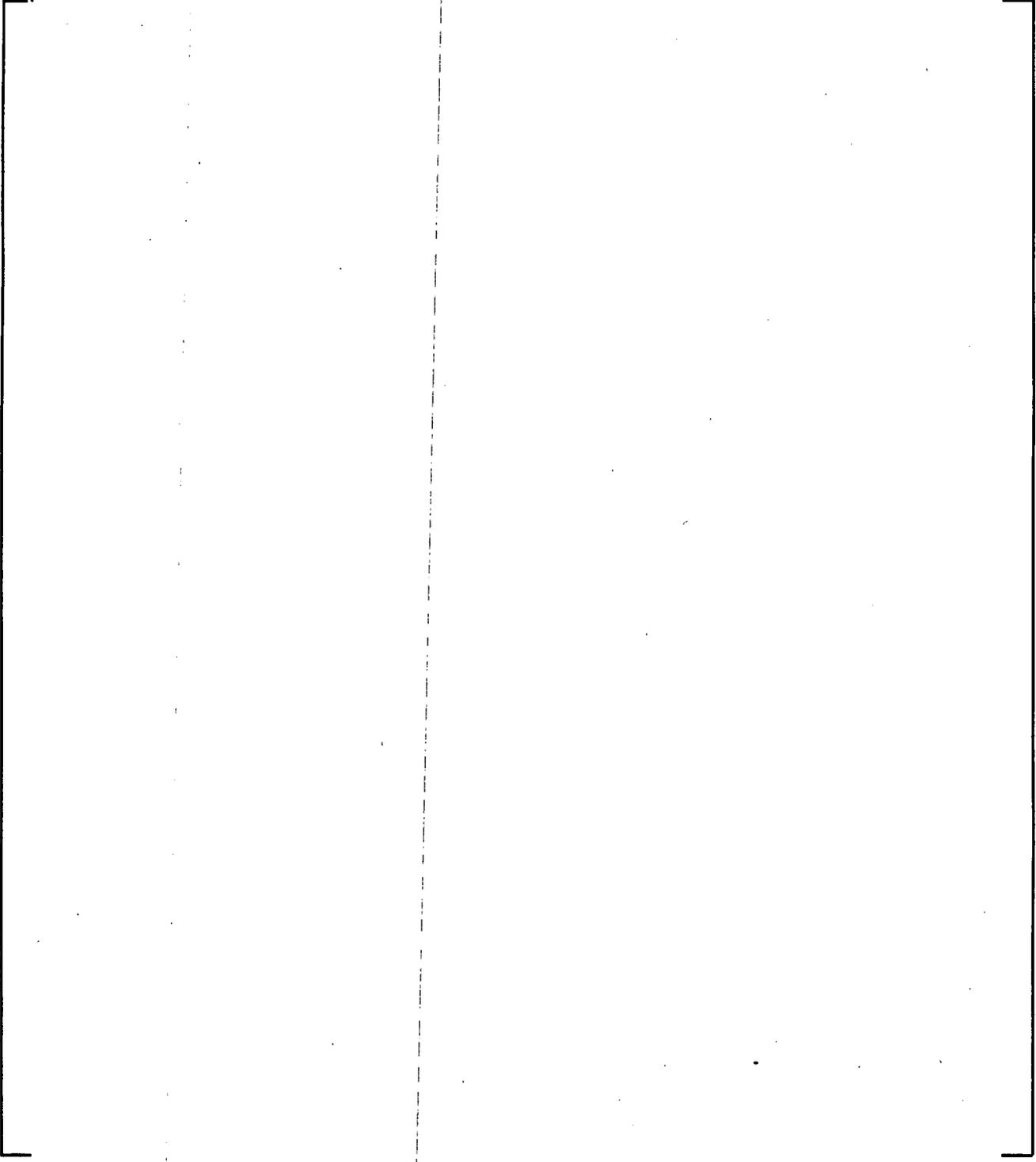
Table 3-15
Summary of Recommended Plugging Margins
Laser Weld Repair of Kewanee HEJ Sleeves

a,c



a,c

Figure 3-1 Location of Assumed Tnhe Severance for Analysis

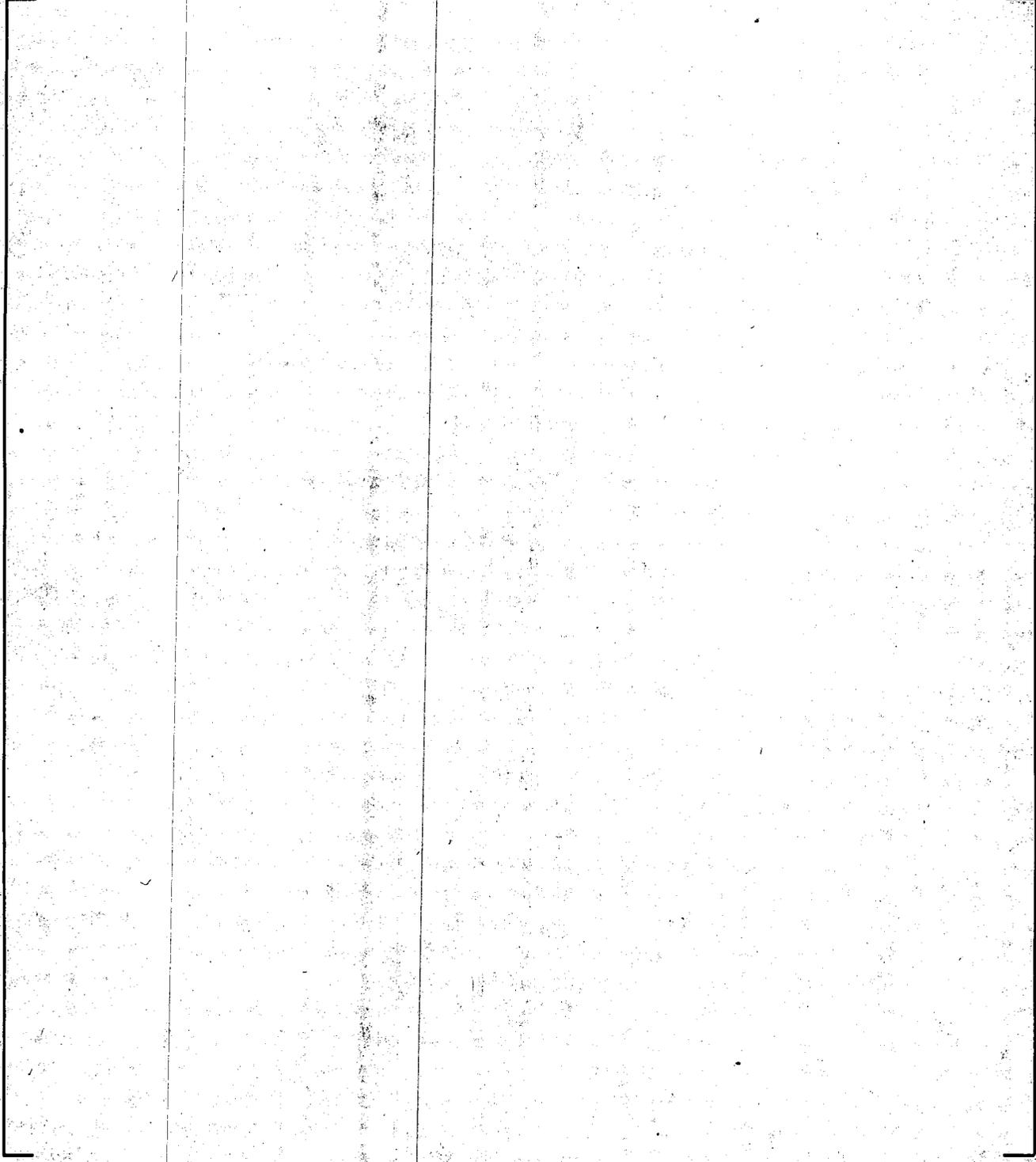


a.

Figure 3-2 FE Model of Laser Welded Repair of HEJ Sleeve (HEJLWR)

a,c

Figure 3-3 FE Model of Generic Laser Welded Sleeve (GENLWS)



a.

Figure 3-4 Close Up View Near Laser Weld

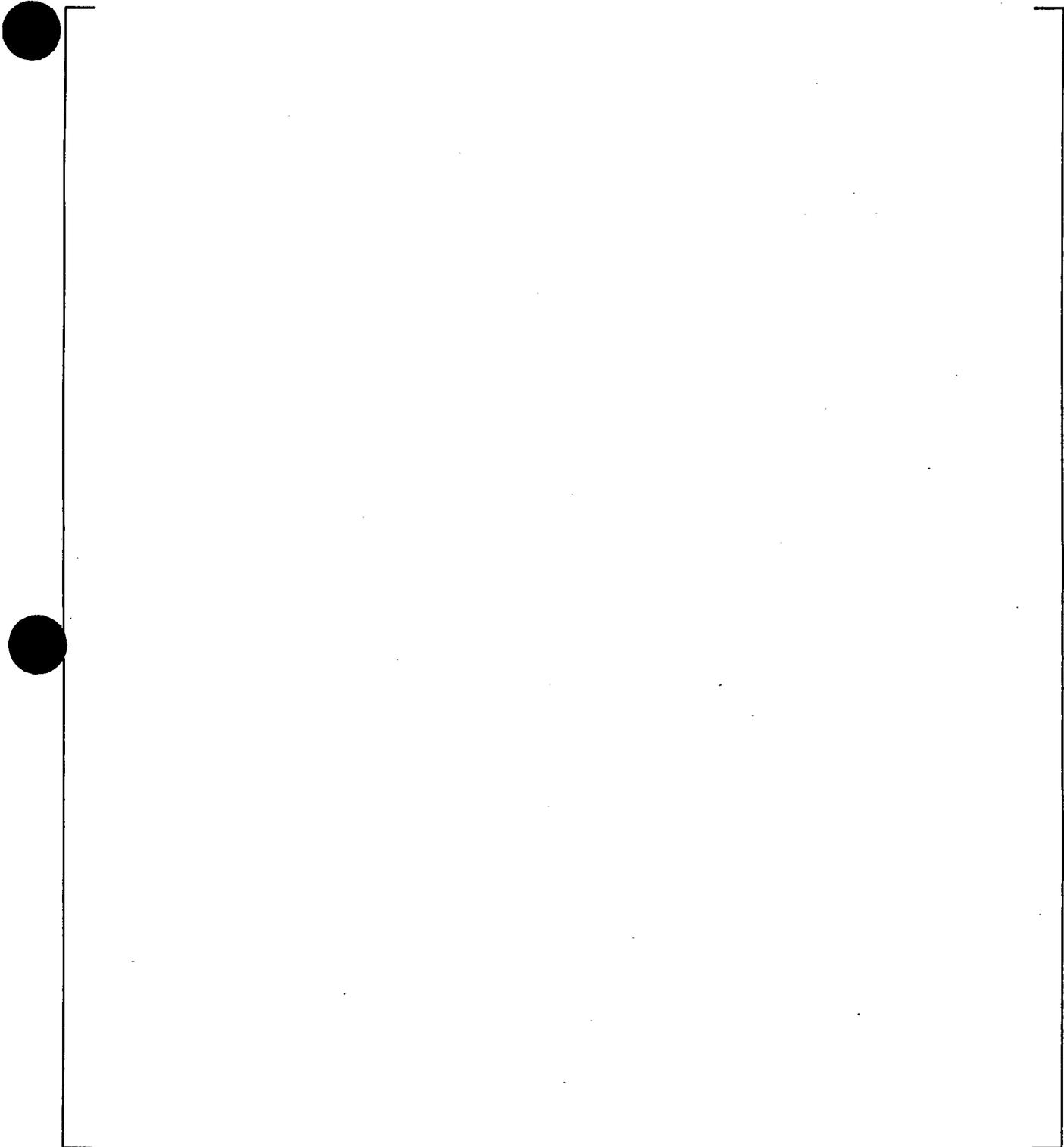


Figure 3-5

Unit Pressure Load and Boundary Conditions Assumed for FE Model of Laser Weld Repair of HEJ Sleeve (HEJLWR)

a,c

Figure 3-6

**Unit Pressure Load and Boundary Conditions Assumed for FE Model
of Generic Laser Welded Sleeve (GENLWS)**

a,c

Figure 3-7
Analysis Sections for Laser Weld Repair of HEJ Sleeve (HEJLWR)

a,c

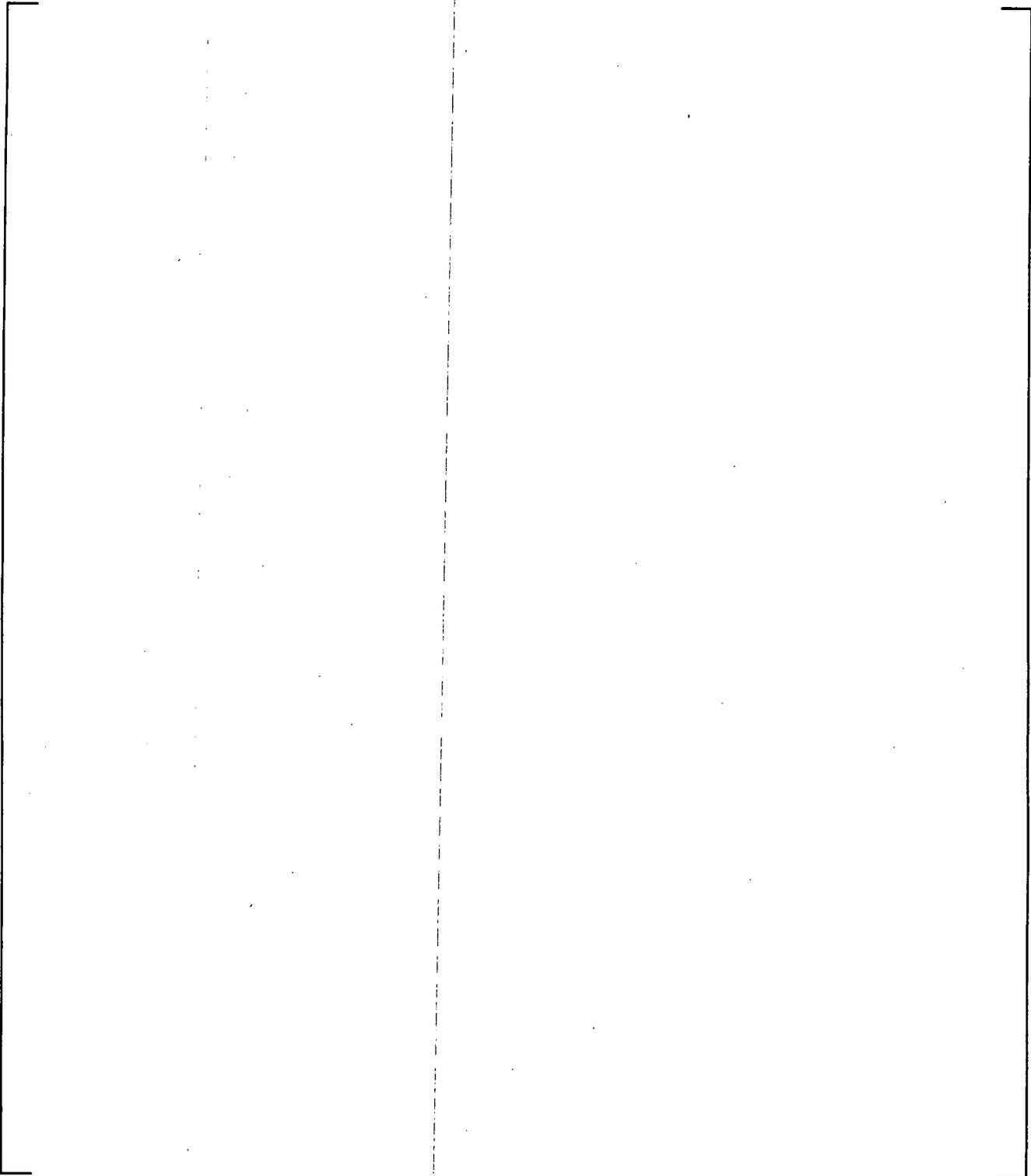


Figure 3-8

Analysis Sections for Generic Laser Welded Sleeve (GENLWS)

4.0 MECHANICAL TESTS

Mechanical tests were described in the generic laser welded sleeving (LWS) report for application in 7/8-inch tubes, Reference 1-1, as well as the HEJ sleeving report for Kewaunee, Reference 1-3.

Reference 1-1 shows that:

- a.) The laser weld is leak tight to pressures greater than 3100 psi at 600°F,
- b.) The load carrying capability of the laser weld exceeds the end cap loadings associated with a safety factor of 3 applied to the Kewaunee normal operating primary-to-secondary pressure differential (most limiting Regulatory Guide 1.121 case).

It was concluded that the LWS test results are directly applicable to the LWR HEJ, and that the upper joint is acceptable based on Reference 1-1 leakage and load carrying criteria and test results.

The leak rate criteria for LWR HEJ sleeves are the same as those for the HEJ sleeves described in the Kewaunee HEJ sleeve report, Reference 1-3. Allowable leak rates for normal and postulated accident conditions were defined in Table 3.3.4.3-1 of Reference 1-3. Since the upper joint in an LWR HEJ sleeve is hermetically sealed by the laser weld, leakage from only the lower joint is considered in evaluating the LWR HEJ sleeve against the acceptance criteria. The HEJ lower joint is unaffected by LWR, and the LWR HEJ leak rates remain well within the allowable limits. Similarly, Reference 1-3 shows that the LWR HEJ lower joint, which has a load carrying capability greater than an end cap loading equal to three times the normal Kewaunee operating primary-to-secondary pressure, continues to meet the limiting Regulatory Guide 1.121 criterion.

The results do not change when considering the LWR HEJ as an assembly (both upper and lower joints), and the mechanical testing confirms LWR HEJ acceptability with regard to leakage and load carrying capability.

5.0 CORROSION TESTING

The following section provides the results of corrosion tests performed in support of HEJ LWR.

5.1 Test Matrix Basis

The corrosion test specimen matrix is presented in Table 5-1. Examination of field HEJs has shown that "roll-down" can occur at the lower end of the upper mechanical roll, so half of the specimens were prepared with the roll-down effect, and half without. To evaluate the effects of post-LWR thermal stress relief on corrosion performance, HEJ LWR specimens were made with and without thermal stress relief of the LWR region.

For corrosion testing in doped steam, it is standard practice to include roll-expansion specimens prepared with tubing of known low resistance to PWSCC, in order to obtain "baseline" data for comparison to the test specimens; this approach was employed in LWR HEJ testing. Six such roll-expansion specimens were prepared, and these were exposed on a distributed basis among the various autoclaves used for the HEJ LWR tests.

5.2 Specimen Preparation

The matrix illustrating the specimens types is shown in Table 5-1. The tubing used in the fabrication of both the HEJ LWR specimens and roll transition specimens is from a reference heat of mill annealed Alloy 600 that was processed to have low resistance to primary water stress corrosion cracking. The corrosion resistance of this material in doped steam has been well-characterized in the doped steam test environment. Sleeves used for fabrication of the specimens were from production lots of thermally treated Alloy 690 sleeving.

Prior to assembly as HEJs, the sixteen sleeve and tube sections were [

]^{a,c,e} The HEJ test

assemblies were then fabricated using the same process as the field HEJs.

All of the specimens were fabricated under conditions believed to conservatively represent those in the field, viz, with the tubes "locked" against axial motion at the tube support plates (TSPs). During specimen fabrication, the far-field stresses from the HEJ sleeving process, and those arising from LWR (including stress relief), were measured and recorded.

The test stand for the fabrication of the specimens is designed to simulate the steam generator structure, assuming the tube is locked at the first support plate. The span between the top of the tubesheet and the support plate, as shown in Figure 5-1, is consistent with that of the Model 51 steam generators. In each specimen, the tubesheet is simulated by a [

]a,c,e

5.2.1 Far-Field Stresses

The far-field fabrication stresses were measured by [

]a,c. Axial stresses were determined at each fabrication step, from the fabrication of the HEJ through the laser weld repair process and thermal stress relief.

All HEJ fabrication processes were consistent with the field process used to install HEJ sleeves in the steam generators. The laser welding process and stress relief process are the same as those which are to be used to effect the field repairs. The stress relief process employed a [

]a,c

The average far-field stresses after HEJ fabrication, laser welding and stress relief operations are summarized in Table 5-2. The data are provided for both the roll-down and no roll-down configurations. Installation and fabrication of the HEJ sleeve joint led to average far-field [

]a,c

A typical time-stress history during the installation of the HEJ and the subsequent repair is shown in Figure 5-2. This figure shows the change in far-field stress as each operation progresses and

shows the final far-field stress state for a laser weld repair in the stress relieved condition.

5.2.2 Sleeved Tube Geometry and Weld Integrity

The laser weld repair, which includes the stress relief of the weld, did not result in any change in tube diameter or the introduction of any significant bowing or buckling of the tube. The typical tube diameter of the repaired HEJ tube in the region of the upper joint is shown in Figure 5-3. The final tube diameter is established during the HEJ sleeve installation and there is no additional diametral change associated with the laser weld repair.

There was no evidence in the data shown in Figure 5-3 of local bulging during the stress relief operation. [

] ^{a,c}.

Visual examination of the weld surface showed the welds to be sound with no evidence of cracking or blowholes. UT examination also showed the welds to be of good quality and as meeting the acceptance criteria defined in Section 7.0. Metallographic sectioning was performed on a number of weld-repaired sections to verify the weld parameters were consistently producing weld axial extents (the structural boundary between the Alloy 690 sleeve and the Alloy 600 parent tube) greater than the analyzed minimum value defined in Section 3.1.1.

5.3 Corrosion Test Method

The resistance of the laser weld repaired HEJ sleeved tube to primary water stress corrosion cracking (PWSCC) was evaluated in accelerated corrosion tests of the specimens prepared under locked tube conditions. The accelerated corrosion tests were conducted in dense steam in a high pressure autoclave operating at [

] ^{a,c}. This test provides an extreme acceleration of the corrosion process relative to that which occurs in an operating steam generator. In some respects, the doped steam test can be viewed as a stress-indexing test;

failure times in the doped steam test can generally be analyzed in terms of the stresses (residual and pressure) present in the test articles. In view of the dominant role of stress in PWSCC of Alloy 600, this is a particularly valuable feature of the test.

To facilitate interpretation of the corrosion test results and to provide verification of the aggressiveness of the test environment, roll expansion transition specimens, prepared of a reference laboratory heat of Alloy 600 with known low resistance to PWSCC, were included in the autoclaves.

For the current test program, the configuration of the test assembly is shown in Figure 5-4. The specimen is loaded axially [

] ^{a,c}. For the LWR HEJ specimens, all specimens were tested with a load which produced an [^{a,c} as measured in the straight portion of tube above the HEJ. This is a conservative (high) value and includes, in addition to the largest above-the-HEJ far field stress measured for the sixteen specimens from Table 5-2 (average of A and B strain gages for specimen KR-02), an adjusted stress contribution for the "end cap load" which conservatively assumes that the tube is *not* locked in the tube support plate, and an adjustment for modulus effects (relative to actual SG operating conditions) that occur in heating the test specimens to 750°F. Note that the addition of the end cap loading is conservative for the majority of Kewaunee tubes, since most of the tubes are believed to be "locked" at the first hot leg TSP.

The corrosion tests were to be run for a period of [

] ^{a,c}. Post-test examinations are done by non-destructive (eddy current) and destructive examinations as necessary, to locate and characterize the degradation.

5.4 Corrosion Test Results

The results of the corrosion tests are presented in Table 5-3. Included in the data are the results for the roll expansion specimens. Autoclave facilities capable of testing specimens of the size and complexity of the LWR HEJ test articles are limited; hence, initial emphasis was placed on the specimens representative of the laser weld repair process proposed for Kewaunee. Tests of several of the non-stress relieved specimens were also performed for reference information.

Nondestructive and destructive tests were performed on all of the stress relieved specimens (KR-1 to KR-8) and the results are presented in Table 5-4. [

] ^{a,c}.

Two of the tube sections (KR-7 and KR-8) showing [

] ^{a,c}. In general, Table 5-4 shows a good agreement between the crack dimensions determined by destructive and nondestructive methods. In some cases, the destructive examination showed greater crack lengths or additional cracks.

The testing of the stress relieved specimens indicated that [

] ^{a,c}.

[

] ^{a,c}.

A review of the time to develop stress corrosion cracking in Table 5-3 indicates that the stress relieved specimens take much longer [] ^{a,c} to crack as compared to the specimens without stress relief [] ^{a,c}. There was [] ^{a,c} specimens.

Of [

] ^{a,c}.

Estimate of LWR Service Performance

The mean time-to-failure of the roll expansion specimens was [] ^{a,c}. Using the data shown in Table 5-3 for total times in test [

] ^{a,c}. Hence,

[] ^{a,c}

However, the stress dependency of cracking in doped steam and in primary water are not the same. In data (Reference 5-1) established from tests on dead-weight loaded specimens that the stress exponent, n, for Alloy 600 in doped steam is [] ^{a,c}.

Hence, in primary water,

[] ^{a,c}

or, times-to-crack in primary water are related to times-to-crack in doped steam by,

[] ^{a,c}

For this set of data, using the average values cited above,

[] ^{a,c}

This implies that the failure of LWR HEJ tubes will not occur before greater than thirty times the operating period required to crack roll-expanded tubing. For SGs operating with an inlet temperature (T_{hot}) on the order of 600°F, the operating time required to crack a roll expansion would be well over [] ^{a,c}. Hence, the projected performance of LWR HEJ sleeves is

greater than []^{a,c}

For the worst case, using only the data for the earliest failure in the doped steam tests, []^{a,c} for the repaired joint on a worst-case basis.

Estimate of Performance of Non-Stress Relieved Specimens

The mean time-to-failure of the roll expansion specimens was []^{a,c}. Using the data shown in Table 5-3 for total times in test, the mean time-to-failure for the []^{a,c}.

Hence,

[]^{a,c}

As noted above, the stress dependency of cracking in doped steam and in primary water are not the same. Applying the same relationships as described above,

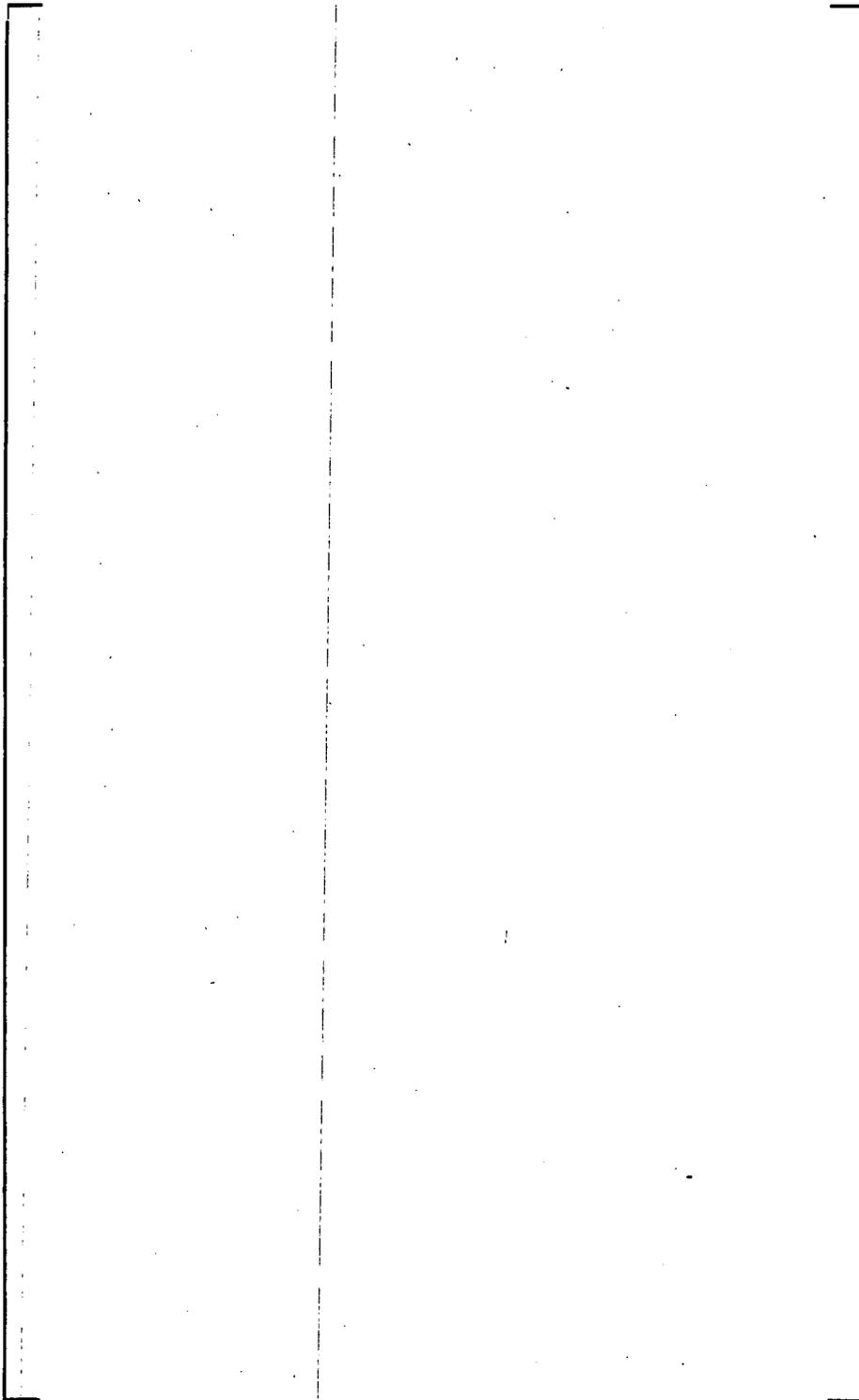
[]^{a,c}

This implies that the failure of non-stress relieved LWR HEJ tubes will not occur before greater []^{a,c} the operating period required to crack roll-expanded tubing. This is a []^{a,c} than the operating period indicated for stress relieved LWR HEJs.

5.5 References for Section 5

- 5-1 "Strain-Rate Damage Model for Alloy 600 in Primary Water", Final Report on Research Project S303-8, EPRI Report NP-7008, October 1990.

Table 5-1
Corrosion Test Matrix for Kewanee HEJ Repair



a,c

Table 5-2 Far-Field Stresses Measured in Mockup Fabrication

a,c



Table 5-2 (Cont'd.) Stresses Measured in Mockup Fabrication

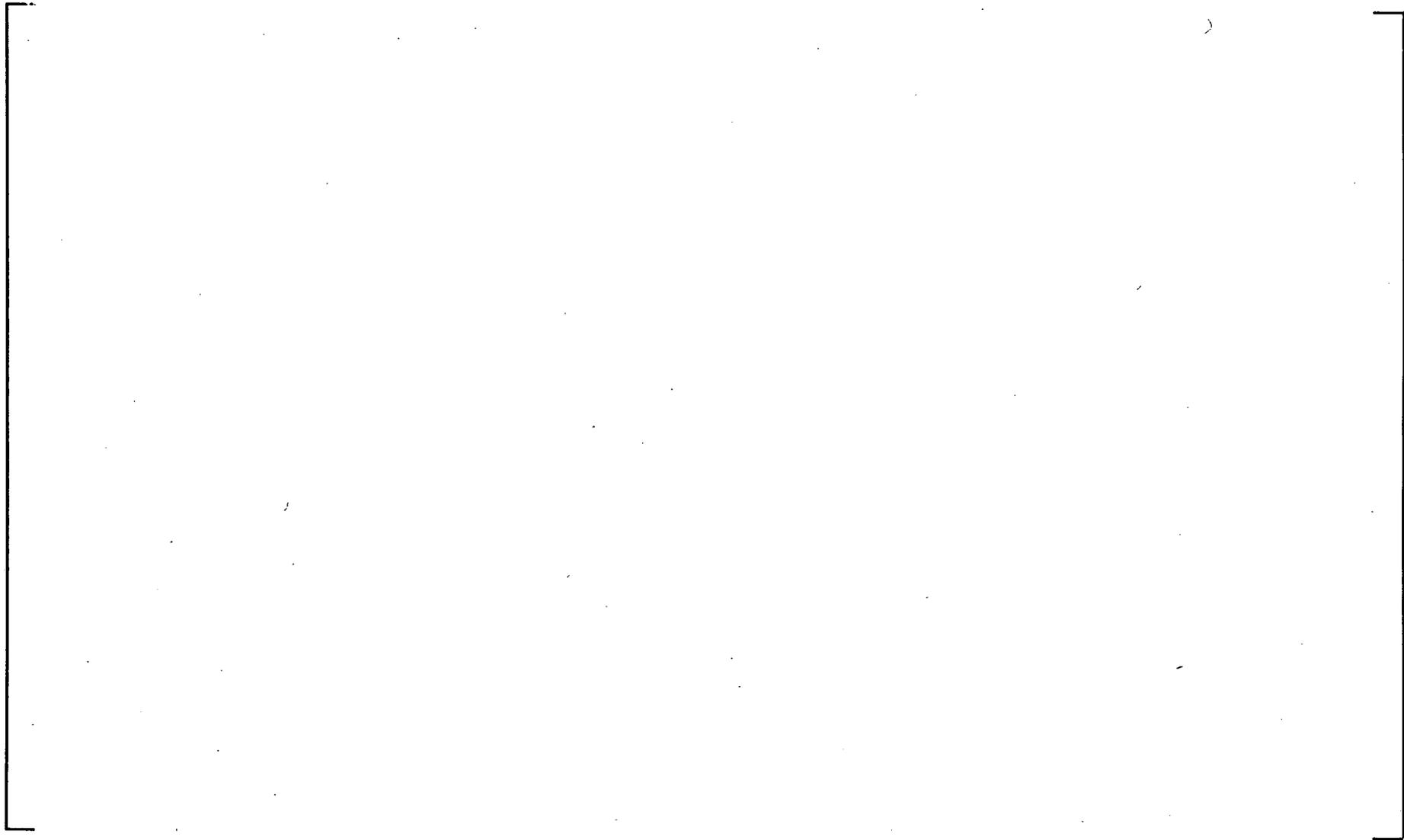
a,c



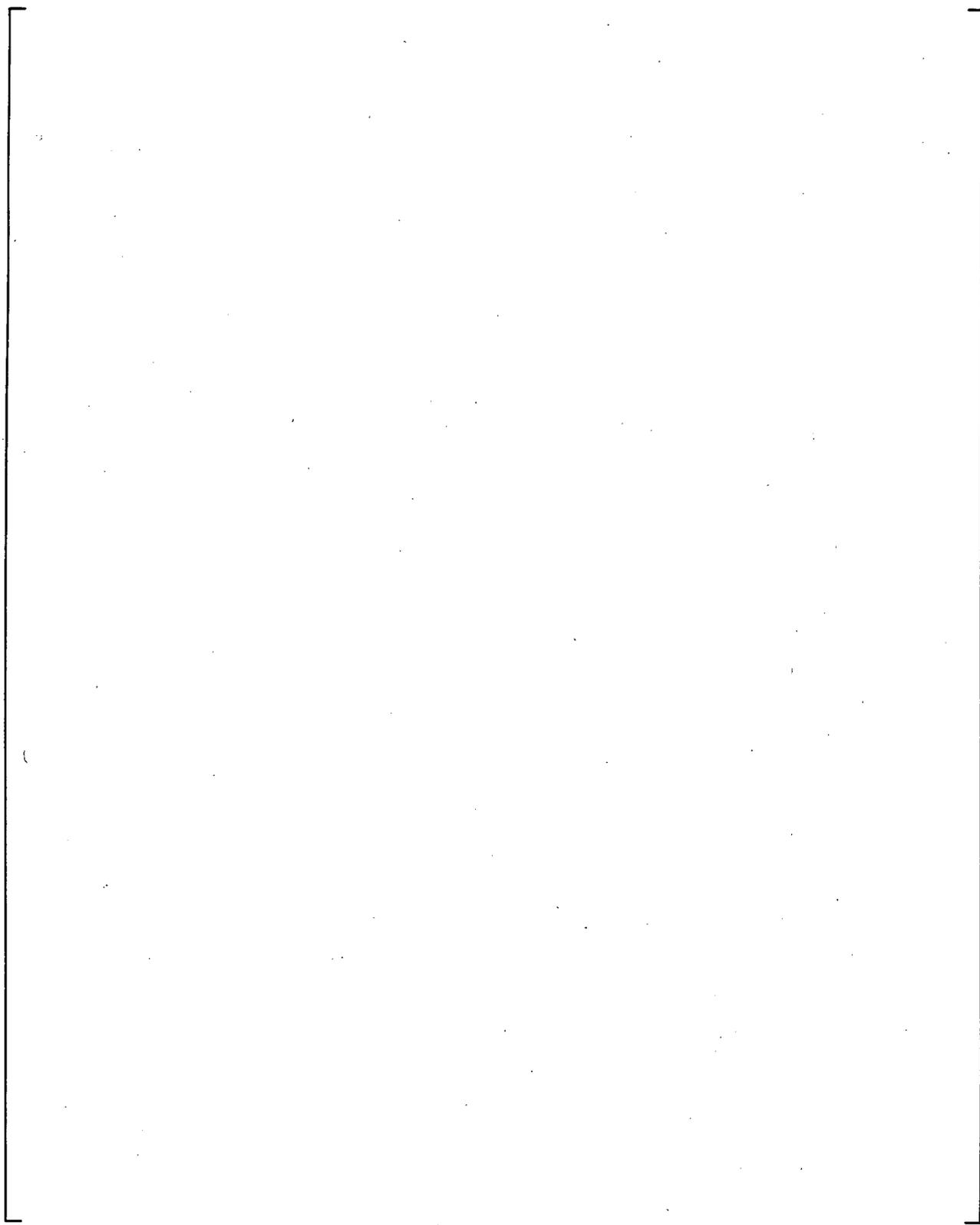
Table 5-3 Results of Corrosion Tests in Doped Steam

a,c

Table 5-4 Test Results of Stress Relieved Corrosion Samples

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a,c



WPS Mockup R1 C2

Figure 5-1

Test Stand for Fabrication of LWS Mockups Under Locked Tube Conditions

Figure 5-2
Stress Time History for HEJ LWS Repair and Stress Relief

a, c, e

Figure 5-3
HEJ Tube OD Dimensions Post-LWS Repair

a,c,e





a.c.c



Corrosion Test Assembly

Figure 5-4

Corrosion Test Sample Configuration

6.0 REPAIR PROCESS DESCRIPTION

The repair of steam generator tubes by laser welded sleeving is a proven technology with over 30,500 installations to date. All of the sleeves installed by the laser welding technique have been Alloy 690TT, which is the material employed for the HEJ sleeves utilized at Kewaunee.

6.1 HEJ Sleeve Installation

The HEJ sleeve design configuration was briefly described in Section 2. Complete information on the HEJ sleeve installation is available in Reference 1-2, the Kewaunee sleeving report.

6.2 Sleeve ID Cleaning

To address the inside surface of the HEJ sleeve at the intended weld location, the HEJ LWR repair process includes a cleaning step to remove potential deposit of boric acid, frangible oxides or other material. Tests show that this process does not remove any significant fraction of the sleeve base material. Cleaning also removes radioactive deposits from the sleeve inside diameter, thereby reducing exposure rates in the channel head.

The interior surface of each candidate sleeve is cleaned by a [

]^{a,c,e} The hone brush is mounted on a flexible drive shaft and driven by a pneumatic motor. The hone brush is driven only in the vicinity of the upper hard roll. [

]^{a,c,e} The Cleaning End Effector mounts to a tool delivery robot and consists of a guide tube sight glass and a flexible seal designed to surround the tube/sleeve end and contain the spent flushing water. A flexible conduit is attached to the guide tube and connects to the cleaning unit on the steam generator platform. The conduit acts as a closed system which serves to guide the drive shaft/hone brush assembly through the guide tube to the candidate tube and also to carry the spent flushing water to an air driven diaphragm pump. The pump routes the water to the radioactive waste drain.

6.3 General Description of Laser Weld Operation

The design of the laser welded HEJ repair was illustrated in Figure 1-4. The repair consists of a laser weld made in the approximate center of the pre-existing hard rolled region of the upper joint. The weld geometry based on field experience is approximately [

] ^{a,c} No changes are made to the HEJ sleeve lower joint.

Welding of the HEJ sleeve is accomplished by a specially developed laser beam transmission system and rotating weld head. This system employs a Nd:YAG laser energy source located in a trailer outside of containment. The energy of the laser is delivered to the steam generator platform junction box through a fiber optic cable. The fiber optic contains an intrinsic safety wire which protects personnel in the case of damage to the fiber. The weld head is connected to the platform junction box by a prealigned fiber optic coupler. Each weld head contains the necessary optics, fiber termination and tracking device to correctly focus the laser beam on the interior of the sleeve.

The weld head/fiber optic assembly is precisely positioned within the hydraulic expansion region using the Select and Locate End Effector (SALEE). The SALEE consists of [

] ^{a,c}

The weld process for laser welded sleeves in 7/8" tubes, which also applies to HEJ LWR, was qualified in accordance with the rules of ASME Code Sections IX and XI (Reference 6-1), and to the additional Westinghouse requirements for weld geometry. The welding parameters are computer controlled at the weld operator's station. The essential variables per Code Case N-395 are monitored and documented for field weld acceptance. The requirements for an acceptable

weld process for a laser welded sleeve that were qualified in the laboratory testing portion of the program included:

- a) Weld width at sleeve to tube interface of greater than the analyzed minimum width (see Section 3.1.1).
- b) No porosity that would reduce the weld throat to below that in a).
- c) No cracks in the weld of base tube when examined at a magnification of at least 10X
- d) No indications when the weld ID surface is subjected to a liquid penetrant testing.

The detailed installation process verification steps will be specified in the Kewaunee HEJ LWR field service procedure.

No special precautions for humidity control other than the primary ventilation air flow will be required as the weld is located in the hard rolled section where []^{a,c}

6.4 Rewelding

Under some conditions, the initial attempt at making a laser weld may be interrupted before completion or determined to be unsatisfactory, []^{a,c}. Also, the ultrasonic test (UT) examination of a completed initial weld may be indeterminate resulting in the weld being rejected. Up to []^{a,c} may be performed at the same location as the original weld. If the sleeve/tube were perforated during interruption of the initial weld, the tube would be removed from service.

6.5 Post-Weld Heat Treatment

Corrosion testing of LWR HEJ mockups, as discussed in Section 5, demonstrated the relative corrosion performance of post-weld thermal stress relieved specimens versus non-stress relieved specimens. The data support the efficacy of post-weld thermal stress relief. This stress relief

operation will be performed with a [

]a.c.e

The field tooling used by Westinghouse for stress relief consists of the heater probes and an end effector. The heater probe is a []^{a,d} The end effector places a probe within the proper zone to perform the stress relief operation. This is done by using the ROSA robotic arm and the SALEE to sequentially place the heater probes at the proper welded sleeve/tube interfaces, including reweld locations, followed by application of the stress relief process. This equipment has been used routinely and consistently for all recent field sleeving efforts.

6.6 Inspection Plan

In order to verify the final sleeve installation, inspections will be performed on sleeved tubes to verify installation and to establish a baseline for future eddy current examination of the sleeved tubes. Specific NDE processes are discussed in Section 7.0. The inspection acceptance criteria are essentially the same as those for newly installed laser welded sleeves. Tubes with laser weld repaired HEJ sleeves which do not meet the inspection acceptance criteria will be removed from service.

6.7 References for Section 6

- 6-1 ASME Boiler and Pressure Vessel Code, Section XI, Article IWB-4300, 1989 Edition, 1989 Addenda.

Table 6-1

HEJ Laser Weld Repair Process Sequence Summary

SLEEVE ID CLEANING	1)	Hone ID of HEJ Sleeves at Weld Location.
WELD OPERATION	2)	Weld Upper HEJ Sleeve Joint
STRESS RELIEF	3)	Post Weld Stress Relief of Weld
INSPECTION	4)	Ultrasonically Inspect Sleeve Weld (Free span welds only on a sample plan)
INSPECTION	5)	Baseline Eddy Current Sleeve

7.0 NDE INSPECTABILITY

Laser welding parameters are computer controlled at the weld operator's station. The essential variables of ASME Code Case N-395 are monitored and documented for each weld. In addition, two non-destructive examination (NDE) techniques are used to evaluate the acceptability of the weld. Ultrasonic examination is used to confirm that the laser weld meets critical dimensional and integrity requirements. Eddy current inspection is then applied to provide baseline data for subsequent in-service inspections.

7.1 Inspection Plan Logic

The basic LWR HEJ sleeve inspection plan consists of:

- A. Ultrasonic Inspection (Section 7.2) []^{a,c,e} or alternate methods (Section 7.4) to:
1. Verify minimum required weld width.
- B. If eddy current inspection of a sleeve is performed prior to, but during the same outage as LWR, inspection of only the weld and heat treat region of the HEJ LWR (as described in Section 7.3) would be required. If no such prior inspection has been performed, eddy current inspection of the full length of the sleeve would be required. In both cases these are to:
1. Verify that the weld is located within the HEJ upper roll expansion.
 2. Verify the presence of a post-weld heat treatment.
 3. Record baseline volumetric inspection of the sleeve, the sleeve/tube joint, and the parent tube in the vicinity of the welded sleeve joint for future inspections.
 4. Verify that a minimum distance exists between the centerline of the weld and potential degradation in the portion of the parent tube immediately below the weld. (Note: This requirement does not exclude pressure boundary inspection requirements.)

C. Weld Process Control [

] to:

1. Demonstrate that the weld process parameters comply with the qualified weld process specification.

7.2 Overview of Ultrasonic Examination Process

The ultrasonic (UT) inspection process for LWR HEJ sleeves is based upon techniques which have been successfully used on Westinghouse laser welded sleeves for 3/4-inch and 7/8-inch OD tubes.

The UT inspection technique has been adapted to examine laser welds. UT transmits ultrasound to the interface region (the sleeve OD /tube ID boundary) and analyzes the amount of reflected energy from that region. An acceptable weld joint should present no acoustic reflectors from this interface above a predetermined threshold.

Appropriate transducer, instrumentation and delivery systems have been designed and techniques established to demonstrate the ability to identify welds with widths below the structural requirements. The entire weld interface (100 per cent of the axial and circumferential extent) will be examined. Acceptance of welds is based upon application of criteria which are qualified by destructive examination of marginal welds. The development of criteria based upon direct evaluation of destructively examined welds provides a high degree of confidence in the weld acceptance criteria. The acceptance criteria are detailed in the appropriate field procedure.

7.2.1 Principle of Operation and Data Processing of Ultrasonic Examination

The ultrasonic examination of a laser weld is schematically outlined in Figure 7-1. An ultrasonic wave is launched by application of an electrical pulse to a piezoelectric transducer. The wave propagates in the couplant medium (water) until it strikes the ID of the sleeve. Ultrasonic energy is both transmitted and reflected at the boundary. The reflected wave returns to the transducer where it is converted back into an electrical signal which is amplified and displayed on the UT display.

The transmitted wave propagates in the sleeve until it reaches the sleeve OD. If fusion between the sleeve and tube exists, the wave continues to propagate through the weld joint into the tube. This wave then reaches the outer wall (backwall) of the tube and is reflected back to the transducer. The resulting UT display from a sound weld joint is a large signal from the sleeve ID, followed by a tube backwall "echo" spaced by the time of travel in the sleeve-tube-weld assembly ($T_{1,2,3}$). If no fusion between the sleeve and the tube exists, another pattern is observed with a large signal from the sleeve ID followed by a reflection from the sleeve OD. The spacing of these echoes depends on the time of travel in the sleeve alone ($T_{1,2}$). Additional reflections after the sleeve OD reflections are considered "multiples" of the sleeve OD reflection. These are caused as the sound energy reflected off the sleeve OD bounces back and forth between the sleeve ID and OD, and decays over time.

[

]a.c.e

Criteria for the acceptance of a laser weld is based upon combination of the observed ultrasonic response at the at the weld surface, the sleeve/tube interface, and the tube OD.

An automated system is used for digitizing and storing the UT wave forms (A-Scans). [

]a.c.e The ultrasonic response from the weld is then digitized for each pulse. A typical digitized A-scan is shown in Figure 7-2. Time intervals known as "gates" are set up over the signals of interest in the A-Scan so that an output known as a "C-Scan" can be generated. The C-Scan is a developed view of the inspection area which maps the amplitude of the signals of interest as a function of position in the tube. A combined C-scan which shows the logical combinations conditions of signals in two gates with respect to predetermined threshold values can also be displayed. Figure 7-3 shows the A, B, C, and combined C-scan display for a weld in a calibration standard.

7.2.2 Laser Weld Test Sample Results

Ultrasonic test process criteria are developed by [

]a.c.e

Field application requires calibration to establish that the system essential variables are set per the same process which was qualified. Elements of the calibration are to:

- Set system sensitivity (gain)
- Provide time of flight reference for sleeve ID, OD and tube OD signals
- Verify proper system function by examination of a workmanship sample

Figure 7-4 depicts a calibration standard for the sleeve weld UT exam. (This figure shows the standard for a 3/4 inch sleeve; a corresponding standard exists for a 7/8 inch sleeve.)

7.2.3 Ultrasonic Inspection Equipment and Tooling

The probe is delivered with a robotic tooling system. The various subsystems include the water couplant, UT, motor control, and data display/storage.

The probe motion is accomplished via rotary and axial drives which allow a range of speeds and axial advances per 360° scan of the transducer head (pitch). The pitch provides a high degree of overlapping coverage without sacrificing resolution or sensitivity.

The controls and displays are configured for remote location in a trailer outside of containment. The system also provides for periodic calibration of the UT system on the steam generator platform.

7.3 Eddy Current Inspection

Upon conclusion of the laser weld repair, eddy current inspection is performed on each repair to meet the process verification and baseline inspection requirements outlined in Section 7.1 B. Probes of either the array- or rotating-type which are qualified to meet ASME XI and EPRI Guideline NP-6201 Appendix H requirements are to be used in the inspection. The minimum allowable distance between the centerline of the weld and potential degradation in the non-pressure boundary portion of the parent tube (i.e., in the parent tube portion immediately below the weld) is [

]a.c.e

7.4 Alternate Post-Installation Acceptance Criteria

Ultrasonic or volumetric inspection is the principal method for post-installation weld quality evaluation, and eddy current examination is the primary in-service examination technique. However, there are cases, due [

]a.c.e

[

]a.c.e

In support of accepting UT indeterminate welds, several alternate strategies are available. These are described below.

7.4.1 Bonding Inspections

[

]a.c.e

[

]a,c,e

7.4.2 Workmanship Samples

[

]a,c,e

As other advanced techniques become available and are qualified for use, they may be implemented in LWR inspection programs.

7.5 Inservice Inspection Plan for LWR HEJs

The need exists to perform periodic inspections of the tube and sleeve pressure boundary. The inservice inspection program of LWR HEJs will consist of the following:

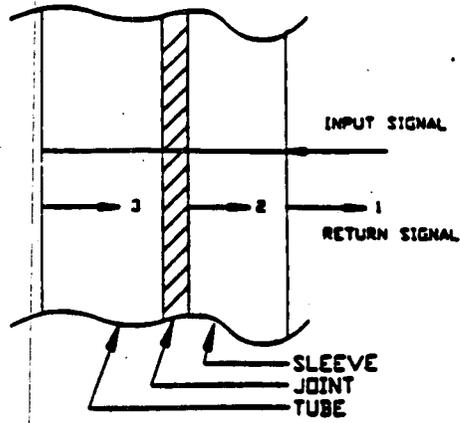
- a.) The LWR region will be eddy current inspected upon completion of installation to obtain a baseline signature to which all subsequent inspections will be compared.
- b.) Periodic inspections will be performed to monitor sleeve and tube wall conditions in accordance with the inspection section of the individual plant Technical Specifications.

The inspection of sleeves will necessitate the use of an eddy current probe that can pass through the sleeve ID. For the tube span between sleeves, this will result in a reduced fill factor for bobbin inspections. The possibility for tube degradation in free span lengths is extremely small. Plant data have shown that this area is less susceptible to degradation than other locations. Any tube indication in this region will require further inspection by alternate techniques (i.e., surface riding probes) prior to acceptance of that indication. Otherwise the tube shall be repaired or

plugged. Any eddy current indication in the free span, sleeve or sleeve/tube joint region which cannot be dispositioned by standard dual-analyst review will require further inspection by alternate techniques, i.e., surface riding probes, prior to acceptance of that indication. Otherwise the tube containing the sleeve shall be repaired or plugged.

7.6 References for Section 7

7-1 Stubbe, J., Birthe, J. Verbeek, K., "Qualification and Field Experience of Sleeving Repair Techniques: CSNI/UNPEDE Specialist Meeting on Operating Experience with Steam Generators, paper 8.7, Brussels, Belgium, September 1991.



IDEALIZED WAVEFORMS

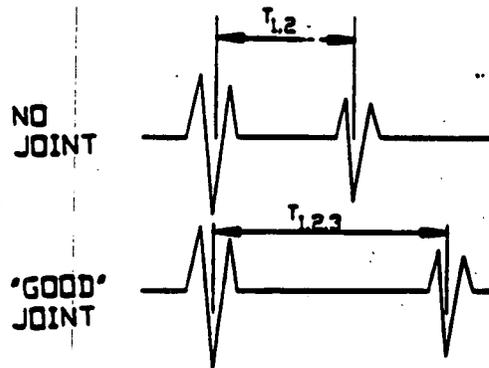


Figure 7-1

Ultrasonic Inspection of Welded Sleeve Joint

a,c

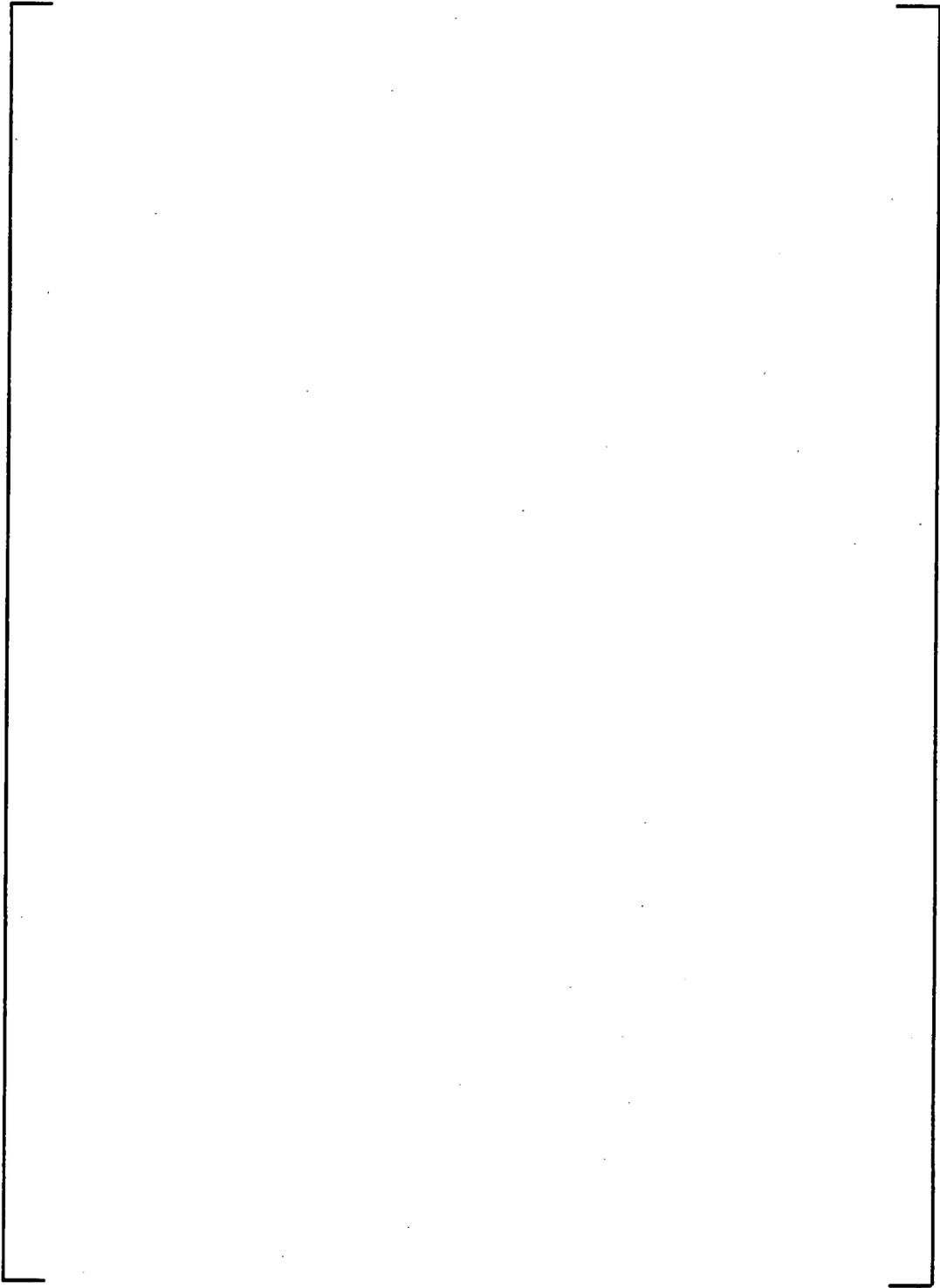


Figure 7-2
Typical Digitized UT Waveform

a,c,e

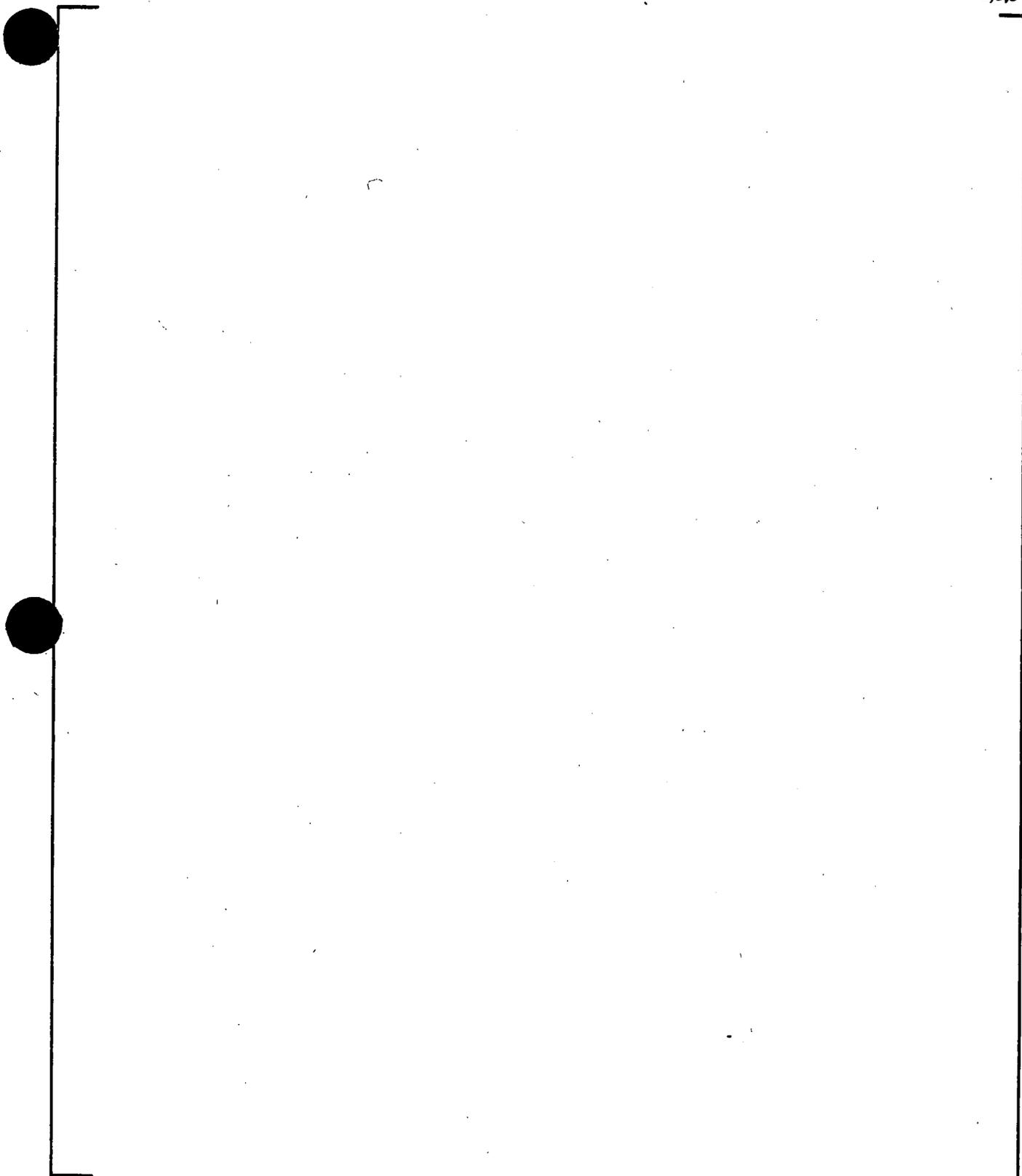


Figure 7-3
A, B, C, and Combined C-Scan Display for Weld in UT Calibration Standard

a,c,e

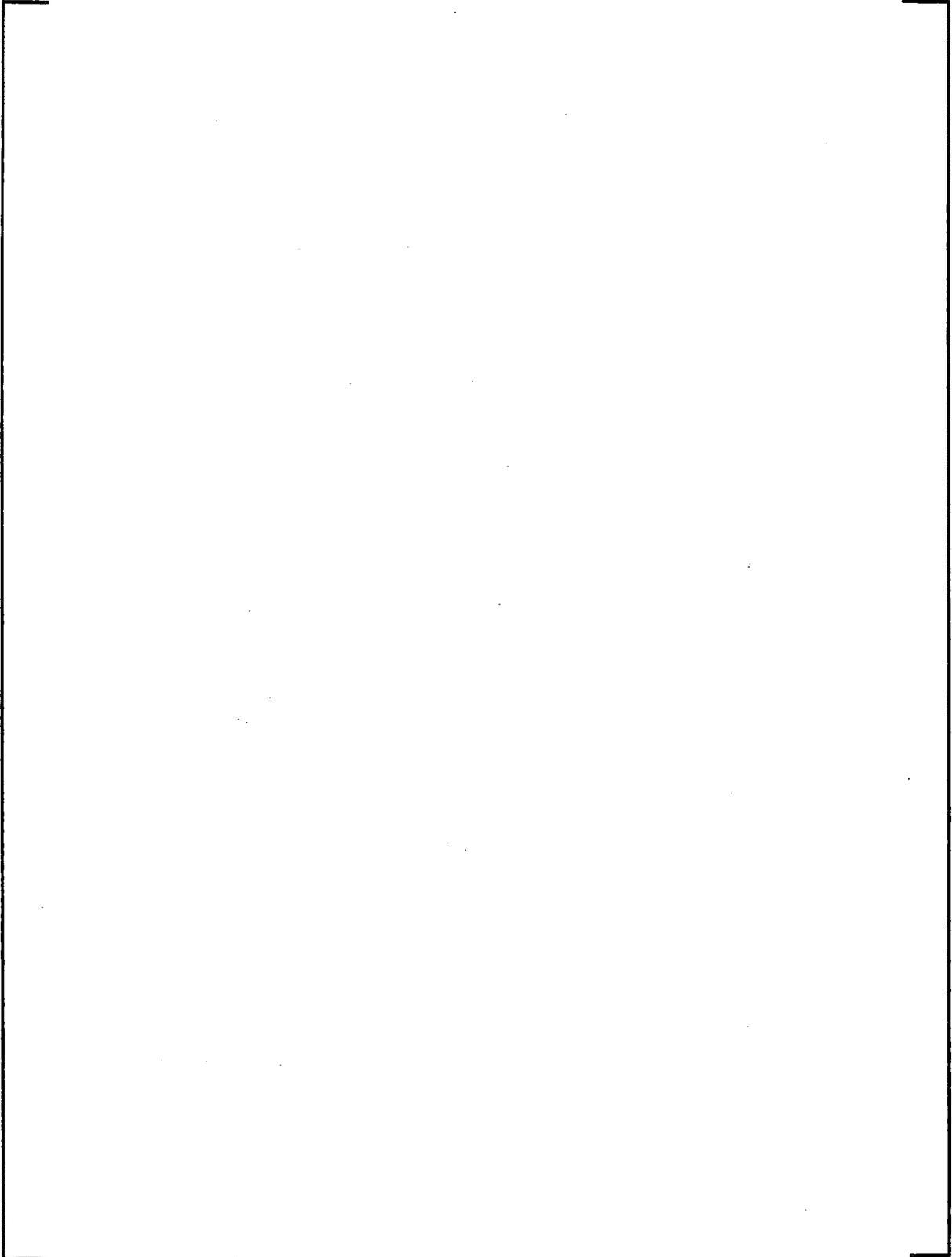


Figure 7-4

UT Calibration Standard