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KEWAUNEE

STEAM GENERATOR SLEEVING REPORT
(Mechanical Sleeves)
November 1988

PREPARED FOR WISCONSIN PUBLIC SERVICE

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1.0 INTRODUCTION

The document herein contains the necessary technical information to support licensing of the sleeving repair process as applied to the Kewaunee (WPS) Model 51 steam generators. As a result of extensive development programs in steam generator repair, Westinghouse has developed the capability to restore degraded steam generator tubes by means of a sleeve.

To date, approximately 22,000 steam generator tubes at six operating nuclear power plants world-wide have been successfully sleeved, tested, and returned to service by Westinghouse. Both mechanical-joint and brazed-joint sleeves of Alloy 600, 690, and bimetallic 625 and 690 have been installed by a variety of techniques - hands-on (manual) installation, Coordinate Transport (CT) system installation, and Remotely Operated Service Arm (ROSA) robotic installation. Westinghouse sleeving programs have been successfully implemented after approval by licensing authorities in the U.S. (NRC - Nuclear Regulatory Commission), Sweden (SKI - Swedish Nuclear Power Inspectorate), and Japan (MITI - Japanese Ministry of International Trade and Industry).

The sleeving technology was originally developed to sleeve degraded tubes (including leakers) in Westinghouse Model 27 series steam generators. A process and a remote sleeve delivery system (CT) were subsequently developed and adapted to Westinghouse Model 44 series steam generators in large scale programs at two operating plants. This technology has also been modified to facilitate installation of sleeves in a plant with non-Westinghouse steam generators.

2.0 SLEEVING OBJECTIVES AND BOUNDARIES

2.1 OBJECTIVES

Kewaunee (WPS) is a Westinghouse-designed 2 loop pressurized water reactor rated at 1,655 MWt. The unit utilizes two vertical U-tube steam generators. The steam generators are Westinghouse Model 51 Series containing heat transfer tubes with dimensions of 0.875 inch nominal OD by 0.050 inch nominal wall thickness.

The sleeving concept and design are based on observations to date that the tube degradation due to operating environmental conditions has occurred near the tubesheet areas of the tube bundle. The sleeve has been designed to span the degraded region in order to maintain these tubes in service.

The sleeving program has two primary objectives:

1. To sleeve tubes in the region of known or potential tube degradation.

2. To minimize the radiation exposure to all working personnel (ALARA)

2.2 SLEEVING BOUNDARY

Tubes to be sleeved will be selected by radial location, tooling access (due to channel head geometric constraints), and eddy current indication elevations and size. An axial elevation tolerance of one inch will be employed to allow for any potential eddy current testing position indication inaccuracies and degradation growth. Tube location on the tubesheet face, sleeve length, tooling dimensions, and tooling access permitted by channelhead bowl geometry define the sleeving boundaries. Figure 2.2-1 shows estimated radial sleeving boundaries for [ ]a,c,e sleeves as determined by a geometric radius computed from the channelhead surface-to-tubesheet primary face clearance distance minus the tooling clearance distance. (The actual "as is" bowl geometry will be slightly different in certain areas.) These are the sleeving boundaries for a generic Westinghouse series 51 steam generator and represents the maximum sleeving potential with a [ ]a,c,e sleeves.

C220M:49/090888-17

MODEL 51 STEAM GENERATOR
SLEEVING BOUNDARIES

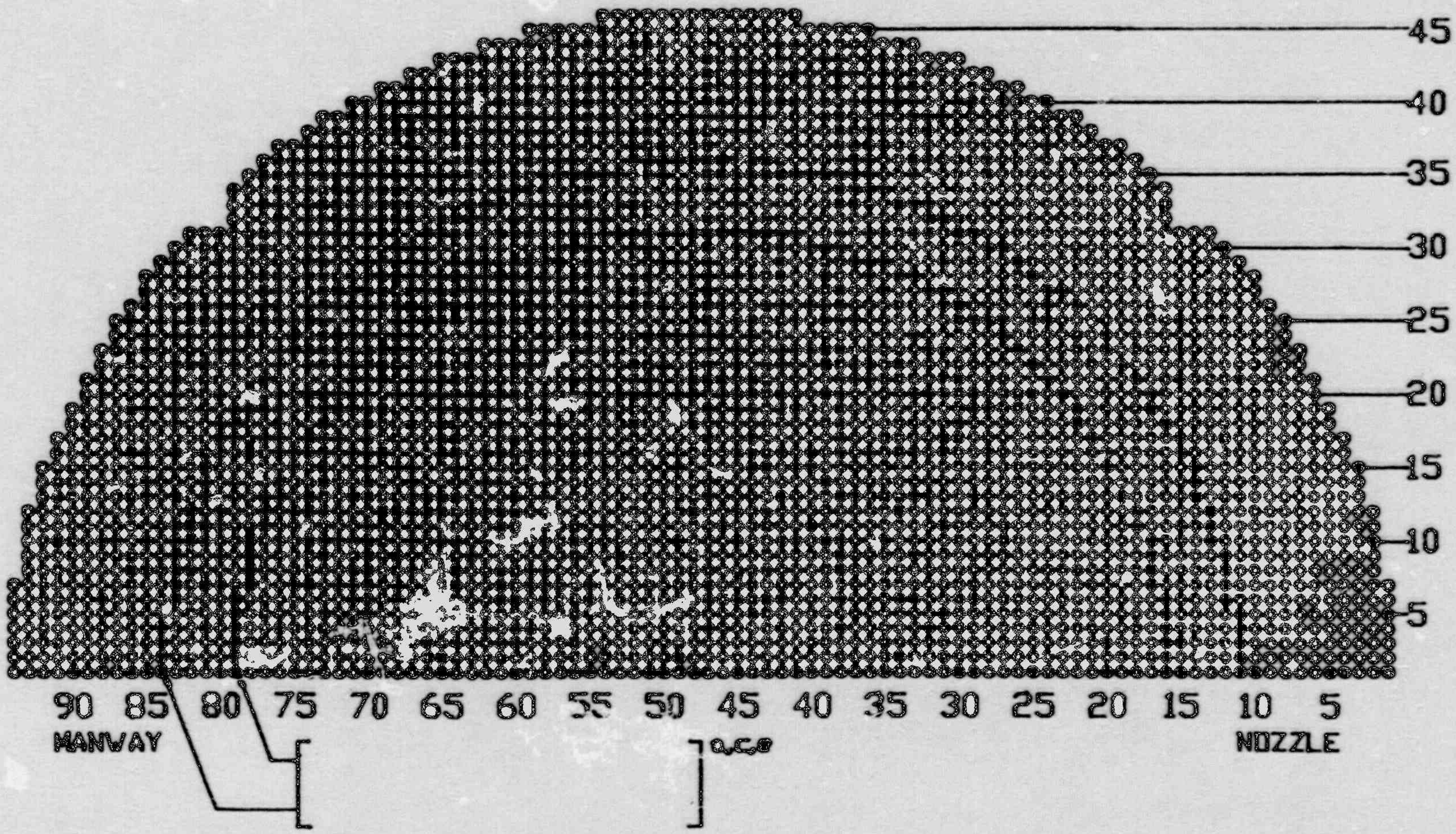


Figure 2.2-1

Sleeving Boundary [30" to 36"] a,c,e Sleeves

Tubes within the sleeving boundary that are degraded beyond the plugging limit but not within the axial restrictions of the [ ]a,c,e sleeve or not within the radial sleeving boundary will be plugged. The actual sleevable region may be modified based on tool length or other variables.

The actual tube plugging/sleeving map for each steam generator will be provided as part of the software deliverables at the conclusion of the sleeving effort.

The specific tubes to be sleeved in each steam generator will be determined based on the following parameters:

1. No indications beyond an elevation spanned by the sleeve pressure boundary which are greater than the plugging limit.

2. Concurrence on the eddy current analysis of the extent and location of the degradation.

2.3 REPORT APPLICABILITY

[

]a,c,e

3.0 DESIGN

3.1 SLEEVE DESIGN DOCUMENTATION

The Keaunee steam generators were built to the 1965 edition of Section III of the ASME Boiler and Pressure Vessel Code, however, the sleeves have been designed and analyzed to the 1983 edition of Section III of the Code through the winter 1983 addenda as well as applicable Regulatory Guides. The associated materials and processes also meet the requirements of the Code. The specific documentation applicable to this program is listed in Table 3.1-1.

3.2 SLEEVE DESIGN DESCRIPTION

The reference design of the sleeve, as installed, is illustrated in Figure 3.2-1. [

]a,c,e

At the upper end, the sleeve configuration (see Figure 3.2-1) consists of a section which is [

]a,c,e This

]a,c,e

In the process of sleeve length optimization and allowing for axial tolerance in locating defects by eddy current inspection, the guideline was that the lower-most elevation of the upper joint's hard roll region is to be positioned a minimum of 1 inch above the degraded area of the tube.

TABLE 3.1-1

ASME CODE AND REGULATORY REQUIREMENTS

Item	Applicable Criteria	Requirement
Sleeve Design	Section III	NB-3200, Analysis NB-3300, Wall Thickness
	Operating Requirements	Analysis Conditions
	Reg. Guide 1.83	S/G Tubing Inspectibility
	Reg. Guide 1.121	Plugging Margin
Sleeve Material	Section II	Material Composition
	Section III	NB-2000, Identification, Tests and Examinations
	Code Case N-20	Mechanical Properties
Sleeve Joint	10CFR100	Plant Total Primary to Secondary Leak Rate
	Technical Specifications	Plant Leak Rate

a,c,e,f

Figure 3.2-1

Installed Sleeve With Hybrid Expansion
Upper Joint Configuration

At the lower end, the sleeve configuration (Figure 3.2-2) consists of a section which is [

]^{a,c,e} The lower end of the sleeve has a preformed section to facilitate the seal formation and to reduce residual stresses in the sleeve.

The sleeve, after installation, extends above the top of the tubesheet and spans the degraded region of the original tube. Its length is controlled by the insertion clearance between the channel head inside surface and the primary side of the tubesheet, and the tube degradation location above the tubesheet. The remaining design parameters such as wall thickness and material are selected to enhance design margins and corrosion resistance and/or to meet ASME Boiler and Pressure Vessel Code requirements. The upper joint is located so as to provide a length of free sleeve above it. This length is added so that if in the unlikely event the existing tube were to become severed just above the upper edge of the mechanical joint, the tube would be restrained by the sleeve and lateral and axial motion, and subsequent leakage would be limited. Restrictied lateral motion would also protect adjacent tubes from impact by the severed tube. The upper end of the sleeve is tapered in the thickness to reduce the effect of double wall in eddy current signal interpretation.

To minimize stress concentrations and enhance inspectability in the area of the upper expanded region, [

]^{a,c,e,f}

The sleeve material, thermally treated Alloy 690, is selected to provide additional resistance to stress corrosion cracking. (See Section 3.3.2 for further details on the selection of thermally treated Alloy 690).

a,c,e

Figure 3.2-2

Sleeve Lower Joint Configuration

3.3 DESIGN VERIFICATION: TEST PROGRAMS

3.3.1 DESIGN VERIFICATION TEST PROGRAM SUMMARY

The following sections describe the material and design verification test programs. The purpose of these programs is to verify the ability of the sleeve concept to produce a sleeve capable of spanning a degraded region in a steam generator tube and maintain the steam generator tubing primary-to-secondary pressure boundary under normal and accident conditions. This program includes assessment of the structural integrity and corrosion resistance of sleeved tubes.

A data base exists from previous test programs which verifies the adequacy of the sleeve design and process. The results of much of this testing is directly applicable to the present sleeving program. The sleeve material is Alloy 690 (UNS 066900) manufactured to the requirements of ASME SB-163 with supplemental requirements of Code Case N-20. The material has been thermally treated (TT) to enhance its resistance to corrosion in steam generator primary water and secondary-side water environments. This TT material has been used in previous sleeving programs.

Most previous testing of the sleeve design has been for sleeves to be installed into Model 44 steam generators. However, the standardized sleeve may be installed in either Model 44 or 51 steam generators. The installation of the sleeves by the combination of [ ]^{a,c,e} is the same as that verified and used in previous sleeving programs. In addition, the operating conditions are similar for sleeves in the Model 44 and 51 steam generators. Thus, the results of the earlier testing programs are considered to be applicable to Model 44 and 51 steam generator sleeving programs.

The objectives of the mechanical testing programs included:

- Verify the leak resistance of the upper and lower sleeve to tube joints.

- Verify the structural strength of the sleeved tube under normal and accident conditions.

- Verify the fatigue strength of the sleeved tube under transient loads considering the remaining design life objective of the reactor plant.

- Confirm capability for installation of sleeves in tubes with conditions such as deep secondary side hard sludge and tubesheet denting.

- Establish the process parameters required to achieve satisfactory installation and performance. These parameters are discussed in Section 4.6.

The acceptance criteria used to evaluate the sleeve performance is leak rate based on the plant technical specifications. Over 100 test specimens were used in the various test programs to verify the design and to establish process parameters. Testing encompassed static and cyclic pressures, temperatures, and loads. The testing also included evaluation of joints fabricated using Alloy 600 sleeves as well as Alloy 690 sleeves in Alloy 600 tubes. While the bulk of the original qualification data is centered on Alloy 600 sleeves, a series of verification tests were run using Alloy 690 sleeves to demonstrate the effectiveness of the joint formation process and design with either material. Additionally an engineering evaluation of those properties which would affect joint performance was made and disclosed no areas which would result in a change of joint performance.

The sections that follow describe those portions of the corrosion (Sections 3.3.2 - 3.3.3) and mechanical (Sections 3.3.4 - 3.3.6) verification programs that are relevant to this sleeving program.

3.3.2 CORROSION AND METALLURGICAL EVALUATION

The objectives of the corrosion evaluations are (1) to verify that thermally treated Alloy 690 is a suitable material for use in steam generator environments and (2) to verify that sleeving does not have a detrimental effect on the serviceability of the existing tube or the sleeve components. The material of construction for the steam generator tubes of the Westinghouse design, including the steam generators at the Kewaunee site, is Alloy 600 in the mill annealed condition. Alloy 600 is a high nickel austenitic alloy that is nominally 72 percent nickel, 14-17 percent chromium, and 6-10 percent iron. The sleeving material proposed for sleeving the Kewaunee steam generators is Alloy 690 in the thermal treated (TT) condition. Alloy 690 is also a high nickel austenitic material but contains a higher chromium content and a correspondingly lower nickel content and has a nominal composition of 60 percent nickel, 30 percent chromium, and 9 percent iron.

Alloy 690 TT is recommended in lieu of Alloy 600 MA or Alloy 600 TT. Laboratory testing has shown the Alloy 690 TT to have a resistance to corrosion in steam generator environments that is equal or better than Alloy 600 in either heat treated condition. The higher chromium content of Alloy 690 is believed to be responsible for this enhanced corrosion resistance. In addition, the alloy is thermally treated to further enhance its stress corrosion cracking resistance properties.

Alloy 690 TT is the current tubing material of construction recommended by Westinghouse for steam generator applications.

The stress corrosion cracking performance of thermally treated Alloys 600 and 690 in both off-chemistry secondary side and primary side environments has been extensively investigated. Results have continually demonstrated the additional stress corrosion cracking resistance of thermally-treated Alloys 600 and 690 as compared to mill annealed Alloy 600 material. Direct comparison of thermally treated Alloys 600 and 690 has further indicated an additional margin of SCC resistance for thermally treated Alloy 690 (Table 3.3.2-1).

The caustic SCC performance of mill annealed and thermally treated Alloys 600 and 690 were evaluated in a 10 percent NaOH solution as a function of temperature from 288°C to 343°C. Since the test data were obtained over various exposure intervals ranging from 2,000 to 8,000 hours, the test data were normalized in terms of average crack growth rate determined from destructive examination of the C-ring test specimens. No attempt was made to distinguish between initiation and propagation rates.

Table 3.3.2-1

SUMMARY OF CORROSION COMPARISON DATA
FOR THERMALLY TREATED ALLOYS 600 AND 690

1. Thermally treated Alloy 600 tubing exhibits enhanced SCC and IGA resistance in both secondary-side and primary-side environments when compared to the mill annealed condition.

2. Thermally treated Alloy 690 tubing exhibits additional SCC resistance compared to thermal treated Alloy 600 in caustic, acid sulfate, and primary water environments.

3. The alloy composition of Alloy 690 along with a thermal treatment provides additional resistance to caustic induced IGA.

4. The addition of 10 percent CuO to a 10 percent deaerated NaOH environment reduces the SCC resistance of both thermal treated Alloys 600 and 690. Lower concentrations of either CuO or NaOH had no effect, nor did additions of Fe_3O_4 and SiO_2.

5. Alloy 690 is less susceptible to sensitization than Alloy 600.

The crack growth rates presented in Figure 3.3.2-1 indicate that thermally treated Alloys 600 and 690 have enhanced caustic SCC resistance compared to that of Alloy 600 in the mill annealed condition. The performance of thermally treated Alloys 600 and 690 are approximately equal at temperatures of 316°C and below. At 332°C and 343°C, the additional SCC resistance of thermally treated Inconel Alloy 690 is observed. In all instances the SCC morphology was intergranular in nature. The enhanced performance of thermally treated Alloy 690 at higher temperatures is a result of a lesser temperature dependency.

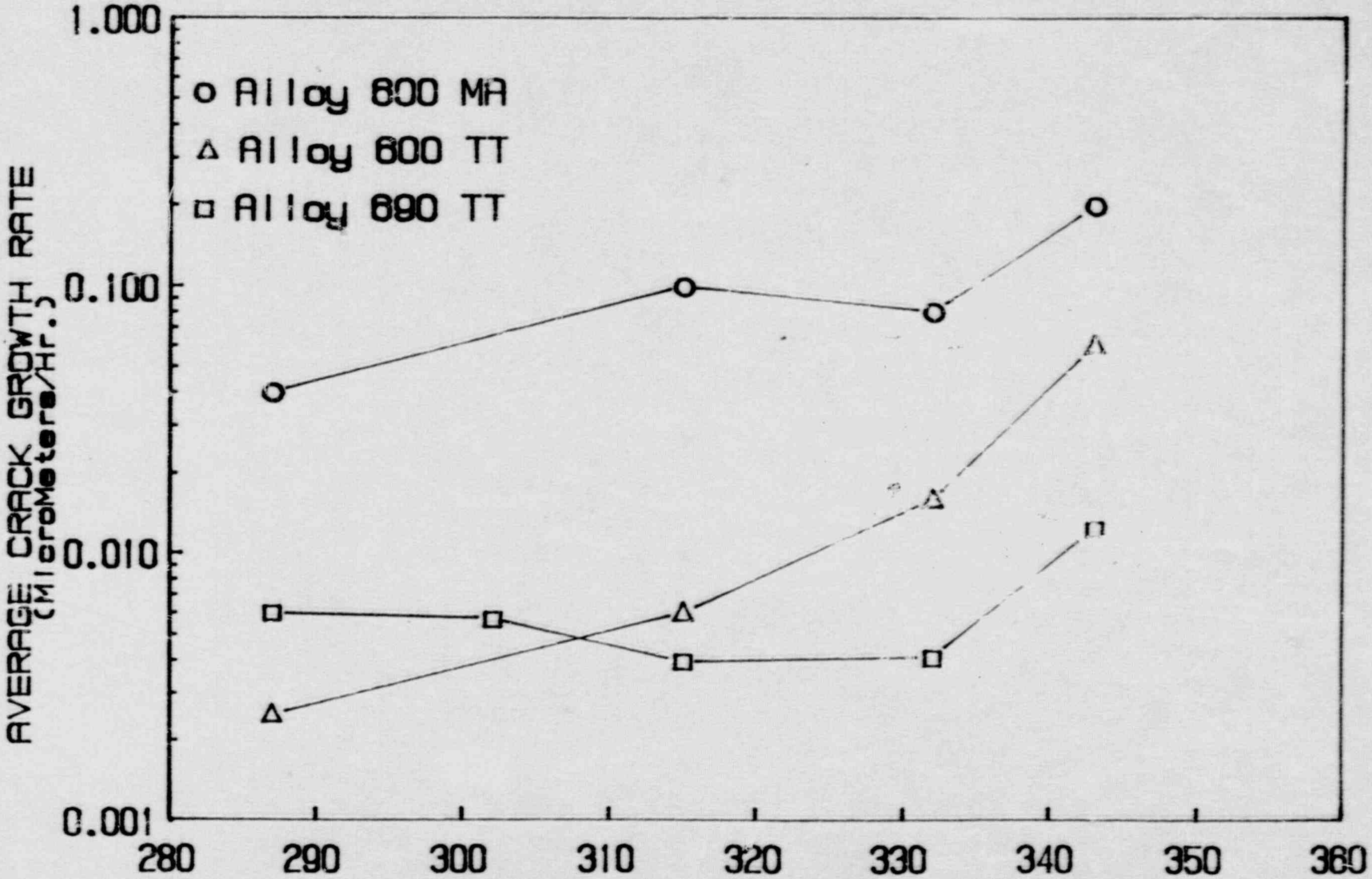
C-ring specimens were tested in 10 percent NaOH solution at 332°C to index the relative intergranular attack (IGA) resistance of Alloys 600 and 690. Comparison of the IGA morphology for these C-rings stressed to 150 precent of the 0.2 percent yield strength is presented in Figure 3.3.2-2. Mill annealed Alloy 600 is characterized by branching intergranular SCC extending from a 200μ front of uniform IGA. Thermally treated Alloy 600 exhibited less SCC and IGA limited to less than a few grains deep. Thermally treated Alloy 690 exhibited no SCC and only occasional areas of intergranular oxide penetrations that were less than a grain deep.

The enhancement in IGA resistance can be attributed to two factors; heat treatment and alloy composition. A characteristic of mill annealed Alloy 600 C-rings exposed to a deaerated sodium hydroxide environment is the formation of intergranular SCC with uniform grain boundary corrosion (IGA). The relationship between SCC and IGA is not well established but it does appear that IGA occurs at low or intermediate stress levels and at electrochemical potentials where the general corrosion resistance of the grain boundary area is a controlling factor. Thermal treatment of Alloy 600 provides additional grain boundary corrosion resistance along with additional SCC resistance. In the case of Alloy 690, the composition provides an additional margin of resistance to IGA and the thermal treatment enhances the SCC resistance.

The addition of oxidizing species to deaerated sodium hydroxide environments results in either a deleterious effect or no effect on the SCC resistance of thermally treated Alloys 600 and 690 and depends on the specific oxidizing.

SCC GROWTH RATE FOR C-RINGS

(150% YS AND TLT) IN 10% NaOH



0226M:49/081888-29

Figure 3.3.2-1

a,c,e

Figure 3.3.2-2 Light Photomicrographs Illustrating IGA after 5000 Hours Exposure of Alloy 600 and 690 C-Rings to 10% NaOH at 332°C (630°F).

specie and concentration (Table 3.3.2-2). The addition of 10 percent copper oxide to 10 percent sodium hydroxide decreases the SCC resistance of thermally treated Alloys 600 and 690, and also modifies the SCC morphology with the presence of transgranular cracks in the case of Alloy 690. The exact mechanism responsible for this change is not well understood, but may be related to an increase in the specimen potential that corresponds to a transpassive potential, which may result in an alternate cracking regime. The specific oxidizing specie and the ratio of oxidizing specie to sodium hydroxide concentration appear to effect the cracking mode. The apparent deleterious effect on SCC resistance is eliminated by lowering the copper oxide or sodium hydroxide concentration.

Mill annealed and thermally-treated Alloys 600 and 690 were also evaluated in 8 percent sodium sulfate environments. The room temperature pH value at the beginning of the test was adjusted using either sulfuric acid and ammonia. As the pH is lowered, the SCC resistance for mill annealed and thermally-treated Alloy 600 is decreased. In comparison, thermally treated Alloy 690 did not crack even at a pH of 2, the lowest tested (Figure 3.3.2-3).

The primary water SCC test data are presented in Figure 3.3.2-4. For the beginning-of-fuel-cycle water chemistries, 10 of 10 specimens of mill annealed Alloy 600 exhibited SCC, while 1 of 10 specimens of thermally-treated Alloy 600 had cracked in exposure times of about 12,000 hours. In the end-of-fuel cycle water chemistries, 9 of 10 specimens of mill annealed Alloy 600 exhibited SCC, while 3 of 10 specimens of thermally-treated Alloy 600 had cracked. After 13,000 hours of testing, no SCC has been observed in the mill annealed or thermally-treated Alloy 690 specimens in either test environment.

Continuing investigation of the SCC resistance of Alloys 600 and 690 in primary water environments has shown mill annealed Alloy 600 to be susceptible to cracking at high levels of strain and/or stress. Thermal treatment of Alloy 600 in the carbide precipitation region enhances its SCC resistance. The performance of Alloy 690, both mill annealed and thermally treated, demonstrates primary water SCC resistance and is believed to be due to alloy composition.

Table 3.3.2-2

EFFECT OF OXIDIZING SPECIES ON THE SCC SUSCEPTIBILITY OF THERMALLY TREATED ALLOY 600 AND 690 C-RINGS IN DEAERATED CAUSTIC

Environment	Temp. (°C)	Exposure Time (Hrs)	Alloy 600 TT	Alloy 690 TT
10 Percent NaOH + 10 Percent CuO	316	4,000	Increased Susceptibility*	Increased Susceptibility*
10 Percent NaOH + 1 Percent CuO	332	2,000	No effect	No effect
1 Percent NaOH + 1 Percent CuO	332	4,000	No effect	No effect
10 Percent NaOH + 10 Percent Fe_3O_4	316	4,000	No effect	No effect
10 Percent NaOH + 10 Percent SiO_2	316	4,000	No effect	No effect

*Intergranular and transgranular SCC.

SCC DEPTH FOR C-RINGS (150% YS)

IN 8% SODIUM SULFATE

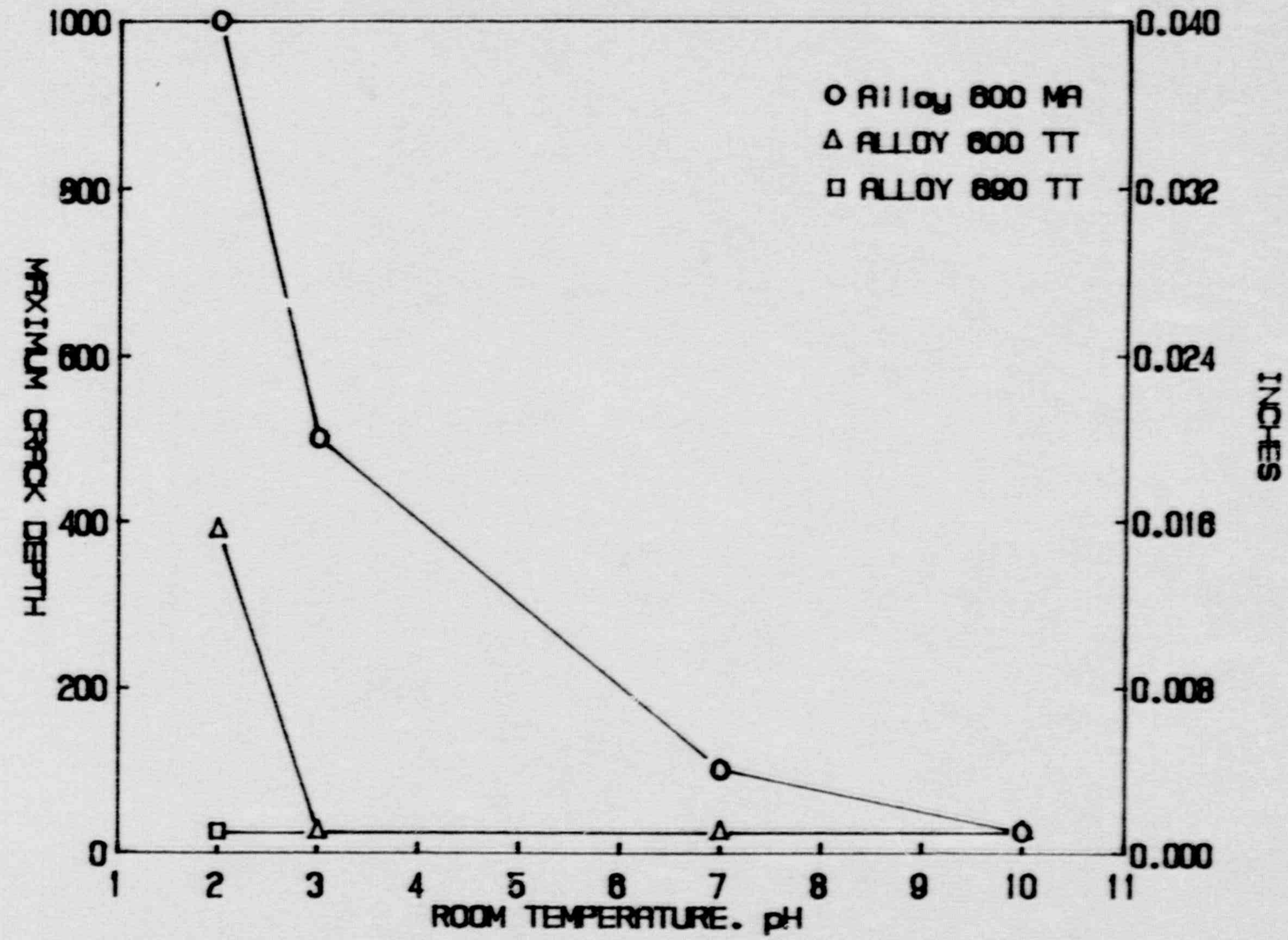


Figure 3.3.2-3

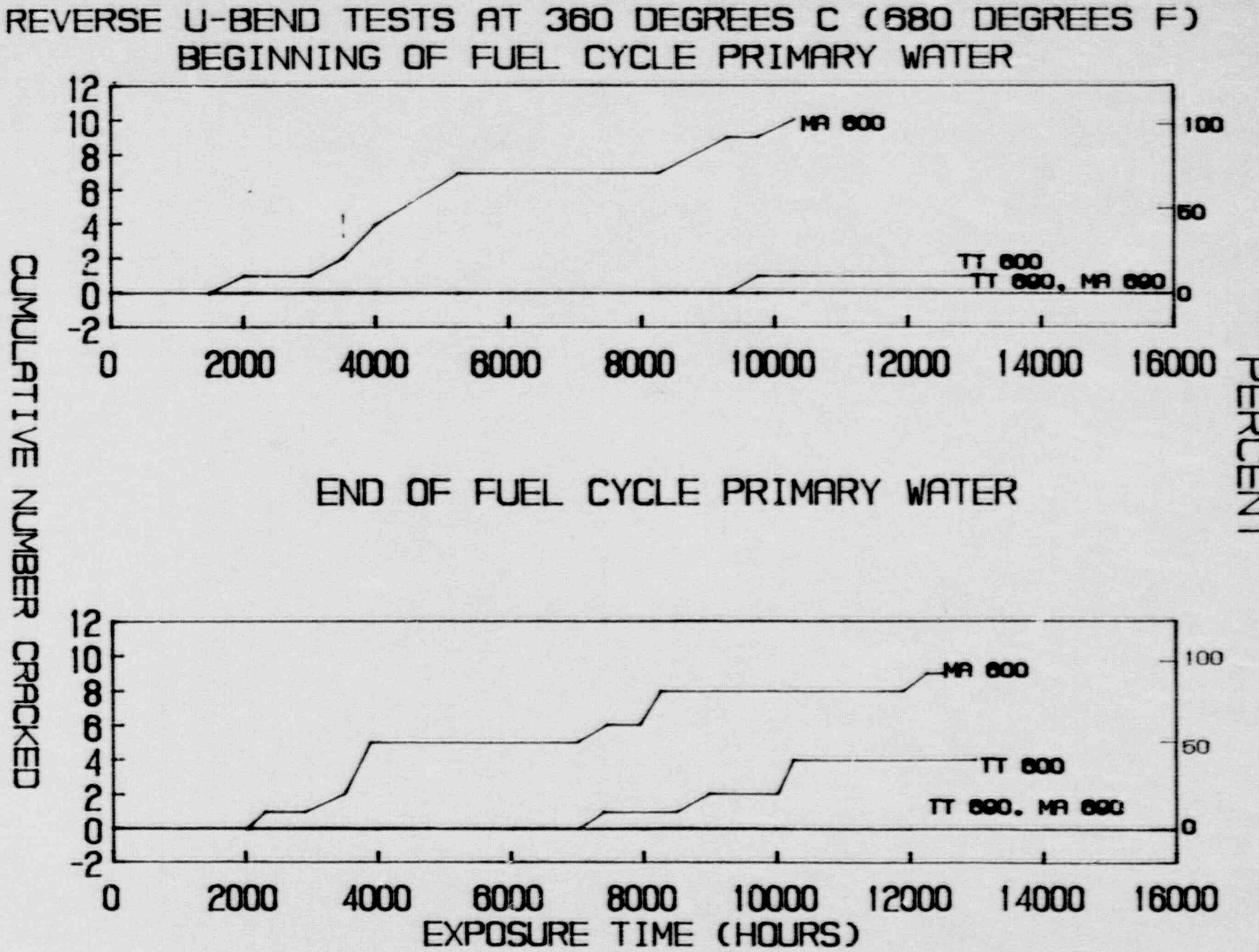

REVERSE U-BEND TESTS AT 360 DEGREES C (680 DEGREES F)
BEGINNING OF FUEL CYCLE PRIMARY WATER
MA 600
TT 600
TT 690, MA 690
END OF FUEL CYCLE PRIMARY WATER
MA 600
TT 600
TT 690, MA 690
CUMULATIVE NUMBER CRACKED
PERCENT
EXPOSURE TIME (HOURS)
0
2000
4000
6000
8000
10000
12000
14000
16000
-2
0
2
4
6
8
10
12
0
50
100

Figure 3.3.2-4

3.3.3 UPPER AND LOWER JOINTS

All the data presented in Section 3.3.2 relative to the corrosion and stress corrosion cracking resistance of thermally treated Alloys 600 and 690 are applicable to the sleeve.

A similar corrosion verification test program has been conducted to demonstrate that the residual stresses induced in the parent tubing by the expansion process does not degrade the integrity of the tubing. Table 3.3.3-1 identifies the various tests which have been performed and the findings. A discussion of the significant tests follows.

The expansion processes for both the lower and upper joints involve a combination of [

]a,c,e The stresses in the sleeve, based on tube to tubesheet data, should be as shown schematically at B and C on Figure 3.3.3-1, which are also judged acceptable, particularly in view of the corrosion resistance of the thermally treated sleeve material. Stress levels in the outer tube are also influenced by the expansion technique. For an outer tube expansion produced solely by [

]a,c,e The absolute magnitude of these stresses will depend on the specific diametral expansion.

Residual stresses on the OD and ID of surrogate Type 304 S.S. tubing which was expanded to varying amounts of [

]a,c,e

Table 3.3.3-1

DESIGN VERIFICATION TEST PROGRAM - CORROSION

ISSUE	FINDINGS
	a,c,e
1. CORROSION AND STRESS CORROSION	
2. CORROSION AND STRESS CORROSION CRACKING OF LOWER SLEEVE JOINT	
3. CORROSION AND STRESS CORROSION CRACKING OF UPPER JOINTS	
4. CORROSION AND STRESS CORROSION CRACKING IN ANNULUS	

a,c,e

Figure 3.3.3-1
Location and Relative Magnitude of Residual Stresses Induced by Expansion

The specimen design is shown in Figure 3.3.3-2 and the test parameters are listed in Table 3.3.3-2. [

]a,c,e

[

]a,c,e

No cracking was detected on the OD surface of any specimen. These results indicate that the OD stresses are below the threshold required to cause cracking in the stainless steel (less than 10 to 15 ksi).

To summarize the results of this test:

o [

o

]a,c,e

a,c,e

Figure 3.3.3-2
Schematic of HEJ Section of Sleeve

Table 3.3.3-2

RESIDUAL STRESSES AT [ ]a,c,e

a,c,e

[ ]

a,c,e

Figure 3.3.3-3
Residual Stresses Determined by Corrosion Tests in $MgCl_2$ (Stainless Steel) or Polythionic Acid (Alloy 600)

a,c,e

Figure 3.3.3-4

Results of C-Ring Tests of Type 304 Heat
No. 605947 in Boiling $MgCl_2$

a,c,e

Table 3.3.3-3

Results of Magnesium Chloride Tests at [Roll Expanded Sections][a,c,e]

a,c,e

Table 3.3.3-4

Results of Magnesium Chloride Tests at [Hydraulic Expanded Sections][a,c,e] o [

]a,c,e

Confirmation that the OD stresses on the parent tubing are very low tensile or compressive was obtained by X-ray diffraction analysis of an Alloy 600 tube expanded 30 mils and by the parting/layer removal technique, as shown below:

X-RAY RESIDUAL STRESS MEASUREMENTS OF HEJ JOINT: OD OF TUBE

a,c,e

[

]

(a) in un-expanded tube above upper-most transition

(b) in un-expanded tube below lower-most transition

CONCLUSION: Residual stresses on OD of tube are compressive and results are consistent with $MgCl_2$ test findings.

The residual stresses in a HEJ with an Alloy 600 MA tube/Alloy 690 TT sleeve were measured using the parting/layer removal technique. The conditions of the joint were as follows:

- o Nominal Tube OD - 0.875 inch
- o Nominal Sleeve OD - 0.740 inch

a,c,e

[
- o
- o
- o
]

The results of these tests are summarized in Figures 3.3.3-5 and 3.3.3.6. These results show an excellent correlation with the $MgCl_2$ tests and the results of the x-ray measurements. The OD surface of the tube was in compression in the axial direction at all locations along the expansion transitions. The ID surface was in tension in the axial direction in the expansion transitions with the highest measured stress located at the hydraulic transition. In the circumferential direction, both surfaces of the tube were generally in compression although low tensile stresses, about 5 ksi or lower, measured on the tube ID in the fully hydraulic expanded region and on the OD in the unexpanded tube near the hydraulic expansion transition. The OD surface of the sleeve was also in compression in the axial and circumferential directions except for one measurement that was in tension (about 5 ksi) in the axial direction in the [ ]^{a,c,e}. The ID surface of the sleeve had areas where the stresses were as high as about 25 ksi in either the axial or circumferential direction. Residual stresses of this magnitude should not effect the special thermally treated sleeve material.

a,c,e

Figure 3.3.3-5
Axial Residual Stresses in Tube/Sleeve Assembly at Depth of 0.001 +- 0.0004 Inches at Five Locations Along Length of Transition

a,c,e

Figure 3.3.3-6
Circumferential Residual Stresses in Tube/Sleeve Assenbly
at Depth of 0.001 +- 0.0004 Inches at Five
Locations Along Length of Transition

Polythionic Acid Tests

To confirm that the $MgCl_2$ results, utilizing stainless steel surrogate tubing, are applicable to Alloy 600 tubing, a corresponding stress indexing test was performed with sensitized Alloy 600 tubing exposed to polythionic acid on the ID. The results, indicated below, support the $MgCl_2$ findings.

Material = Sensitized Alloy 600 tubing

[

]^{a,c,e}

Summary: The results of the various stress indexing tests indicate that the residual stress imposed on the parent tubing by the HEJ process are of a sufficiently low magnitude as to not constitute a concern. [

]^{a,c,e}.

Primary Water Tests

Two tests to confirm the primary water stress corrosion cracking resistance of HEJ's have been conducted. A summary of the results of these tests is as follows:

680°F Primary Water Tests:

Material = a. Alloy 600 mill annealed tubing with known susceptibility to primary water stress corrosion cracking.

b. Alloy 600 special thermally treated sleeves.

Expansion Matrix:

a,c,e

Number of Specimens	
4	[
4	
3	]

*Not within the normal expansion ranges for HEJ field installation.

Total Expansion, ΔD, inch - [

]a,c,e

Test Environment:

Temperature: 680°F

Pressure : Primary Side - 2,850 psig

Secondary Side - 1,450 psig

Chemistry : Primary Side - Hydrogenated Pure water

Secondary Side - Pure water

Results: 2000 hour exposure with no primary to secondary leakage. Destructive examination detected no tube wall degradation.

750°F Steam Tests:

Material = a. Alloy 600 mill annealed tubing with known susceptibility to primary and pure water.

b. Alloy 600 special thermally treated sleeves.

Expansion Matrix:

Number of Specimens

Number of Specimens	
2	
2	
2	

[ ]a,c,e

*Not within normal expansion ranges for HEJ field installation

NOTE

Total Expansion, ΔD, inch [

]a,c,e

Test Environment:

Temperature: 750°F

Pressure : Secondary and Primary at the same pressure

Chemistry : Hydrogenated pure water

Results: 1,700 hour exposure with no degradation of tube or sleeve defect by NDE including ID ECT and OD UT or by destructive examination.

In addition, both temperature and stress influence the time required to initiate primary water stress corrosion cracking (PWSCC). Calculations have been made using an equation suggested by the Brookhaven National Laboratory[1)] for the prediction of PWSCC. [

]a,c,e

1) R. Bandy and D. van Rooyen, A Model for Predicting the Initiation and Propagation of Stress Corrosion Cracking of Alloy 600 in High Temperature Water.

o For MA Alloy 600 in Primary Water:

[ ]a,c,e

o For Typical Primary Temperature Conditions:

[ ]a,c,e

Location	Temp. °K	Residual Stress ksi	Pressure (Hoop) Stress ksi	Total (Hoop) Stress ksi
Hard roll transition	[			]a,c,e
HEJ joint				]

Postulation of PWSCC at the HEJ vs Hard Roll Transition:

[ ]a,c,e

o The time to initiate PWSCC at the HEJ is calculated to be a factor of [

]a,c,e

3.3.4 TEST PROGRAM FOR THE LOWER JOINT

3.3.4.1 DESCRIPTION OF LOWER JOINT TEST SPECIMENS

The tube/tubesheet mockup was manufactured so that it was representative of the partially rolled tube to tubesheet joint (Figure 3.3.4.1-1) of the model 44/51 steam generators. The Kewaunee steam generator tubes are partial depth rolled inside the tubesheet. The formation of lower mechanical rolled joint of tube/sleeve is simulated by the mockup. The tube was examined with a fiberscope, [ ]^{a,c,e} cleaned by swabbing, and re-examined with the fiberscope. Then the preformed sleeve (made of Thermally Treated Alloy 600 or 690) was inserted into the tube and the lower joint formed. [

]^{a,c,e}

3.3.4.2 DESCRIPTION OF VERIFICATION TESTS FOR THE LOWER JOINT

The as-fabricated specimens for the Model 44/51 (as discussed in Section 3.3.1, Model 51 parameters and conditions are similar to those of Model 44 parameters and conditions) were tested in the sequence described below. Note that the tests of the Alloy 690 sleeve are similar to those performed on the Alloy 600 sleeve except that the Steam Line Break (SLB) and Extended Operation Period (EOP) tests were not considered necessary based on previous data.

1. Initial leak test: The leak rate was determined at room temperature, 3,110 psi and at 600°F, 1,600 psi. These tests established the leak rate of the lower joint after it has been installed in the steam generator and prior to long-term operation.

2. The specimens were fatigue loaded for 5,000 cycles.

3. The specimens were temperature cycled for 25 cycles.

a,c,e

Figure 3.3.4.1-1
Lower Joint As-Rolled Test Specimen

4. The specimens were leak tested at 3,110 psi room temperature and at 1600 psi 600°F. This established the leak rate after a simulation of 5 years of normal operation (plant heatup/cooldown cycles) produced by steps 2 and 3.

   Several specimens were removed from this test sequence at this point and were subjected to the EOP Test. See Step 7, below.

5. The specimens were leak tested while being subjected to SLB conditions.

6. The specimens were leak tested as in Step 1 to determine the post-accident leak rate.

7. The EOP test was performed after Step 4 for three as-rolled specimens.

3.3.4.3 LEAK TEST ACCEPTANCE CRITERIA

Site specific or bounding analyses have been performed to determine the allowable leakage during normal operation and the limiting postulated accident condition. The leak rate criteria that have been established are based on Technical Specifications and Regulatory requirements. Table 3.3.4.3-1 shows the leak rate criteria for the Kewaunee steam generators. These criteria can be compared to the actual leak test results to provide verification that the mechanical sleeve exhibits no leakage under what would be considered normal operating conditions and only slight leakage under the umbrella test conditions used. It should be noted that any leakage experienced is well within the allowable limits. Leak rate measurement is based on counting the number of drops leaking during a 10-20 minute period. Conversion to volumetric measurement is based on assuming 19.8 drops per milliliter.

TABLE 3.3.4.3-1

MAXIMUM ALLOWABLE LEAK RATES FOR KEWAUNEE STEAM GENERATORS

Condition	Allowable Leak Rate+	Allowable Leak Rate per Sleeve* [d,e]
Normal Operation	.35 gpm (500 gpd)	[ ]

	Limiting Leak Rate	Leak Rate per Sleeve [b,d,e]
Postulated Accident Condition (Steamline Break)	[	]

* Based on [ ][d,e] sleeves per steam generator.

\+ Standard Technical Specification Limit for 1 steam generator.

++ [

][b,d,e]

The analysis assumes primary and secondary coolant initial inventories of 1μCi/gm and 0.1μCi/gm of Dose Equivalent I-131, respectively. In addition, as a result of the reactor trip, an iodine spike is initiated which increases the iodine appearance rate in the primary coolant to a value equal to 500 times the equilibrium appearance rate.

3.3.4.4 RESULTS OF VERIFICATION TESTS FOR LOWER JOINT

It should be noted that in many cases reference is made to "simulated" conditions. In fact these test conditions simulate only one key aspect of operation. For example, in the case of the fatigue testing, 5,000 cycles were used. This number does not represent the number of cycles expected in one year, it actually represents the number of expected yearly cycles multiplied by a suitable factor to establish an accelerated test condition. On that basis the test results provide data which is conservative in nature and exceed the actual operating conditions. The other parameters associated with the thermal cycle test, for example the temperature ramp, hold time and temperature gradient, are accelerated to achieve appropriate test results within an abbreviated time frame. Consequently, the test results obtained and discussed throughout the rest of this report are those of accelerated conditions designed to test the sleeve at its endurance limit. Sleeving qualification tests demonstrate that under extreme accelerated test conditions leakage is minimal so that in the actual operating case the sleeves will perform within acceptable leakage margin. Additionally, by using that same test series for all sleeve designs it is possible to measure consistency in process modification and or small changes in the overall design to facilitate an assessment of their effect on total sleeve performance.

Reference is occasionally made to the "leakage-reducing" qualities of the mechanical joint design. This is in reference to the phenomena (observed in the test data) which shows that as the mechanical joints operate, if they exhibited leakage at the outset of the test, the rate of leakage decreases gradually with operation, to zero in most cases. This characteristic has been observed consistently in all mechanical joint testing.

Another consistent characteristic observed in the testing of mechanical joints is that the leakage, when observed, is generally higher at room temperature conditions and, as in the case of the leakage-reducing phenomena, decreases as the temperature is elevated. This characteristic has lead to the almost exclusive use of the room temperature hydrostatic test in the process, tooling, personnel, procedure and demonstration phases associated with a plant specific sleeving operation.

The test results for the Model 44/51 lower joint specimens are presented in Table 3.3.4.4-1. The specimens did not leak before or during fatigue loading. After simulating five years of normal operation due to [

]a,c,e All of the three as-rolled specimens were leak-tight during the Extended Operating Period (EOP) test.

For the Alloy 690 sleeve tests the following were noted:

Specimens MS-2 (Alloy 690 Sleeve): Initial leak rates at all pressures and at normal operating pressure following thermal cycling were [

]a,b,c,e

TABLE 3.3.4.4-1

TEST RESULTS FOR AS ROLLED LOWER JOINTS[1] (Page 1 of 3)

a,c,e

(1) all leak rates are in drops/minute

0226M:49/090688-59

Table 3.3.4.4-1 (cont)

TEST RESULTS FOR AS ROLLED LOWER JOINTS[1] (Page 2 of 3)

a,c,e

(1) All leak rates are in drops/minute.

0226M:49/090688-60

Table 3.3.4.4-1 (cont)

TEST RESULTS FOR AS-ROLLED - LOWER JOINTS (Page 3 of 3)

a,c,e

Specimen MS-3 (Alloy 690 Sleeve): [

]a,b,c,e

Specimen MS-7 (Alloy 690 Sleeve): [

]a,b,c,e

3.3.4.5 DESCRIPTION OF ADDITIONAL TEST PROGRAMS- LOWER JOINT WITH EXCEPTIONAL CONDITIONS

Additional test programs were performed to verify acceptable performance of the sleeve lower mechanical joint to accommodate exceptional conditions which may exist in the steam generator tubes and anticipated conditions which may be employed during installation of sleeves.

Exceptional conditions in steam generator tube characteristics and sleeving operation process parameters included;

+ shorter lengths of roller expanded lower tube joints
+ shorter lengths of roller expanded lower sleeve joints
+ lower applied torque values employed in sleeve lower joints
+ simulated circumferential cracks in tubes

The specific exceptional tube conditions and changes to the sleeving process parameters tested in the first program, are shown in table 3.3.4.5-1.

Each process operation and sequence of operations employed in fabricating each test sample was consistent with those specified for sleeves to be installed by field procedures. In addition, the exceptional tube conditions and changes to the sleeving process parameters described in Table 3.3.4.5-1 were included in the assembly of tube and collar sub assemblies.

The as-fabricated specimens for this program were tested in the sequence described below.

1. Initial leak tests: Each specimen was checked for leak tightness prior to any verification tests. The leak tests were performed at room temperature and 2,450 psig followed by a second leak test at 600°F and 2,450 psig. These tests established the leak rate of the lower joint after it had been installed in the steam generator and prior to long-term operation.

2. Thermal Soak Test: Each specimen was subjected to an unpressurized thermal soak at 600°F for 1 hour minimum, and cooled to room temperature. After this test each specimen was subjected to the leak tests described above.

3. Thermal Cycling Test: Some specimens were subjected to a pressurized (1,600 psig) thermal cycling test from ambient to 600°F for a total of 25 cycles. After this test each specimen was subjected to the leak tests described above.

4. Fatigue Test: Some specimens were subjected to a pressurized (1,600 psi) fatigue test at 600°F for a total of 35,000 cycles. After this test each specimen was subjected to the leak tests described above.

5. Compression Tests: Some specimens were subjected to a destructive non-pressurized compression test. Some were tested at room temperature and others at 600°F to determine the buckling resistance of the sleeve.

6. Tensile Test: Some specimens were subjected to a destructive non-pressurized tensile test at 600°F to determine the resistance of the sleeve.

7. Steam Line Break Test: Some specimens were subjected to a steam line break test at 650°F and 2,560 psi. After this test each specimen was subjected to the leak tests described above.

Results from the first program are shown in table 3.3.4.5-2.

The as-fabricated specimens for the second program were tested in the sequence described below.

1. Initial leak tests: Each specimen was checked for leak tightness prior to any verification tests. The leak tests were performed at room temperature and 3,110 psig followed by a second leak test at 600°F and 3,110 psig. These tests established the leak rate of the lower joint after it had been installed in the steam generator and prior to long-term operation.

2. Fatigue Test: Some specimens were subjected to a pressurized (1,600 psi) fatigue test at 600°F for a total of 20,000 cycles. After this test each specimen was subjected to the leak tests described above.

3. Tensile Test: Some specimens were subjected to a destructive non-pressurized tensile test at 600°F to determine the resistance of the sleeve.

Results from the second program are shown in table 3.3.4.5-3,

Results from both programs indicate that the lower sleeve tube joint when installed with these exceptional steam generator tube physical conditions or changes to process parameters described, will provide:

+ adequate leak resistance,
+ adequate structural strength under normal and accident conditions,
+ adequate fatigue strength under transient loads for the remaining design life objective of the reactor plant.

Table 3.3.4.5-1

EXCEPTIONAL TUBE CONDITIONS AND SLEEVING PROCESS PARAMETERS

a,c,e

TABLE 3.3.4.5-2

TEST RESULTS FOR LOWER JOINTS WITH EXCEPTIONAL CONDITIONS FOR TUBE AND SLEEVE

a,c,e

TABLE 3.3.4.5-3

ADDITIONAL TEST RESULTS FOR LOWER JOINTS WITH EXCEPTIONAL CONDITIONS FOR TUBE AND SLEEVE

a,c,e

0226M:49/090688-67

3.3.5 TEST PROGRAM FOR THE UPPER HYBRID EXPANSION JOINT (HEJ)

The discussion contained in Section 3.3.4.4 is relevant to testing in general and applies in the following tests conducted on upper joints as well.

3.3.5.1 DESCRIPTION OF THE UPPER HEJ TEST SPECIMENS

Two types of HEJ test specimens were fabricated for the Model 44 testing [

]^{a,b,c}. The first type was a short specimen as shown in Figure 3.3.5.1-1. Some of these specimens were fitted with pots containing a hard sludge simulant to test the structural effects of sludge on the joint. The only type of sludge simulated in this program was hard sludge. Soft sludge effects were bounded by the hard sludge effects and by the out-of-sludge conditions. [

]^{a,b,c} Leakage was collected and measured as it issued from the annulus between the tube and sleeve. This type of specimen was used in the majority of the tests.

The second type of test specimen was a modification of the first type. It was utilized in the reverse pressure tests, i.e., for LOCA and secondary side

a,c,e

Figure 3.3.5.1-1

Hybrid Expansion Joint (HEJ) Test Specimen hydrostatic pressure tests. As shown in Figure 3.3.5.1-2, the specimen was modified by [

]a,b,c The possible reverse pressure test leak path is shown in Figure 3.3.5.1-2.

Only specimens like Figure 3.3.5.1-1 (excluding the sludge conditions) were used in the Alloy 690 HEJ specimen fabrication as the effects of sludge had been established in the earlier Model 44 tests.

3.3.5.2 DESCRIPTION OF VERIFICATION TESTS FOR THE UPPER HEJ

The verification test program for the HEJ was similar to that for the lower joint.

The HEJ was subjected to fatigue loading cycles and temperature cycles to simulate five years of normal operation and the leak rate was determined before and after this simulated normal operation. For a number of the specimens, the leak rate was also determined as a function of static axial loads which were bounded by the fatigue load. It is important to note that the fatigue load used in testing was that which was caused by loading/ unloading. Hence, it was judged necessary to determine that the leak rate at static and fatigue conditions were comparable. The upper HEJ specimens were also subjected to the loadings/deflections corresponding to a steam line break (SLB) accident and the leak rate was determined during and after this simulated accident. The upper HEJ was also leak tested while being subjected to two reverse pressure conditions, a LOCA and a condition which simulated a secondary hydrostatic test. An extended operation period test was also performed.

3.3.5.3 RESULTS OF VERIFICATION TESTS FOR THE UPPER HEJ

The test results are presented in Tables 3.3.5.3-1 through 3.3.5.3-5.

a,c,e

Figure 3.3.5.1-2

HEJ Specimens for the Reverse Pressure Tests

Table 3.3.5.3-1

TEST RESULTS FOR HEJ'S FORMED OUT OF SLUDGE (Page 1 of 2)

(FATIGUE AND EXTENDED OPERATION TESTS INCLUDED)

a,c,e

0227M:45/090688-5

Table 3.3.5.3-1 (cont)

TEST RESULTS FOR HEJ'S FORMED OUT OF SLUDGE (Page 2 of 2)
(FATIGUE AND EXTENDED OPERATION TESTS INCLUDED)

a,c,e

0227M:49/090688-6

Table 3.3.5.3-2

TEST RESULTS FOR HEJ'S FORMED OUT OF SLUDGE (Page 1 of 2)
(STATIC AXIAL LOAD LEAK TEST SLB AND REVERSE PRESSURE TEST INCLUDED)[1]

a.c.e

0227M:49/090688-7

Table 3.3.5.3-2 (cont)

TEST RESULTS FOR HEJ'S FORMED OUT OF SLUDGE (Page 2 of 2)
(STATIC AXIAL LOAD LEAK TEST SLB AND REVERSE PRESSURE TEST INCL.)[1]

[ ]a,c,e

0227M:49/090688-8

TABLE 3.3.5.3-3

TEST RESULTS FOR HEJ'S FORMED IN SLUDGE (Page 1 of 2)
(FATIGUE AND REVERSE PRESSURE TESTS INCLUDED)

a,c,e

0227M:49/090688-9

TABLE 3.3.5.3-3 (Page 2 of 2)

TEST RESULTS FOR HEJ'S FORMED IN SLUDGE
(FATIGUE AND REVERSE PRESSURE TESTS INCL.) (CONT)

a,c,e

TABLE 3.3.5.3-4

TEST RESULTS FOR HEJ'S FORMED IN SLUDGE
(AXIAL LOAD LEAK TEST AND POST-SLB TEST INCLUDED)

a,c,e

0227W:49/090688-11

TABLE 3.3.5.3-5 (Page 1 of 3)

UPPER HEJ TEST RESULTS

a,c,e

0227M:49/080688-12

TABLE 3.3.5.3-5 (Page 2 of 3)

UPPER HEJ TEST RESULTS

a,c,e

0227M:40/080888-13

TABLE 3.3.5.3-5 (Page 3 of 3)

UPPER HEJ TEST RESULTS

a,c,e

0227N:49/090688-14

As can be seen from Table 3.3.5.3-1, the HEJ's formed out-of-sludge. i.e., in air, had an average initial leak rate of approximately [ ]^{b,c,e} at the normal operating condition of 600°F and 1,600 psi. After simulating five years of normal operation due to 5,000 fatigue cycles and 29 to 32 temperature cycles, the leak rate was [ ]^{b,c,e} at the normal operating condition. Furthermore, for the EOP test, i.e., after simulating thirty-five years of normal operation due to 208 temperature cycles and a total of 35,000 fatigue cycles, the leak rate was [ ].^{b,c,e}

Table 3.3.5.3-2 contains data for upper HEJ's formed out-of-sludge. It includes the same basic test data as Table 3.3.5.3-1, i.e., initial leak rate data. However, it includes static axial load leak tests, SLB and reverse pressure tests in place of the fatigue and EOP tests included in Table 3.3.5.3-1. Five of the six specimens were leaktight at normal operating conditions during the initial leak test. The leak rate during static axial sleeve loads, bounded by the fatigue load and caused by normal operating conditions was measured for four out-of-sludge HEJs. [

]^{b,c,e} These same four specimens were then subjected to the SLB temperature, pressure and axial load conditions. [

]^{b,c,e} The results for the post-SLB leak test, at the same temperature and pressure conditions, were similar to the during-SLB results, [
]^{b,c,e}

The results for the out-of-sludge HEJ reverse pressure test are shown in Table 3.3.5.3-2. For both the simulated LOCA and secondary side hydrostatic pressure test the leak rate was zero for the two specimens tested.

The process used for forming HEJ's in sludge, in Tables 3.3.5.3-3 and 3.3.5.3-4, was the reference process, per Table 4.0-1 except that the

[

]a,c,e

The initial leak rate of the first group of upper HEJs formed in sludge was [ ]b,c,e at the normal operating condition as is shown in Table 3.3.5.3-3. Only one specimen had a [

]b,c,e After exposure of the specimens to five years of simulated normal operation due to fatigue and temperature cycling, the average leak rate remained very low, [ ]b,c,e at the 600°F and 1,600 psi condition.

The results of the reverse pressure test for the in-sludge upper HEJs are also shown in Table 3.3.5.3-3. [ ]a,b,c It was also zero for the simulated secondary side hydrostatic pressure test.

Table 3.3.5.3-4 also contains data for HEJs formed in-sludge. It includes the same basic initial leak tests as Table 3.3.5.3-3. However, it includes axial load leak test and post-SLB leak tests in place of the fatigue and reverse pressure tests included in Table 3.3.5.1-2. All of the four specimens were leaktight during the initial leak test, per Table 3.3.5.3-4. Two specimens did not leak at any static axial load and two others did not leak until a compressive load of 2,950 lbs was reached. However, the two leak rates at 2,950 lbs were low, [ ]b,c,e for specimens Number PTSP-23 and PTSP-33, respectively. The average leak rate for the four specimens during the SLB test was [
]a,c,e

In general, the leak rates for static loads were approximately the same as for dynamic (fatigue) loads of the same magnitude. However, a specific set of specimens was not subjected to both types of loads.

The test data generated for the Alloy 690 and Alloy 625/690 samples is presented in Table 3.3.5.3-5. The following observations were noted:

Specimen S-5 (Alloy 690): [ ]a,b,c were found at initial leak testing at room temperature (R.T.). At 600°F, the leak rates reduced significantly and remained below [ ]a,b,c during a subsequent thermal cycling test. This specimen was formed with a tube diametral bulge that was smaller than will be used in the field.

Specimens S-8 (Alloy 690); B-4, B-6, and B-7 (Alloy 625/690 - 0.740 in. Sleeve Dia.), and BA-11 (Alloy 625/690- 0.630 in. Sleeve Dia.): These five specimens all exhibited moderate to small or very small leaks, mostly during the initial leak testing at R. T. In all cases, by the end of the testing, including thermal cycling and fatigue in some cases, the leak rates had reduced to zero (or near zero), illustrating the leakage reducing characteristic of rolled joints.

Specimen BA-1 (Alloy 625/690, 0.630 Sleeve Dia.): This specimen exhibited zero leak rate at initial testing, both R.T. and 600°F. Small leak rates were found at R.T. after fatigue testing; however, they reduced to very small values, less than 0.5 drops/min. after testing. This specimen was formed with a tube diametral bulge at the low end of the field acceptance range.

3.3.6 TEST PROGRAM FOR THE FIXED/FIXED MOCKUP

3.3.6.1 DESCRIPTION OF THE FIXED/FIXED MOCKUP

The fixed/fixed full scale mockup is shown in Figure 3.3.6.1-1. This mockup simulated the section of the steam generator from the primary face of the

a,c,e

Figure 3.3.6.1-1

Fixed/Fixed Mockup - HEJ
(For HEJ In-Situ Leak Tests)

tubesheet to the first support plate. The bottom plate of the mockup represented the bottom of the tubesheet, the middle plate simulated the top of the tubesheet and the upper plate simulated the first support plate. The tubes were roll expanded into the bottom plate to simulate the tube/tubesheet joint and into the upper plate to simulate a dented tube condition at the tube support plate. The term "fixed/fixed" was derived from the fact that the tubes were fixed at these two locations. There were thirty-two tubes in two clusters of sixteen. A sludge simulant composed of alumina was formed around one cluster of sixteen. Alloy 600 sleeves, thirty inches long, were installed in the tubes by [ ].a,c,e Each tube was perforated between the upper and lower joints to simulate tube degradation and thereby provide a primary-to-secondary leak path. End plugs were welded to the tubes to permit pressurization with water. No fixed/fixed mockup tests were performed on the Alloy 690 samples based on the results of the earlier tests performed.

3.3.6.2 DESCRIPTION OF VERIFICATION TESTS FOR THE FIXED/FIXED MOCKUP

The fixed/fixed mockup was used first to verify the full length sleeve installation parameters and tooling. It was then used to measure the leak rate of the lower joint and upper HEJ. This leak rate was determined with the sleeve installed in a tube fixed at the tubesheet and dented at the first support plate, i.e., for the fixed/fixed condition.

3.3.6.3 RESULTS OF VERIFICATION TESTS FOR THE FIXED/FIXED MOCKUP

Table 3.3.6.3-1 contains leak test results recorded for full length sleeves formed and tested in-situ, in the fixed/fixed mockup, in-sludge and out-of-sludge. All of the room temperature initial leak tests produced [

]a,b,c

Table 3.3.6.3-1

TEST RESULTS FOR FULL LENGTH SLEEVES

FORMED AND LEAK TESTED IN FIXED/FIXED MOCKUP
(IN SLUDGE AND OUT-OF-SLUDGE)

a,b,c,e

0227M:49/090688-20

These initial leak rate results were similar to the initial leak rate results in which the short specimens were structurally unconstrained during forming of the upper HEJ. Therefore, it was concluded that the results of the other several tests performed only on short specimens would be similar if the test had been performed in-situ, in the fixed/fixed mockup. During the pre-test evaluation, it was determined that the fixed/fixed mockup duplicated the most stringent structural loading conditions for sleeves. Therefore, it was concluded that all of the testing with short specimens was valid. Because the model 44 loads envelope the model 51 loads, this testing is considered applicable to model 51 units and consequently validates the results for both units.

3.3.7 EFFECTS OF SLEEVING ON TUBE-TO-TUBESHEET WELD

The effect of hard rolling the sleeve over the tube-to-tubesheet weld was examined in the sleeving of 0.750 inch OD tubes. Although the sleeve installation roll torque used in a 0.750 inch OD tube is less than a .875 inch OD tube, the radial forces transmitted to the weld are comparable. Evaluation of the 0.750 inch tubes showed no tearing or other degrading effects on the weld after hard rolling. Therefore, no significant effect on the tube-to-tubesheet weld is expected for the larger 0.875 inch OD tube configuration.

3.4 ANALYTICAL VERIFICATION

3.4.1 INTRODUCTION

This section contains the structural evaluation of the sleeve and tube assembly with HEJ, sleeve material Alloy 690[1] and sleeve length [ ]^{a,c,e} in relation to the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Subsection NB, 1983 Edition (Reference 1)

The analyses include primary stress intensity evaluations, maximum range of stress intensity evaluations, and fatigue evaluations for various mechanical and thermal conditions which umbrella the loading conditions specified by the Westinghouse Equipment Specification G-677031, Revision 4 (Reference 2).

3.4.2 COMPONENT DESCRIPTION

The general configuration of the sleeve-tube assembly with HEJ is presented in Figure 3.4.2-1.

The critical portions of the sleeve-tube assembly are two joints, the upper and lower Hybrid Expansion Joints (HEJ), and straight sections of the sleeve and tube between the two joints. The finite element model developed contains both upper and lower joints. A detailed stress evaluation for the upper joint is addressed in this section. Structural analysis of the lower joint is presented in Section 3.5. The tolerances used in developing the models were such that the maximum sleeve and tube outside diameters were evaluated in combination with the minimum sleeve wall thickness. This allowed maximum stress levels to be developed in the roll transition regions.

---

1) Sleeve Material Alloy 600 is considered in Section 3.5.

a,c,e

Figure 3.4.2-1

Hybrid Expansion Upper Joint/Roll Expanded Lower Joint Sleeve Configuration

3.4.3 MATERIAL PROPERTIES

The sleeve material is Alloy 690[1] described in ASME Code Case N-20 (Reference 3). The tube material is SB-163 (Alloy 600).

An air gap was included between the tube and sleeve below the HEJ as well as between the tube and the tubesheet. Although this space may be filled with secondary fluid, assuming the physical properties of air for these elements is conservative for the thermal analysis. Primary fluid physical properties were used for the gap medium above the HEJ.

All material properties used in the analyses were as specified in the ASME Boiler and Pressure Vessel Code, Section III, Appendix 1 (Reference 4) and Code Cases (Reference 3).

3.4.4 CODE CRITERIA

The ASME Code Stress Criteria which must be satisfied are given in Tables 3.4.4-1 through 3.4.4-4.

3.4.5 LOADING CONDITIONS EVALUATED

The loading conditions are specified below:

1. Design conditions
   a. Primary side design conditions
      P = 2,485 psig
      T = 650°F

   b. Secondary side design conditions
      P = 1,085 psig
      T = 600°F

   c. Maximum primary to secondary pressure differential - 1,600 psig,
      T = 650°F

---

1) Sleeve material Alloy 600 is considered in Section 3.5.

Table 3.4.4-1

CRITERIA FOR PRIMARY STRESS INTENSITY EVALUATION
(SLEEVE)

a,c,e

Table 3.4.4-2

CRITERIA FOR PRIMARY STRESS INTENSITY EVALUATION

(TUBE)

a,c,e

TABLE 3.4.4-3

CRITERIA FOR PRIMARY PLUS SECONDARY AND TOTAL STRESS INTENSITY EVALUATION (SLEEVE)

a,c,e

TABLE 3.4.4-4

CRITERIA FOR PRIMARY PLUS SECONDARY AND TOTAL STRESS INTENSITY EVALUATION (TUBE)

a,c,e

d. Maximum secondary to primary pressure differential - 670 psig, T = 650°F

2. Full load steady state conditions are:
Primary side pressure = 2,235 psig
Hot leg temperature = 616.8°F
Cold leg temperature = 552.3°F
Secondary side pressure = 705 psig
Feedwater temperature = 427.3°F
Steam temperature = 506.3°F
Zero load reactor coolant temperature = 547.0°F

Other operating conditions are specified in Tables 3.4.7.1-1 and 3.4.7.2-1.

3.4.6 METHODS OF ANALYSIS

Structural analysis of the sleeve-tube assembly includes finite element model development, thermal, pressure stress and thermal stress calculations, primary membrane and primary membrane plus bending stress intensity evaluation, primary plus secondary stress intensity range evaluation, and fatigue evaluation for various mechanical and thermal conditions which umbrella the loading conditions specified by the appropriate Design and Equipment Specifications. Two computer programs, WECAN and WECEVAL, are used in structural analyses of the sleeved tubes.

The WECAN program (Reference 5) performs thermal and stress analyses of the structure. Pressure stress is calculated separately for a 1000 psi primary and a 1000 psi secondary pressure. The results of these "unit pressure" runs are then scaled to the actual primary side and secondary side pressures corresponding to the load conditions considered in order to determine the total pressure stress distribution.

Thermal analysis provides the temperature distribution needed for thermal stress calculations. Thermal stress calculations are performed for fixed times under thermal transients. These times for the total pressure and thermal analysis are chosen for the anticipated maximum and minimum total stresses in critical regions of the structure.

Total stress distribution is determined by combining the pressure and thermal stress results.

Total stress calculations as well as stress evaluations are carried out by the WECEVAL computer program (Reference 6). WECEVAL is a multi-purpose code which performs ASME Code, Section III, Subsection NB stress evaluations.

At any given point or section of the model, the program WECEVAL is used to determine the total stress distribution per the Subsection NB requirements. That is, the total stress at a given cross-section through the thickness, so-called analysis section, ASN, is categorized into membrane, linear bending, and non-linear components which are compared to Subsection NB allowables. In addition, complete transient histories at given locations on the model are used to calculate the total cumulative fatigue usage factor per Code Paragraph NB-3216.2.

3.4.6.1 MODEL DEVELOPMENT

A finite element model was developed for evaluating the sleeve design. Some significant considerations in developing the model are:

1. The model has been divided in two parts: upper model and lower model. Structural integrity of the whole model was provided by all direction coupling of the nodes along the upper model and lower model interface.

2. Mechanical roll fixities between the sleeve and tube at the hard roll regions were achieved by coupling the interface nodes in the radial direction. For conservatism, locations of contact in the

sleeve-tube interfaces along the upper hard roll region contain elements which share nodes. This approximates a rigid fix by the rolling process involved. Additional axial coupling was effected also for the lower sleeve-tube and tube-tubesheet interface nodes.

3. The interface nodes along the upper and lower hydraulic expansion regions of the HEJ were coupled in the radial direction for temperature and thermal stress runs. In the cases when pressure may penetrate into the interface, the interface nodes along these areas were disconnected for pressure stress runs.

4. By varying the boundary conditions at a specified region of the model, conditions of either intact tube or discontinuous tube were simulated.

The element types chosen for the finite element analysis were the following WECAN (Reference 5) elements:

a,c,e

[ ]

All the element types are quadratic, having a node placed in the center of each surface in addition to nodes at each corner.

3.4.6.2 THERMAL ANALYSIS

The purpose of the thermal analysis is to provide the temperature distribution needed for thermal stress evaluation.

Thermal transient analyses were performed for the following events:

- Small step load increase
- Small step load decrease
- Large step load decrease
- Hot standby operations
- Loss of load
- Loss of power
- Loss of secondary flow
- Reactor trip from full power

The plant heatup/cooldown, plant loading/unloading and steady fluctuation events were considered under thermal steady state conditions.

The finite element types chosen for the thermal analysis were [ ].^{a,c,e}

In order to perform the WECAN thermal analysis, boundary conditions consisting of fluid temperatures and heat transfer coefficients (or film coefficients) for the corresponding element surfaces are necessary. The conditions considered in the thermal analysis are based on the following assumptions:

- The temperature induced stresses are most pronounced for sleeves in the hot leg (where the temperature difference between the primary and secondary fluids is a maximum) and therefore, only the hot leg sleeves were considered. This condition bounds the thermal stresses on the cold leg.

- The sleeves may be installed in nearly any tube in the generator. Thus, to be conservative, it is assumed that the sleeve to be evaluated is sufficiently close to the periphery of the bundle that it experiences the water temperature exiting the downcomer.

Special hydraulic and thermal analysis was performed to define the primary and secondary side fluid temperatures and film coefficients as a function of time. Both boiling and convective heat transfer correlations were taken into consideration.

3.4.6.3 STRESS ANALYSIS

A WECAN (Reference 5) finite element model was used to determine the stress levels in the tube/sleeve configuration.

Elements simulating the medium between the tube and the sleeve were considered as dummy elements. The element types employed were [ ]a,c,e

Based on the results demonstrating the applicability of a linear elastic analysis, thermally induced and pressure induced stresses were calculated separately and then combined to determine the total stress distribution using the WECEVAL computer program (Reference 6).

Pressure Stress Analysis

For superposition purposes, the WECAN model was used to determine stress distributions induced separately by a 1,000 psi primary pressure and a 1,000 psi secondary pressure. The results of these "unit pressure" runs were then scaled to the actual primary side and secondary side pressures corresponding to the loading condition considered in order to determine the total pressure stress distribution.

The two modeling considerations in determining the unit pressure load stress distributions were tube intact and tube discontinuous. Therefore, the following unit pressure loading conditions were evaluated to determine the maximum anticipated stress levels induced by primary and secondary pressures:

Primary pressure - tube intact
Primary pressure - tube discontinuous
Secondary pressure - tube intact
Secondary pressure - tube discontinuous

The end cap forces due to the axial pressure stress induced in the tube away from discontinuities were taken into consideration.

Thermal Stress Analysis

The WECAN model was used to determine the thermal stress levels in the tube/sleeve configuration that were induced by the temperature distribution calculated by the thermal analysis. Thermal stresses were determined for each steady state solution as well as for the thermal transient solutions at those times during the thermal transient which were anticipated to be limiting from a stress standpoint.

Combined Pressure Plus Thermal Stress Evaluation

As mentioned previously, total stress distributions were determined by combining the unit pressure and thermal stress results as follows:

$$\sigma_{total} = \frac{P_{pri}}{1{,}000} \cdot (\sigma)_{\text{unit primary pressure}}$$

$$+ \frac{P_{sec}}{1,000} \cdot (\sigma)_{\text{unit secondary pressure}}$$

$$+ (\sigma)_{thermal}$$

This procedure was performed with the program WECEVAL (Reference 6).

Stress and Fatigue Evaluation

Stress and fatigue evaluation were completed using the program WECEVAL (Reference 6). The program WECEVAL performed primary stress intensity evaluation, primary plus secondary stress intensity range evaluation, and fatigue evaluation of the sleeved tube assembly.

Complete transient histories at given locations on the model were used to calculate the total cumulative fatigue usage factor per Code Paragraph NB-3216.2. For the fatigue evaluation, the effect of local discontinuities was considered.

3.4.7 RESULTS OF ANALYSES

Analyses were performed for both intact and discontinuous tubes. Design and operating transient parameters (pressure, temperature, etc.) were selected from the applicable Westinghouse Design Specifications for the Model 44 and 51 Series steam generators in such a manner as to be conservative in structural effect and frequency of occurrence. Fatigue and stress analyses of the sleeved tube assembly have been completed in accordance with the requirements of the ASME Boiler and Pressure Vessel Code, Section III.

3.4.7.1 PRIMARY STRESS INTENSITY

The umbrella loads for the primary stress intensity evaluation are given in Table 3.4.7.1-1.

TABLE 3.4.7.1-1

UMBRELLA PRESSURE LOADS FOR
DESIGN, FAULTED, AND TEST CONDITIONS

a,c,e

The results of primary stress intensity evaluation for the analysis sections are summarized in Tables 3.4.7.1-2 and 3.4.7.1-3. All primary stress intensities for the sleeved tube assembly are well within allowable ASME Code limits.

The largest value of the ratio "Calculated Stress Intensity/Allowable Stress Intensity" of [

]a,b,c

3.4.7.2 RANGE OF PRIMARY PLUS SECONDARY STRESS INTENSITIES

Table 3.4.7.2-1 contains the pressure and temperature loads for maximum range of stress intensity evaluations as well as for fatigue evaluation. The maximum range of stress intensity values for the sleeved tube assemblies are summarized in Table 3.4.7.2-2.

The requirements of the ASME Code, Paragraph NB-3222.2, were met for all test cases.

TABLE 3.4.7.1-2

RESULTS OF PRIMARY STRESS INTENSITY EVALUATION

(Upper Hybrid Expansion Joint)

PRIMARY MEMBRANE STRESS INTENSITY, P_m

LOCATION	CALCULATED MAXIMUM OF STRESS INTENSITY, ksi	ALLOWABLE STRESS INTENSITY, ksi	RATIO CALCULATED S.I. / ALLOWABLE S.I.
TUBE INTACT			a,c,e
Sleeve			
Tube			
TUBE DISCONTINUOUS			
Sleeve			
Tube			

TABLE 3.4.7.1-3

RESULTS OF PRIMARY STRESS INTENSITY EVALUATION

(Upper Hybrid Expansion Joint)

PRIMARY MEMBRANE PLUS BENDING STRESS INTENSITY, $P_L + P_b$

LOCATION	CALCULATED MAXIMUM OF STRESS INTENSITY, ksi	ALLOWABLE STRESS INTENSITY, ksi	RATIO CALCULATED S.I. / ALLOWABLE S.I.
TUBE INTACT			a,c,e
Sleeve			
Tube			
TUBE DISCONTINUOUS			
Sleeve			
Tube			

TABLE 3.4.7.2-1

PRESSURE AND TEMPERATURE LOADINGS FOR MAXIMUM RANGE OF STRESS INTENSITY AND FATIGUE EVALUATIONS

CONDITION	CASE NAME	CASE NO.	CYCLES	PRESSURE, PSIG PRIMARY	PRESSURE, PSIG SECONDARY	Time, sec/Thermal Conditions
Ambient	Ambient	1	200	0	0	NA/No Thermal Stress
Plant Loading*						
Plant Heatup	1PLLD	2	18,300	2,235	1,005	0/UF
Plant Cooldown	2PLLD	3	18,300	2,235	705	3200/ST
Plant Unloading						
Small Step Load Decrease	1SSLD	4	2,000	2,310	795	30/TR
	2SSLD	5	2,000	2,160	760	150/TR
Small Step Load Increase	1SSLI	6	2,000	2,215	610	50/TR
	2SSLD	7	2,000	2,130	660	185/TR
Large Step Load Decrease	1LSLD	8	200	2,355	100	36/TR
	2LSLD	9	200	2,160	830	480/TR
Hot Standby Operations	1HSTB	10	18,300	2,235	855	0/ST
	2HSTB	11	18,300	2,235	925	400/ST

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TABLE 3.4.7.2-1 (cont)

PRESSURE AND TEMPERATURE LOADINGS FOR MAXIMUM RANGE OF STRESS INTENSITY AND FATIGUE EVALUATIONS

CONDITION	CASE NAME	CASE NO.	CYCLES	PRESSURE, PSIG PRIMARY	PRESSURE, PSIG SECONDARY	Time,sec/Thermal Conditions
Turbine Roll Test	1TRT	12	10	2,235	1,035	0/No Thermal Stress
	2TRT	13	10	1,875	525	1,680/No Thermal Stress
Loss of Load	1LLD	14	100	2,585	1,020	12/TR
	2LLD	15	100	1,600	1,020	100/TR
Loss of Power	1LPW	16	50	2,060	1,065	125/TR
	2LPW	17	50	2,485	1,065	2,000/TR
Loss of Flow	1LFW	18	100	1,860	875	140/TR
Reactor Trip from Full Power	1RTR	19	500	1,855	935	100/ST
Steady State Fluctuations	1SFL	20	10^6	2,335	725	NA/ST
	2SFL	21	10^6			
Tube Leak Test	1TLT	22	800	0	840	NA/No Thermal Stress
Primary Side Leak Test	1PSLT	23	200	2,485	885	NA/No Thermal Stress
Secondary Side Leak Test	1SSLT	24	50	415	1,085	NA/No Thermal Stress

*Umbrella transient
Note: Thermal conditions: TR = transient, ST = steady state, UF = Uniform temperature

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TABLE 3.4.7.2-2

RESULTS OF MAXIMUM RANGE OF STRESS INTENSITY EVALUATION
(Upper Hybrid Expansion Joint)

LOCATION	CALCULATED MAXIMUM RANGE OF SI ksi	ALLOWABLE MAXIMUM RANGE OF SI ksi	RATIO CALCULATED S.I. / ALLOWABLE S.I.
TUBE INTACT			a,c,e
Sleeve			
Tube			
TUBE DISCONTINUOUS			
Sleeve			
Tube			

3.4.7.3 RANGE OF TOTAL STRESS INTENSITIES

Based on the sleeve design criteria, the fatigue analysis considered a design life objective of 40 years for the sleeved tube assemblies. Table 3.4.7.2-1, describes the umbrella transient conditions used in the fatigue analysis. Because of possible opening of the interface between the sleeve and the tube along the hydraulic expansion regions, the maximum fatigue strength reduction factor of 5.0 (NB-3222.4(3)) was applied in the radial direction at the "root" interface nodes of the hard roll region. The results of the fatigue analysis for the sleeved tube assemblies are summarized in Table 3.4.7.3-1.

All of the cumulative usage factors are below the allowable value of 1.0 specified in the ASME Code.

TABLE 3.4.7.3-1

RESULTS OF FATIGUE EVALUATION

(Upper Hybrid Expansion Joint)

LOCATION	CUMULATIVE USAGE FACTOR	ALLOWABLE USAGE FACTOR
TUBE INTACT	a,c,e	
Sleeve		1.0
Tube		1.0
TUBE DISCONTINUOUS		
Sleeve		1.0
Tube		1.0

3.4.8 REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section III, Subsection NB, 1983 Edition, July 1, 1983.

2. Equipment Specification G-677031, Westinghouse, Revision 4, March 20, 1975.

3. ASME Boiler and Pressure Vessel Code, Code Cases, Case N-20, 1983 Edition, July 1, 1983.

4. ASME Boiler and Pressure Vessel Code, Section III, Appendix 1, 1983 Edition, July 1, 1983.

5. WECAN, WAPPP and FIGURES II, F. J. Bogden Editor, Second Edition, May 1981, Westinghouse Advanced System Technology, Pittsburgh, PA 15235.

6. J. M. Hall, A. L. Thurman, "WECEVAL, A Computer Code to Perform ASME BPVC Evaluations Using Finite Element Model Generated Stress States," Westinghouse, April, 1985.

3.5 SPECIAL CONSIDERATIONS

3.5.1 FLOW SLOT HOURGLASSING

Along the tube-lane, the tube support plate has several long rectangular flow slots that have the potential to deform into an "hourglass" shape with significant denting. The effect of flow-slot hourglassing is to move the neighboring tubes laterally inward to the tube lane from their initial positions. The maximum bending would occur on the innermost row of tubes in the center of the flow slots.

3.5.1.1 EFFECT ON BURST STRENGTH

The effect of bending stresses on the burst strength of tubing has been studied. Both the axial and circumferential crack configurations were investigated. [

]a,e,f

3.5.1.2 EFFECT ON STRESS CORROSION CRACKING (SCC) MARGIN

Based on the results of a caustic corrosion test program on mill-annealed tubing, the bending stress magnitude due to flow-slot hourglassing is judged to have only a small effect, if any, on the SCC resistance margins. Two long term modular model boiler tests have been conducted to address the effect of bending stresses on SCC. No SCC or Inter Granular Attack (IGA) was detected by destructive examination. It is to be noted that thermally treated Alloy 600 and 690 have additional SCC resistance compared to the resistance of mill annealed Alloy 600 tubing.

3.5.1.3 EFFECT ON MAXIMUM RANGE OF STRESS INTENSITY AND FATIGUE USAGE FACTOR

In addition to the above two considerations, one should also consider the effect of the hourglassing induced bending stresses on maximum range of stress intensity and fatigue usage factor of the sleeve. Taking into account the hourglassing induced bending stress along with the transient pressure and thermal stress, the largest value of maximum stress intensity would be 59.70 ksi (allowable 79.80 ksi), fatigue usage factor is negligible.

3.5.2 TUBE VIBRATION ANALYSIS

Analytical assessments have been performed to predict nodal natural frequencies and related dynamic bending stresses attributed to flow-induced vibration for sleeved tubes. The purpose of the assessment was to evaluate the effect on the natural frequencies, amplitude of vibration, and bending stress due to installation of various lengths of sleeves.

Since the level of stress is significantly below the endurance limit for the tube material and higher natural frequencies result from the use of a sleeve/tube versus an unsleeved-tube, the sleeving modification does not contribute to cyclic fatigue.

3.5.3 SLUDGE HEIGHT THERMAL EFFECTS

In general, with at least 2.0 inches of sludge, the tubesheet is isothermal at the bulk temperature of the primary fluid. The net effect of the sludge is to reduce tube/tubesheet thermal effects.

3.5.4 ALLOWABLE SLEEVE DEGRADATION

3.5.4.1 MINIMUM REQUIRED SLEEVE THICKNESS

The minimum required sleeve wall thickness, t_r, to sustain normal and accident condition loads is calculated in accordance with the guidelines of Regulatory Guide 1.121, as outlined in Table 3.5.4-1. In this evaluation, the surrounding tube is assumed to be completely degraded; that is, no design credit is taken for the residual strength of the tube.

The sleeve material may be either thermally treated Alloy 600 or thermally treated Alloy 690. It has been shown that the mechanical properties of Alloy 600 are very similar to those of Alloy 690. In particular, the yield strength and ultimate strength are very similar.

Table 3.5.4-1

REGULATORY GUIDE 1.121 CRITERIA

1. Normal and Upset Condition Loadings

Normal Operations

Criterion: $S_u \leq 90.58$ ksi

Loading: $P_p = 2250$ psia

$P_s = 720$ psia $\Delta P = 1{,}530$ psi

Hence, miminum required sleeve wall thickness t_r is

$$t_r = \frac{\Delta P \cdot R_i}{\frac{S_u}{3} - 0.5\,(P_p + P_s)} = [\quad]\ \text{inch}^{a,c,e}$$

which is [49] a,c,e percent of the nominal wall thickness.

Upset Conditions

Criterion: $S_y = 39.59$ ksi

$P_p = 2{,}600$ psia

$P_s = 1{,}035$ psia $\Delta P = 1{,}565$ psi

Hence, $t_r = \frac{\Delta P \cdot R_i}{S_y - 0.5\,(P_p + P_s)} = [\quad]$ inch a,c,e

which is [ ]a,c,e percent of the nominal wall thickness.

2. Accident Condition Loadings

a. LOCA + SSE

The major contribution of LOCA and SSE loads is the bending stresses at the top tube support plate due to a combination of the support motion, inertial loadings, and the pressure differential across the tube U-bend resulting from the rarefaction of the wave during LOCA. Since the sleeve is located below the first support, the LOCA + SSE bending stresses in the sleeve are quite small. The governing event for the sleeve therefore is a postulated secondary side blowdown.

b. FLB + SSE

The maximum primary-to-secondary pressure differential occurs during a postulated feedline break (FLB) accident. Again, because of the sleeve location, the SSE bending stresses are small. Thus, the governing stresses for the minimum wall thickness requirement are the pressure membrane stresses.

Criterion: $P_m \leq$ smaller of $0.7S_u$ or $2.4S_m$ i.e. 63.4 ksi

Loadings: P_p = 2,650 psig

$P_s = 0$ $\quad \Delta P = 2,650$

$$\text{Hence, } t_r = \frac{\Delta P \cdot R_i}{0.7\,S_u - 0.5\,(P_p + P_s)} = [\qquad]^{a,c,e}$$

or, [ ] ^{a,c,e} percent of nominal wall.

The required sleeve wall thickness is [ ]^{a,c,e}. [ ]^{a,c,e} percent minus growth and uncertainty, could be the plugging criteria with confirmation of leak-before-break. A [ ]^{a,c,e} percent criteria would permit [ ]^{a,c,e} per cent for growth and uncertainty.

3. Leak-Before-Break Verification

The leak-before-break evaluation for the sleeve is based on leak rate and burst pressure test data obtained on 7/8 inch OD x 0.050 inch wall and 11/16 inch OD x 0.040 inch wall cracked tubing with various amounts of uniform thinning simulated by machining on the tube OD. The margins to burst during a postulated SLB (Steamline Break Accident) condition are a function of the mean radius to thickness ratio, based on a maximum permissible leak rate of 0.35 gpm due to a normal operating pressure differential of 1,530 psi.

Table 3.5.4-1 (cont.)

Using a mean radius to thickness factor of 9.5 for the nominal sleeve, the current Technical Specifications allowable a leak rate of .35 gpm, a SLB pressure differential of 2,560 psi, and the nominal leak and nominal burst curves, a 29.8 percent margin exists between the burst crack length and the leak crack length. For a sleeve thinned 51 percent through wall over a 1.0 inch axial length, a 24.8 percent margin to burst is demonstrated. Thus the leak-before break behavior is confirmed for unthinned and thinned conditions.

Since Regulatory Guide 1.121 is to be addressed, it is permissible to derive the allowable stress limits based on expected lower bound material properties, as opposed to the Code minimum values. Expected strength properties were obtained from statistical analyses of tensile test data of actual production tubing. These data were used for the lower tolerance limits of material. Lower tolerance limit, LTL, means there is 95 percent of confidence that 95 percent of the sleeve/tubes will have strength greater than LTL.

3.5.4.2 DETERMINATION OF PLUGGING LIMITS

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

As provided in paragraph C.2.b. of the Regulatory Guide, an additional thickness degradation allowance should be factured into the minimum acceptable tube wall thickness to establish the operational tube thickness acceptance for continued service. Paragraph C.3.f. of the Regulatory Guide provides that the basis used in setting the operational degradation allowance include the method and data used in predicting the continuing degradation and consideration of eddy current measurement errors and other significant eddy current testing parameters.

As outlined in Section 6.0 of this report, the capability of eddy current inspection of the sleeve and tube in the sleeve area has been demonstrated. The [ ]^{c,e} eddy current measurement uncertainty value of [ ]^{a,c,e} of the tube wall thickness is appropriate for use in the determination of the operational tube thickness acceptable for continued service and thus determination of the plugging limit.

Paragraph C.3.f of the Reg. Guide specified that the basis 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. No degradation has been detected to date on Westinghouse designed sleeves and no sleeved tube has been removed from service due to degradation of any portion of the sleeve. This result would be expected due in part to the changes in the sleeve material relative to the tube and the lower heat flux due to the double wall in the sleeved region.

It is the position of Westinghouse Electric that since no degradation has been detected in the sleeves, presently any allowance for continuing degradation [ ]c,e would be an arbitrary value not supported by the data and would represent a conversatism in addition to the safety factors implicit in the determination of minimum acceptable tube wall thickness using Reg. Guide 1.121.

In summary, the operational tube thickness acceptable for continued service includes the minimum acceptable tube wall thickness ([ ]a,b,c of wall thickness, see Table 3.5.4-1), the combined allowance for eddy current uncertainty and operational degradation ([ ]a,c of wall thickness as recommended by Westinghouse). These terms total to 59% resulting in a plugging limit as determined by Regulatory Guide 1.121 guidelines of 41% of the tube wall thickness.

The plugging limit for the tube, where applicable as defined below is as specified in the Technical Specifications for the non-sleeved portions of the tube, currently 40% of the tube wall thickness.

3.5.4.3 APPLICATION OF PLUGGING LIMITS

Sleeves or tubes which have eddy current indications of degradation in excess of the plugging limits must be repaired or plugged. Those portions of the tube and the sleeve (shown in Figure 3.5.4-1) for which indications of wall degradation must be evaluated are summarized as follows:

a,c,e

Figure 3.5.4-1

Application of Plugging Limits

1) Indications of degradation in the entire length of the sleeve must be evaluated against the sleeve plugging limit.

2) Indication of tube degradation of any type including a complete guillotine break in the tube between the bottom of the upper joint and the top of the lower roll expansion does not require that the tube be removed from service.

3) The tube plugging limit continues to apply to the portion of the tube in the upper joint and in the lower roll expansion. As noted above the sleeve plugging limit applies to these areas also.

4) The tube plugging limit continues to apply to that portion of the tube above the top of the upper joint.

3.5.5 EFFECT OF TUBESHEET INTERACTION

Since the pressure is normally higher on the primary side of the tubesheet than on the secondary side, the tubesheet becomes concave upward. Under these conditions, the tubes protruding from the top of the tubesheet will rotate from the vertical. This rotation develops stresses in the sleeved tube assembly. Analysis performed showed that these stresses do not affect significantly the fatigue usage factors.

3.5.6 STRUCTURAL ANALYSIS OF THE LOWER JOINT

3.5.6.1 Primary Stress Intensity

The results of primary stress intensity evaluation for the analysis sections located at the lower joint are summarized in Tables 3.5.6.1-1 and 3.5.6.1-2. All primary stress intensities for the sleeved tube assembly at the lower joint meet the ASME code limits.

3.5.6.2 Range of Primary Plus Secondary Stress Intensities

Primary plus secondary stress at the Lower Joint are developed by the pressure acting on the sleeve, tube and tubesheet ligament surfaces (primary stress), and by thermal stress and deformations imposed by the tubesheet motion (secondary stress). The tubesheet motion results from the primary and secondary side pressure and interactions among the tubesheet, support ring, channel head, and the stub barrel. The worst case, tube intact, was analyzed. The maximum range of stress intensity values for the sleeved tube assembly are summarized in Table 3.5.6.2-1.

The requirements of the ASME Code, paragraph NB-3222.2 were satisfied.

TABLE 3.5.6.1-1

RESULTS OF PRIMARY STRESS INTENSITY EVALUATION

(Lower Joint)

PRIMARY MEMBRANE STRESS INTENSITY, P_m

LOCATION	CALCULATED MAXIMUM OF STRESS INTENSITY, ksi	ALLOWABLE STRESS INTENSITY, ksi	RATIO CALCULATED S.I. / ALLOWABLE S.I.
TUBE INTACT			a,c,e
Sleeve			
Tube			
TUBE DISCONTINUOUS			
Sleeve			
Tube			

TABLE 3.5.6.1-2

RESULTS OF PRIMARY STRESS INTENSITY EVALUATION

(Lower Joint)

PRIMARY MEMBRANE PLUS BENDING STRESS INTENSITY, $P_L + P_b$

LOCATION	CALCULATED MAXIMUM STRESS INTENSITY, ksi	ALLOWABLE STRESS INTENSITY, ksi	RATIO CALCULATED S.I. / ALLOWABLE S.I.
TUBE INTACT			a,c,e
Sleeve			
Tube			
TUBE DISCONTINUOUS			
Sleeve			
Tube			

3.5.6.3 Range of Total Stress Intensities

The fatigue analysis considered a design life objective of 40 years for the sleeved tube assemblies. The maximum fatigue strength reduction factor of 5.0 was applied in the radial direction at the "root" interface nodes of the hard roll region.

All of the cumulative usage factors are negligible, hence, they are below the allowable value of 1.0 specified in the ASME Code.

TABLE 3.5.6.2-1

RESULTS OF MAXIMUM RANGE OF STRESS INTENSITY EVALUATION

(Lower Joint)

LOCATION	CALCULATED MAXIMUM RANGE OF SI ksi	ALLOWABLE MAXIMUM RANGE OF SI ksi	RATIO CALCULATED S.I. / ALLOWABLE S.I.
			a,c,e
TUBE INTACT			
Sleeve			
Tube			

3.5.7 EFFECT OF AN AXIAL TUBE LOCK-UP ON FATIGUE USAGE FACTOR

In this analysis, only one tube is considered to be locked-up at the first tube support plate under 100 percent power conditions.

The following effects on the stress components of the locked-up tube were analyzed:

- effect of primary and secondary pressure stresses
- effect of thermal stresses in the assembly
- effect of tubesheet rotations
- effect of axial thermal displacements in tube, tube/sleeve, and wrapper/shell regions

The effects of pressure drops across the tubesheet and the tube support plates as well as the tubesheet-tube support plate assembly interactions were taken into account for central locked-up tubes while they were neglected for the outermost tubes. The results of maximum range of stress intensity and fatigue evaluations are given in Tables 3.5.7-1 and 3.5.7-2

For the central locked-up tubes, only the sleeve for the worst case, i.e., tube discontinuous, was considered.

It is seen that the requirements of the ASME Code are satisfied for both outermost and central axial locked-up sleeved tubes.

3.5.8 Minimum Sleeve Wall Thickness

Nominal and minimum sleeve wall thickness was analyzed.

Taking into account plus [0.003][a,c,e] inches for corrosion/errosion, the recommended sleeve wall thickness is:

Nominal Sleeve Wall Thickness	[	][a,c,e]
Minimum Local Sleeve Wall Thickness		

TABLE 3.5.7-1

RESULTS OF MAXIMUM RANGE OF STRESS INTENSITY EVALUATION
AXIAL TUBE LOCK-UP

LOCATION	CALCULATED MAXIMUM RANGE OF SI ksi	ALLOWABLE MAXIMUM RANGE OF SI ksi	RATIO CALCULATED S.I. / ALLOWABLE S.I.
	Outermost Tubes		
			a,c,e
TUBE INTACT			
Sleeve			
Tube			
TUBE DISCONTINUOUS			
Sleeve			
Tube			
TUBE DISCONTINUOUS			
Sleeve			

TABLE 3.5.7-2

RESULTS OF FATIGUE EVALUATION

AXIAL TUBE LOCK-UP

LOCATION	CUMULATIVE USAGE FACTOR	ALLOWABLE USAGE FACTOR
	Outermost Tubes	
TUBE INTACT		
Sleeve	Negligible	1.0
Tube	Negligible	1.0
TUBE DISCONTINUOUS		
Sleeve	Negligible	1.0
Tube	Negligible	1.0
	Central Tubes	
TUBE DISCONTINUOUS		
Sleeve	Negligible	1.0

3.5.9 EVALUATION OF OPERATION WITH FLOW EFFECTS SUBSEQUENT TO SLEEVING

The most recent Emergency Core Cooling System (ECCS) performance analysis completed for Kewaunee was done to support Technical Specification changes required to allow operation at up to 10 per cent steam generator tube plugging (SGTP). This analysis was not performed by Westinghouse. However, this analysis and the corresponding non-LOCA study are considered applicable for the steam generator sleeving program with a combination of plugging and sleeving flow restriction equal to or less than the restriction due to 10 per cent tube plugging. In addition, in support of the steam generator sleeving program, Westinghouse has performed an evaluation of selected LOCA and non-LOCA transients to demonstrate that use of sleeves resulting in a plugging equivalency of up to 10 per cent will not have an adverse affect on the thermal-hydraulic performance of the plant. For the accidents evaluated, the effect of a combination of plugging and sleeving up to the equivalent of 10 per cent tube plugging would not be expected to result in any design or regulatory limit being exceeded.

The LOCA type accidents which were evaluated were those that were previously analyzed by Westinghouse and currently in the Kewaunee licensing basis. The fuel in the Kewaunee plant is from a supplier other than Westinghouse and that supplier or Wisconsin Public Service is responsible for the evaluation of large break LOCA and other transients. The evaluation of the transients listed below was based on the assumption that the fuel currently in the Kewaunee core performs the same as Westinghouse 14x14 Standard Fuel. The items listed below were evaluated for a sleeving and plugging combination equivalent to 10 per cent tube plugging and the results indicated no adverse effects.

Small Break LOCA	
Containment Integrity	Short and Long Term Mass and Energy Releases
Containment Integrity	Main Steamline Break
Reactor Blowdown	Vessel and Loop Forces
Steam Generator Tube Rupture	
Hot Leg Switchover	Prevention of Potential Boron Precipitation

The effect of sleeving on the non-LOCA transient analyses has been reviewed. Analyses of the level of sleeving and plugging discussed in this report have shown that the Reactor Coolant System (RCS) flow rate will not be less than the Thermal Design Flow rate. The Thermal Design Flow rate is the value used in the non-LOCA safety analyses and is designed to be less than the minimum RCS flow rate that occurs under normal or degraded conditions. Since the reduced RCS flow rate is not less than the assumed flow rate (Thermal Design Flow), the non-LOCA safety analyses are bounded by the anticipated maximum amount of steam generator tube sleeving ([ ]^{d,e} sleeves per steam generator). Therefore, the steam generator sleeve installation up to the equivalent of 10 per cent plugging would not invalidate any non-LOCA safety analyses. Any smaller number of sleeves would have less of an effect.

For the Series 51 steam generators in Kewaunee, 10 percent of the total tubes (3388 tubes per S/G) equals 338 tubes of any one steam generator. The ECCS analysis model typically is set up such that a uniform steam generator tube plugging condition is modeled. The NRC staff has required that the LOCA analysis for a plant with steam generator tube plugging model the maximum tube plugging level present in any of the plant steam generators.

Inserting a sleeve into a steam generator tube results in a reduction of primary coolant flow. The anticipated total number of sleeves to be installed into the Kewaunee steam generators is [ ]^{d,e}. For the purposes of this section, it is assumed that [ ]^{d,e} tubes in each steam generator will be sleeved. The evaluation of flow effects for sleeving at Kewaunee assumes the use of [ ]^{a,c,e} inch long sleeves which are expected to be long enough to span the degraded areas in the tubesheet region and to place the upper joint above the sludge pile in either the hot or cold leg side of the steam generators. The flow effects of this sleeve length bound a range of sleeve lengths ([ ]^{a,c,e} inches) which could be used in the sleeving of the Kewaunee steam generators.

The flow reduction through a tube due to the installation of a sleeve can be considered equivalent to a portion of the flow loss due to a plugged tube. The hydraulic equivalency ratio of the number of sleeved tubes required to result in the same flow loss as that due to a plugged tube can be used to determine the allowable number of plugs and sleeves in combination. The hydraulic equivalency ratio for LOCA fluid conditions was established using flow rates which would be used based on the most recent Westinghouse analysis with Westinghouse supplied fuel. The hydraulic loss coefficients used to determine the flow reduction for nominal conditions are as follows: for an unsleeved tube [ ]^{b,c,e}, for a sleeve in the hotleg end of the tube [ ]^{b,c,e}, for a sleeve in the cold leg end of the tube [ ]^{b,c,e}, and for two ends sleeved [ ]^{b,c,e}. The hydraulic loss coefficients used to determine the flow reduction for LOCA conditions are as follows: for an unsleeved tube [ ]^{b,c,e}, for a sleeve in the hotleg end of the tube [ ]^{b,c,e}, for a sleeve in the cold leg end of the tube [ ]^{b,c,e}, and for two ends sleeved [ ]^{b,c,e}. All of these coefficients are based on the nominal tube inside diameter. The hydraulic equivalency ratios for both one and two sleeves installed into a tube have been developed as outlined in the following sections.

3.5.9.1 ONE SLEEVE PER TUBE

For a single [ ]^{a,c,e} inch sleeve installed in the hot leg of a tube the primary coolant flow reduction per tube is approximately equal to [ ]^{b,c,e} percent of normal flow under nominal conditions. This reduction in primary coolant flow equates to a hydraulic equivalency ratio of [ ]^{b,c,e} sleeved tubes to one plugged tube under normal conditions. For a sleeve installed on the cold leg side the flow reduction per tube is approximately [ ]^{b,c,e} per cent which equates to a hydraulic equivalency ratio of [ ]^{b,c,e}.

Using the [ ]^{b,c,e} to 1 ratio for sleeves installed on the cold leg side and the 10 percent tube plugging limit for Kewaunee, Table 3.5.9-1 provides a reference calculation of the number of additional plugs which could be installed based on [ ]^{d,e} sleeves installed per steam generator and nominal conditions. Note [ ]^{d,e} sleeved tubes are equivalent to approximately [ ]^{b,d,e} plugged tubes or [ ]^{b,d,e} percent plugging.

For typical predicted LOCA fluid conditions the flow reduction for a sleeve on the hot leg side is approximately [ ]^{b,c,e} per cent or a hydraulic equivalency ratio of [ ]^{b,c,e}. For a sleeve on the cold leg side the values are [ ]^{b,c,e} respectively.

For the condition presented above for Kewaunee the most limiting equivalent plugged condition in the two steam generators occurs in steam generator B where 214 tubes are currently plugged. It is seen in Table 3.5.9-1 that with [ ]^{d,e} tubes sleeved there would be a margin of [ ]^{d,e} tubes (124 minus [ ]^{d,e}) available for additional plugging before exceeding the equivalent of 10 percent SGTP for nominal fluid conditions. Note, because of the larger hydraulic equivalency ratio for LOCA conditions, using the nominal condition hydraulic equivalency ratio to determine plugging margin to 10 per cent plugging is conservative.

TABLE 3.5.9-1

SLEEVING PARAMETERS EXAMPLE UNDER NORMAL CONDITIONS

(ONE SLEEVE PER TUBE)

Steam Generator	A	B	
Total equivalent plugged tubes allowed	338	338	
Maximum possible sleeves	[	]	b,d,e,
Maximum possible sleeved tubes			
Equivalent plugged tubes			
Existing plugs	128	214	
Total equivalert plugged tubes	[	]	b,d,e
Percent equivalent SGTP (Based on 3388 tubes/SG)			
No. of additional plugs allowed			

3.5.9.2 TWO SLEEVES PER TUBE

When a single tube has one [ ]^{a,c,e} inch sleeve on the hot-leg side and a second [ ]^{a,c,e} inch sleeve on the cold leg side the primary coolant flow loss per tube is approximately equal to [ ]^{b,c,e} percent of normal flow. This reduction in primary coolant flow equates to a hydraulic equivalency ratio of [ ]^{b,c,e} sleeved tubes to one plugged tube during nominal fluid conditions.

Using this [ ]^{b,c,e} to 1 ratio and the assumed 10 percent tube plugging limit for Kewaunee, Table 3.5.9-2 provides a reference calculation of the number of additional plugs which could be installed based on [ ]^{d,e} sleeves installed for [ ]^{d,e} tubes per steam generator during nominal conditions with two sleeves per tube. Note that [ ]^{d,e} double sleeved tubes are equivalent to approximately [ ]^{b,c,e} plugged tubes, or [ ]^{b,c,e} percent plugging under normal conditions.

For typical predicted LOCA fluid conditions the flow reduction for a sleeve on the both ends of the tube is approximately [ ]^{b,c,e} per cent or a hydraulic equivalency ratio of [ ]^{b,c,e}.

For the condition presented above for Kewaunee, the most limiting equivalent plugged tube condition in the two steam generators occurs in steam generator B where 214 tubes are currently plugged. It is seen in Table 3.5.9-2 with [ ]^{d,e} tubes double sleeved, there would be a margin of [ ]^{d,e} tubes (124 minus [ ]^{d,e}) available for additional plugging before exceeding the basis of the LOCA and non-LOCA analyses with 10 percent SGTP. Note, because of the larger hydraulic equivalency ratio for LOCA conditions using the nominal condition hydraulic equivalency ratio to determine plugging margin to 10 per cent plugging is conservative.

The method and values of hydraulic equivalency and flow loss per sleeved tube outlined above and in the previous section can also be used for a combination of one and two sleeves per tube. Due to the many possible combinations, such a combination is not provided in this report.

TABLE 3.5.9-2

SLEEVING PARAMETERS EXAMPLE UNDER NORMAL CONDITIONS

(TWO SLEEVES PER TUBE)

Steam Generator	A	B	
Total equivalent plugged tubes allowed	338	338	
Maximum possible sleeves	[	]	b,d,e,
Maximum possible sleeved tubes			
Equivalent plugged tubes			
Existing plugs	128	214	
Total equivalent plugged tubes	[	]	b,d,e
Percent equivalent SGTP (Based on 3388 tubes/SG)			
No. of additional plugs allowed			

3.5.9.3 FLOW EFFECTS SUMMARY

The effects of sleeving on LOCA and non-LOCA transient analyses has been reviewed. No adverse result is expected for sleeve and plug combination up to an equivalent of 10 per cent SGTP. The existing ECCS performance analysis and the corresponding non-LOCA evaluation are considered applicable for the steam generator sleeving program with a combination of plugging and sleeving flow restriction equal to or less than 10 percent tube plugging. Steam generator sleeve installation up to the equivalent of 10 percent plugging would not invalidate any non-LOCA safety analyses or the evaluation of design transients.

The results of evaluations show that any combination of sleeving and plugging may be utilized at Kewaunee as long as the effective SGTP of 10 percent is not exceeded. Given the maximum number of tubes which may be sleeved, Tables 3.5.9-1 and 3.5.9-2 provide the number of additional plugs per steam generator that could be installed at the present plugging levels of Kewaunee without exceeding the 10 percent SGTP.

As a result of tube plugging and sleeving, primary side fluid velocities in the steam generator tubes will increase. The effect of this velocity increase on the sleeve and tube has been evaluated assuming a conservative limiting condition in which 10 percent of the tubes are plugged. As a reference, normal flow velocity through a tube is approximately [ ]^{c} ft/sec, for the unplugged condition. With 10 percent of the tubes plugged, the fluid velocity through an non-plugged and non-sleeved tube is [ ]^{b,c} ft/sec, and for a tube with a sleeve, the local fluid velocity in the sleeve region is estimated at [ ]^{b,c,e} ft/sec. Because these fluid velocities are less than the inception velocities for fluid impacting, cavitation, and erosion-corrosion, the potential for tube degradation due to these mechanisms is low.

Accordingly, using the assumptions stated in Section 3.5.9, no ECCS results more adverse than those in the existing Kewaunee safety analysis are anticipated for equivalent tube plugging projected to occur at Kewaunee Nuclear Power Plant with up to [ ]^{d,e} sleeves installed per steam generator using [ ]^{a,c,e} sleeves.

4.0 PROCESS DESCRIPTION

The sleeve installation consists of a series of steps starting with tube end preparation (if required) and progressing through sleeve insertion, hydraulic expansion at both the lower joint and upper Hybrid Expansion Joint (HEJ) regions, hard roll joining at both joint locations, and joint inspection. The sleeving sequence and process are outlined in Table 4.0-1. All these steps are described in the following sections.

4.1 TUBE PREPARATION

There are two steps involved in preparing the steam generator tubes for the sleeving operation. These consist of light rolling (as required) at the tube end and tube cleaning.

4.1.1 TUBE END ROLLING (CONTINGENCY)

If gaging or inspection of tube inside diameter measurements indicate a need for tube end rolling to provide a uniform tube opening for sleeve insertion, a light mechanical rolling operation will be performed. This is sufficient to prepare the mouth of the tube for sleeve insertion without adversely affecting the original tube hard roll or the tube-to-tubesheet weld. Tube end rolling will be performed only as a contingency.

Testing of similar lower joint configurations in Model 27 steam generator sleeving programs at a much higher torque showed no effect on the tube-to-tubesheet weld. Because the radial forces transmitted to the tube-to-tubesheet weld would be lower for a larger Model 51 sleeve than for the above test configuration no effect on the weld as a result of the light roll is expected.

TABLE 4.0-1

SLEEVE PROCESS SEQUENCE SUMMARY

a,c,e

TUBE PREPARATION

SLEEVE INSERTION

LOWER JOINT FORMATION

UPPER JOINT FORMATION

INSPECTION
(Process Verification)

4.1.2 TUBE CLEANING

The sleeving process includes cleaning the inside diameter area of tubes to be sleeved to prepare the tube surface for the hybrid expansion joint and the lower joint by removing loose oxide and foreign material. Cleaning also reduces the radiation shine from the tube inside diameter, thus contributing to reducing man-rem exposure.

Tube cleaning may be accomplished by either wet or dry methods. Both processes have been shown to provide tube inside diameter surfaces compatible with mechanical joint installation. The selection of the cleaning process used is dependent primarily on the installation technique utilized, the scale of the sleeving operation (small scale vs. large scale sleeving), and the customers site specific rad-waste requirements. Evaluation has demonstrated that neither of these processes remove any significant fraction of the tube wall base material.

4.1.2.1 WET CLEANING

Tube cleaning will be performed using a [

]a,c,e

A waste handling system is used to collect the [
],a,c,e and the oxide removed from the tube ID. [

]a,c,e There may also be an inlet to the suction pump which subsequently pumps the debris and water directly to the plant waste disposal system.

4.1.2.2 DRY CLEANING

The dry cleaning process is similar to the wet cleaning process with the notable exception that the water jet and the attendant systems needed to handle the effluent are omitted. The dry cleaning process is typically more applicable to hands-on (manual) or small scale sleeving operations.

In order to remove loose oxide debris produced by the dry cleaning operation, the tube interior is swabbed utilizing a fluid (typically deionized water or isopropyl alcohol) soaked felt pad to an elevation slightly less than the cleaned length, but above the top of the installed sleeve.

4.2 SLEEVE INSERTION AND EXPANSION

The following paragraphs describe the insertion of the sleeves and mandrels and the hydraulic expansion of the sleeves at both the lower joint and upper HEJ locations.

The sleeves are fabricated under controlled conditions, serialized, machined, cleaned, and inspected. They are typically placed in plastic bags, and packaged in protective styrofoam trays inside wood boxes. Upon receipt at the site, the boxed sleeves are stored in a controlled area outside containment and as required moved to a low radiation, controlled region inside containment. Here the sealed sleeve box is opened and the sleeve removed, inspected and placed in a protective sleeve carrying case for transport to the steam generator platform. Note that the sleeve packaging specification is extremely stringent and, if unopened, the sleeve package is suitable for long term storage.

[

]a,c,e

[

]a,c,e This process is repeated until all sleeves are installed and hydraulically expanded.

4.3 LOWER JOINT SEAL

At the primary face of the tubesheet, the sleeve is joined to the tube by a [

].a,c,e

The appropriate extent of hard roll expansion of the sleeve is attained by [ ]a,c,e The hard roller torque is calibrated on a standard torque calibrator prior to initial hard rolling operations and subsequently recalibrated at the beginning of each shift for automatic tooling. This control and calibration process is a technique used throughout industry in the installation of tubes in heat exchangers.

4.4 UPPER HYBRID EXPANSION JOINT (HEJ)

The HEJ first utilizes a [

]a,c,e An upper hard roller is inserted into the sleeve until it is positioned at the prescribed axial location. The hard roller is then operated for a fixed time. At the end of this time the roller will have expanded to its set diameter and the total tube diametral expansion will have been accomplished. The maximum torque of the hydraulic or air operated drive motor is set at a value which is sufficient to achieve the desired tube expansion.

4.5 PROCESS INSPECTION SAMPLING PLAN

In order to verify the final sleeve installation, an eddy current inspection will be performed on all sleeved tubes to verify that all sleeves received the required hydraulic and roll expansions. The basic process check on 100 percent of the sleeved tubes will be:

1. Verify presence of lower hydraulic expansion zone.
2. Measure lower hydraulic expansion and roll average diameter and verify location within the lower hydraulic expansion.
3. Verify presence of upper hydraulic expansion zone.
4. Measure upper hydraulic expansion and roll average diameter and verify location within the upper hydraulic expansion.
5. Check for the presence of any anomalies.

In order to monitor the sleeving process, an in-process application of the eddy current profilometry may be performed to obtain sleeve ID data. As acceptable diameters are verified and the sleeving process is proceeding as anticipated, this inspection may be eliminated. These average diameters will be evaluated versus the expected tolerances established through the design requirements, laboratory testing results, and previous experience. This evaluation will determine whether or not the equipment/tooling is performing satisfactorily. If process data is determined to be outside of expected ranges, a non-conformance report is issued and further analysis performed.

If required, mechanical measurement may be used in lieu of eddy current to perform sleeve installation acceptance and in-process monitoring evaluations. Undersized diameters will be corrected by an additional expansion step to produce the desired degree of expansion. Oversized diameters will be dispositioned by a specific evaluation process on an individual tube basis, to determine their acceptability with respect to specified sleeving parameters.

If it is necessary to remove a sleeved tube from service as judged by an evaluation of a specific sleeve/tube configuration, tooling and processes will be available to plug the sleeve or the lower portion of the sleeve will be removed and the tube will be plugged.

As mentioned previously, the basic process dimensional verification will be completed and evaluated for 100 percent of all installed sleeves.

4.6 ESTABLISHMENT OF SLEEVE JOINT MAIN FABRICATION PARAMETERS

4.6.1 LOWER JOINT

The main parameter for fabrication of acceptable lower joints is sleeve [ ].[a,c,e] Sleeve [ ][a,c,e] is determined by [ ].[a,c,e] Accordingly, rolling torque was varied to achieve the desired sleeve [ ][a,c,e] in the original Model 44 program (also applicable to the model 51). [ ][a,c,e] was achieved was used throughout the program verification testing.

4.6.2 UPPER HEJ

The main parameter for fabrication of HEJ's (in-sludge and out-of-sludge) which met the leak rate acceptance criteria was [

]a,c,e

[

]a,c,e (Refer to Section 3.3.5.3 for an additional discussion of the roll expansion torque for the in-sludge case.)

In the first sleeving project performed by Westinghouse, hydraulic expansion axial length was also evaluated. [ ].a,c,e Therefore, in later programs, the HEJ hydraulic expansion axial length [

]a,b,c,e

5.0 SLEEVE/TOOLING POSITIONING TECHNIQUE

With all positioning techniques, the process actually used to install the sleeves (hydraulic expansion, mechanical rolling, etc.) will not be changed due to the use of any sleeve/tooling positioning technique. It is the processes which the sleeves are subjected to that are critical to a successful installation; the technique used to position the sleeves and tooling is not critical so long as it does not affect the sleeve installation processes.

Some techniques used to position the sleeve installation tooling are: fully robotic (ROSA and SM10-WS) and hands-on (manual), or the combination of two or more tooling installation modes utilized is dependent upon many variables and what is mutually decided between the utility and Westinghouse.

6.0 NDE INSPECTABILITY

The Non-Destructive Examination (NDE) development effort has concentrated on two aspects of the sleeve system. First, a method of confirming that the joints meet critical process dimensions is required. Secondly, it must be shown that the tube/sleeve assembly is capable of being evaluated through subsequent routine in-service inspection. In both of these efforts, the inspection process has relied upon eddy current technology.

Previous sleeve installations have had baseline and subsequent in-service inspections of the sleeved tubes. Presently, no change has been observed in any of the in-service eddy current inspections compared to the baseline inspections.

6.1 EDDY CURRENT INSPECTIONS

The eddy current inspection equipment, techniques, and results presented herein apply to the proposed Westinghouse sleeving process. Eddy current inspections are routinely carried out on the steam generators in accordance with the plant's Technical Specifications. The purpose of these inspections is to detect at an early state tube degradation that may have occurred during plant operation so that corrective action can be taken to minimize further degradation and reduce the potential for significant primary-to-secondary leakage.

The standard inspection procedure involves the use of a bobbin eddy current probe, with two circumferentially wound coils which are displaced axially along the probe body. The coils are connected in the so-called differential mode; that is, the system responds only when there is a difference in the properties of the material surrounding the two coils. The coils are excited by using an eddy current instrument that displays changes in the material surrounding the coils by measuring the electrical impedance of the coils. Presently, this involves simultaneous excitation of the coils with several different test frequencies.

The outputs of the various frequencies are combined and recorded. The combined data yield an output in which signals resulting from conditions that do not affect the integrity of the tube are reduced. By reducing unwanted signals, improved inspectability of the tubing results (i.e., a higher signal-to-noise ratio). Regions in the steam generator such as the tube supports, the tubesheet, and sleeve transition zones are examples of areas where multifrequency processing has proven valuable in providing improved inspectability.

After sleeve installation, all sleeved tubes are subjected to an eddy current inspection which includes a verification of correct sleeve installation for process control and a degradation inspection for baseline purposes to which all subsequent inspections will be compared.

While there are a number of probe configurations that lend themselves to enhancing the inspection of the tube/sleeve assembly in the regions of configuration transitions, the crosswound coil probe has been selected as offering a significant advancement over the conventional bobbin coil probe, yet retaining the simplicity of the inspection procedure.

Verification of proper sleeve installation is of critical importance in the sleeving process. The process control eddy current verification is conducted utilizing one frequency in the absolute mode with a crosswound coil probe. The purpose is to provide "in-process" verification of the existence of proper hydraulic expansion and hard roll configurations and also to allow determination of the sleeve process dimensions both axially and radially. Figure 6.1-1 illustrates the coil response and measurement technique for typical sleeve/tube joint.

The inspection for degradation of the tube/sleeve assembly has typically been performed using crosswound coil probes operated with multifrequency excitation. For the straight length regions of the tube/sleeve assembly, the inspection of the sleeve and tube is consistant with normal tubing inspections. In tube/sleeve assembly joint regions, data evaluation becomes more complex. The results discussed below suggest the limits on the volume of degradation that can be detected in the vicinity of geometry changes.

a,c,e

Figure 6.1-1 - Absolute Eddy Current Signals at 400 khz (Front and Rear Coils)

The detection and quantification of degradation at the transition regions of the sleeve/tube assembly depends upon the signal-to-noise ratio between the degradation response and the transition response. As a general rule, lower frequencies tend to suppress the transition signal relative to the degradation signal at the expense of the ability to quantify. Similarly, the inspection of the tube through the sleeve requires the use of low frequencies to achieve detection with an associated loss in quantification. Thus, the search for an optimum eddy current inspection represents a trade-off between detection and quantification. With the crosswound coil type inspection, this optimization leads to a primary inspection frequency for the sleeve on the order of [ ]^{a,c,e} and for the tube and transition regions on the order of [ ]^{a,c,e}

Figure 6.1-2 shows a typical [ ]^{a,c,e} phase angle versus degradation depth curve for the sleeve from which OD sleeve penetrations can be assessed.

In the regions of the parent tube above the sleeve, conventional bobbin coil or crosswound coil inspections will continue to be used. However, since the diameter of the sleeve is smaller than that of the tube, the fill factor of a probe inserted through the sleeve may result in a decreased detection capability for tubing degradation. Thus, it may be necessary to inspect the unsleeved portion of the tube above the sleeve by inserting a standard size probe through the U-bend from the unsleeved leg of the tube.

For the tube sleeve combination, the use of the crosswound probe, coupled with a multifrequency mixing technique for further reduction of the remaining noise signals significantly reduces the interference from all discontinuities (e.g. transition) which have 360-degree symmetry, providing improved visibility for discrete discontinuities. As is shown in the accompanying figures, in the laboratory this technique can detect OD tube wall penetrations with acceptable signal-to-noise ratios at the transitions when the volume of metal removed is equivalent to the ASME calibration standard.

a,c,e

Figure 6.1-2 - [ ][a,c,e] Calibration Curve

The response from the tube/sleeve assembly transitions with the crosswound coil is shown in Figures 6.1-3, 6.1-4, and 6.1-5 for the sleeve standards, tube standards and transitions, respectively. Detectability in transitions is enhanced by the combination of the various frequencies. For the cross-wound probe, two frequency combinations are shown; [

]^{a,b,c,e} Figure 6.1-6 shows the phase/depth curve for the tube using this combination. As examples of the detection capability at the transitions, Figures 6.1-7 and 6.1-8 show the responses of a 20 percent OD penetration in the sleeve and 40 percent OD penetration in the tube, respectively.

For inspection of the region at the top end of the sleeve, the transition response signal-to-noise ratio is about a factor of four less sensitive than that of the expansions. Some additional inspectability has been gained by tapering the wall thickness at the top end of the sleeve. This reduces the end-of-sleeve signal by a factor of approximately two. The crosswound coil, however, again significantly reduces the response of the sleeve end. Figure 6.1-9 shows the response of various ASME tube calibration standards placed at the end of the sleeve using the cross-wound coil and the [ ]^{a,c,e} frequency combination. Note that under these conditions, degradation at the top end of the sleeve/tube assembly can be detected.

6.2 SUMMARY

Conventional eddy current techniques have been modified to incorporate the more recent technology in the inspection of the sleeve/tube assembly. The resultant inspection of the sleeve/tube assembly involves the use of a cross-wound coil for the straight regions of the sleeve/tube assembly and for the transition regions. The advent of MIZ-18 digital E/C instrumentation and its attendant increased dynamic range and the availability of 8 channels for four raw frequencies has expanded the use of the crosswound coil for sleeve inspection. While there is a significant enhancement in the inspection of portions of the assembly using the cross-wound coil over conventional bobbin coils, efforts continue to advance the state-of-the-art in eddy current

a,c,e

[ ]

Figure 6.1-6 - Eddy Current Calibration Curve for ASME Tube Standard at [ ]a,c,e and a Mix Using the Cross Wound Coil Probe

a,c,e

Figure 6.1-3 - E.C. Signals from the ASTM Standard, Machined on the Sleeve O.D. of the Sleeve-Tube Assembly Without Expansion (Cross Wound Coil Probe)

a,c,e

Figure 6.1-4 - E.C. Signals from the ASTM Standard, Machined on the Tube O.D. of the Sleeve-Tube Assembly Without Expansion (Cross Wound Coil Probe)

a,c,e

Figure 6.1-5 - E.C. Signals from the Expansion Transition Region of the Tube-Sleeve Assembly (Cross Wound Coil Probe)

a,c,e

Figure 6.1-7 - E.C. Signal from a 20% Deep Hole, Half the Volume of ASTM Standard, Machined on the Sleeve O.D. in the Expansion Transition Region of the Sleeve-Tube Assembly (Cross Wound Coil Probe)

a,c,e

Figure 6.1-8 - E.C. Signal from a 40% ASTM Standard, Machined on the Tube O.D. in the Expansion Transition Region of Sleeve-Tube Assembly (Cross Wound Coil Probe)

a,c,e

Figure 6.1-9 - Eddy Current Response of the ASME Tube Standard at the End of the Sleeve Using the Cross Wound Coil Probe and Multifrequency Combination inspection techniques. As advanced state-of-the-art techniques are developed and verified, they will be utilized. For the present, the cross-wound coil probe represents an inspection technique that provides additional sensitivity and support for eddy current techniques as a viable means of assessing the tube/sleeve assembly.

7.0 ALARA CONSIDERATIONS FOR SLEEVING OPERATIONS

The repair of steam generators in operating nuclear plants requires the utilization of appropriate dose reduction techniques to keep radiation exposures As Low As Reasonably Achievable (ALARA). Westinghouse maintains an extensive ALARA program to minimize radiation exposure to personnel. This program includes: design and improvement of remote and semi-remote tooling, including state-of-the-art robotics; decontamination of steam generators; the use of shielding to minimize radiation exposure; extensive personnel training utilizing mock-ups; dry runs; and strict qualification procedures. In addition, computer programs (REMS) exist which can accurately track radiation exposure accumulation.

The ALARA aspect of the tool design program is to develop specialized remote tooling to reduce the exposure that sleeving personnel receive from high radiation fields. A design objective of a remote delivery sleeving system is to eliminate channel head entries and to complete the sleeving project with total exposures kept to a minimum, i. e., ALARA. A manipulator arm can be installed on a fixture attached to the steam generator manway after video cameras and temporary nozzle covers have been installed. A control station operator (CSO) then manually operate controls to guide the manipulator arm through the manway and attach a baseplate to the tubesheet. The installation of the arm requires only one platform operator to provide visual observation and assistance with cable handling from the platform. The control station for the remote delivery system is located outside containment in a specially designed control station trailer. As previously indicated, under some conditions positioning of sleeve/tooling with the base Robotic system may not be practical. In these circumstances alternate techniques may be utilized, such as hands-on (manual position, alternate robotic or semi-remotely operated equipment or a combination of the two.

The control of personnel exposures can also be effected by careful planning, training, and preparation of maintenance procedures for the job. This form of administrative control can help to provide that the minimum number of personnel will be used to perform the various tasks. Additional methods of minimizing exposure include the use of remote TV and radio surveillance of all platform and channel head operations and the monitoring of personnel exposure to identify high exposure areas. Local shielding will be used whenever possible to reduce the general area background radiation levels at the work stations inside containment.

7.1 NOZZLE COVER AND CAMERA INSTALLATION/REMOVAL

The installation of temporary nozzle covers in the reactor coolant pipe nozzles in preparation of the steam generators for sleeving operations may require channel head entries. The covers are installed to prevent the accidental dropping of any foreign objects (i.e., tools, nuts, bolts, debris, etc.) into the reactor coolant loops during sleeving operations. In the event that an accident did occur, an inspection of the loop would be required and any foreign objects or debris found would be retrieved. The impact on schedule and radiation exposures associated with these recovery operations would far exceed the time and exposures expended to install or remove loop nozzle covers. Consequently, it is considered an ALARA-efficient procedure to utilize temporary nozzle covers during sleeving operations.

The use of video monitoring systems to observe robotic operations in the channel head may require manual installation. The installation of overview cameras to monitor sleeving operations may require a full or partial channel head entry.

The installation and removal of this equipment in the steam generators are the only anticipated potentials requirements for channel head entries during the sleeving project.

7.2 PLATFORM SETUP/SUPERVISION

The majority of the radiation exposures recorded for the sleeving program is expected to result primarily from personnel working on or near the steam generator platforms and in the channel head for hands-on operations. The setup and checkout of equipment for the various sleeving processes, installation/removal of tooling, and the operation of the tooling are the major sources of radiation exposure. In addition to channel head video monitoring systems, visual monitoring and supervision by one or more workers on the platform will be required for a major part of the sleeving schedule. Experience has shown that rapid response to equipment adjustment requirements is efficiently accomplished by having a platform worker standing by in a relatively low radiation area during operations. Worker standby stations have ranged from the low radiation fields behind the biological shield to lead blanket shielding installed on the platform. Even though radiation levels on the platform are much lower than channel head levels, a substantially larger amount of time will be spent on the platforms giving rise to personnel exposures. An evaluation of radiation surveys around the steam generators should indicate appropriate standby stations.

7.3 RADWASTE GENERATION

The surface preparation of tubes for the installation of sleeves requires that the oxide film be removed by a honing process. A flexihone attached to a flexible rotating cable will be used to remove the oxide film on the inside surface of the steam generator tubes. The volume of solid radwaste is expected to consist of spent hones, flexible honing cables, hone filter assemblies (optional), [ ]a,c,e and the normal anti-C consumables associated with steam generator maintenance. The anti-C consumables are the utility's responsibility and will not be addressed in this report.

For the [ ]a,c,e approximately thirty tubes can be honed before the hone is changed for process control and [ ].a,c,e A typical estimate of the radioactive concentration from a honed tube transported by the [ ]a,c,e is given in Table 7.3-1. These concentrations are based on a general area radiation level of 4R/HR. The tube hones as well as the tubes [ ]a,c,e Consequently, radiation levels of the spent hones are normally 1-2 r/hr based on field measurements in previous sleeving projects.

TABLE 7.3-1

ESTIMATE OF RADIOACTIVE CONCENTRATION IN WATER PER TUBE HONED (TYPICAL)

a,c,e

[ ]

ASSUMPTIONS

1) Tube honed 45 inches (in length)

2) Water flow rate of 0.6 gallons per tube honed

3) Essentially all radioactivity removed from tubes honed.

The flexible honing cable used to rotate the hone inside the tubes is also flushed during the honing process. However, the construction of the stainless steel cable will cause radioactivity to build up over the course of the project. Radiation levels on segments of the cable could reach 5-10 R/Hr contact dose rates for major sleeving jobs. It is expected that an average of one cable per steam generator will be used during the sleeving project. The cables are consumables and are drummed as solid radwaste.

7.4 HEALTH PHYSICS PRACTICES AND PROCEDURES

The Health Physics (HP) requirements for sleeving will be those establshed by the licensee. Westinghouse will provide radiological engineering assistance, as needed, to assist in coordination of the radiological aspects of the Westinghouse activities. Open communications between involved parties will be maintained so that the best possible health physics practices can be established for the sleeving program. The HP procedures of the utility will be the guidelines followed during the sleeving operation. However, in specific instances where beneficial changes to the techniques are mutually recognized but not covered in these HP procedures, appropriate changes will be made according to established change procedures.

The field service procedures which are prepared by Westinghouse for the complete setup of equipment and subsequent sleeving operations include the specific radiologically related responsibilities, prerequisites and precautions. These will further minimize exposure and control contamination.

Mockup training at the Westinghouse Waltz Mill Training Center includes the following radiological practices:

- o Technical skill training while dressed in full Anti-C clothing including bubble hoods.

- o Identification of high radiation zones on the work platform and emphasis of minimizing stay times.

- o Handling of contaminated tools and changeout of contaminated mandrels.

- o Location and use of waste disposal containers.

Westinghouse implements an extensive training and qualification program to prepare supervisory, maintenance and operations personnel for field implementation of the sleeving process. Satisfactory completion of this training program verifies that the personnel addressed are qualified to perform all assigned operations from a technical as well as radiological aspect in keeping with the ALARA principals.

The qualification program consists of two phases:

Phase I - classroom
Phase II - mockup

Phase I - Consists of classroom training and addresses subject material that is related to the overall sleeving program. The Phase I instructors generate and administer an examination for Phase I training of sufficient difficulty to demonstrate that a trainee has sufficient knowledge of the material presented. This examination is written. All trainees will be tested. A minimum grade of 80 percent is required. The test results shall be documented and retained for audit.

Phase II - Consists of hands-on and mockup sleeving training during which the trainee must demostrate a capability to perform a function or operation in a limited amount of time. If team training is required, each trainee must be able to perform all tasks required of the team.

7.5 AIRBORNE RELEASES

The implementation of the proposed sleeving processes in operating nuclear plants has indicated that the potential for airborne releases is minimal. The major operations include [ ]^{a,c,e} and sleeve installation.

Experience has shown that these sleeving processes do not contribute to airborne releases.

7.6 PERSONNEL EXPOSURE ESTIMATE

The total personnel exposures for steam generator sleeving operations will depend on several plant dependant and process related factors. These may include, but not be limited to; the scope of work (quantity of sleeves, etc), plant radiation levels, ingress/egress to the work stations, equipment performance and overall cognizance of ALARA principles. Consequently, the projection of personnel exposures for each specific plant must be performed at the completion of mockup training when process times for each operation have been recorded. The availability of plant radiation levels and worker process times in the various radiation fields will provide the necessary data to project personnel exposure for the sleeving project.

The calculation of the total MAN-REM exposure for completing a sleeving project may typically be expressed as follows:

$$P = ((N_s \cdot D_s) + S_g) \cdot N_g$$

P = Project total exposure (MAN-REM)

N_s = Number of sleeves installed/steam generator

D_s = Exposure/sleeve installed

S_g = Equipment setup/removal exposure per steam generator

N_g = Number of steam generators to be sleeved

This equation and appropriate variations are used in estimating the total personnel exposures for the sleeving project.

Man-rem exposure results obtained during a recent Westinghouse steam generator sleeving operation showed approximately 50 to 100 millirem/tube, using the Remote Operating Service Arm (ROSA).

Man-rem exposure results obtained from recent Westinghouse steam generator manual sleeving operations show approximately 300 man-rem for sleeving of 650 tubes. This estimate is based on chemical decontamination of the steam generator channel heads including approximately 4 feet inside the steam generator tubes with a resulting field of approximately 4 R/HR.

8.0 INSERVICE INSPECTION PLAN FOR SLEEVED TUBES

In addressing current NRC requirements, the need exists to perform periodic inspections of the supplemented pressure boundary. This new pressure boundary consists of the sleeve with a joint at the primary face of the tubesheet and a joint at the opposite end of the sleeve.

The inservice inspection program will consist of the following. Each sleeved tube will be eddy current inspected on completion of installation to obtain a baseline signature to which all subsequent inspections will be compared. Periodic inspections to monitor sleeve wall conditions will be performed in accordance with the inspection section of the plant Technical Specifications. This inspection will be performed with multi-frequency eddy current equipment.

Periodic pressure testing of the steam generator, similar to that performed following tube plugging will be performed as recommended in the technical manual.