TOLEDO
EDISON

RICHARD P. CROUSE
Vice President
Nuclear
(419) 259-5221

Docket No. 50-346
License No. NPF-3
Serial No. 1029
March 9, 1984

Director of Nuclear Reactor Regulation
Attention: Mr. John F. Stolz
Operating Reactor Branch No. 4
Division of Operating Reactors
United States Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Mr. Stolz:

This letter is submitting the "Babcock & Wilcox 177 Fuel Assembly Owner's Group Safe End Task Force Report on Generic Investigation of HPI/MU Nozzle Cracking (B&W Document Number: 77-1140611-00) as it relates to Davis-Besse Nuclear Power Station Unit No. 1 (DB-1).

The purpose of this report is to summarize the Safe-End Task Force's (SETF) involvement in the high pressure injection/makeup (HPI/MU) nozzle cracking problems. Formed by the Babcock & Wilcox (B&W) 177 Fuel Assembly Owner's Group, the Task Force has identified the root cause of the failures, recommended modifications to eliminate future failures, and identified studies to support modifications on a long term basis.

Section 15 of the report contains the recommendations by SETF for the B&W plants. Davis-Besse specific commitments are provided below. The reason for the difference from the SETF recommendation is that during plant construction the nozzles were found to be loose and they were re-rolled (hard rolled instead of contact expanded as originally specified). The inspections of the nozzles during 1982 and 1983 refueling outages showed the thermal sleeves were in position and tight with no deterioration of the weld buttons (restraints).

Davis-Besse commitments for Section 15:

1. In keeping with the long standing Toledo Edison policy to repair and/or replace damaged components, the following commitment is made for future repairs of nozzles with original design thermal sleeves. If, by means of the augmented ISI plan, gap formation is detected, Toledo Edison will reroll the upstream end of the thermal sleeve to a known maximum of 5% wall reduction. It is felt that future repairs are of a low probability due to the corrective action taken by Toledo Edison in 1977 to upgrade the contact expansion of the thermal sleeves to a hard roll, e.g., wall thinning (reference Section 3.2

A001 1/1 Lgantest Dust

and Table 1, Note 5). With respect to this corrective action, the most probable root cause of failure of the thermal sleeves, e.g., variations in contact expansion, was eliminated at Davis-Besse.

2. HPI/MU system operation will continue to be bounded by the Babcock & Wilcox recommendation of 1-3 gpm continuous bypass makeup flow as established by Davis-Besse System Procedure 1104.02, Makeup and Purification System. This is supported by the 1982 and 1983 radiographic examinations that showed no abnormalities after approximately 3.01 EFPY.

3. Toledo Edison hereby commits to the augmented in-service inspection plan of Section 12 for both MU and HPI nozzles of Category 3, Repaired Nozzles (rerolled), with the following exception: RT during the DB-1 second refueling outage to ensure that the thermal sleeve is in proper location and no gap has formed. RT again at the DB-1 third, fifth and seventh refueling outages and every fifth refueling outage thereafter. This exception is predicated on the effective corrective action by Toledo Edison in 1977 (pre-operation) and confirmed by radiographic examinations in 1982 and 1983. These inspections revealed that the Davis-Besse MU/HPI thermal sleeves are tight (no gap) and in place with no deterioration of the weld buttons. This exception is justified by Section 14 (conclusions) Item 3: If continued inspections show that the sleeves are properly in place, it is not expected that the sleeves will loosen during plant operation prior to subsequent inspections.

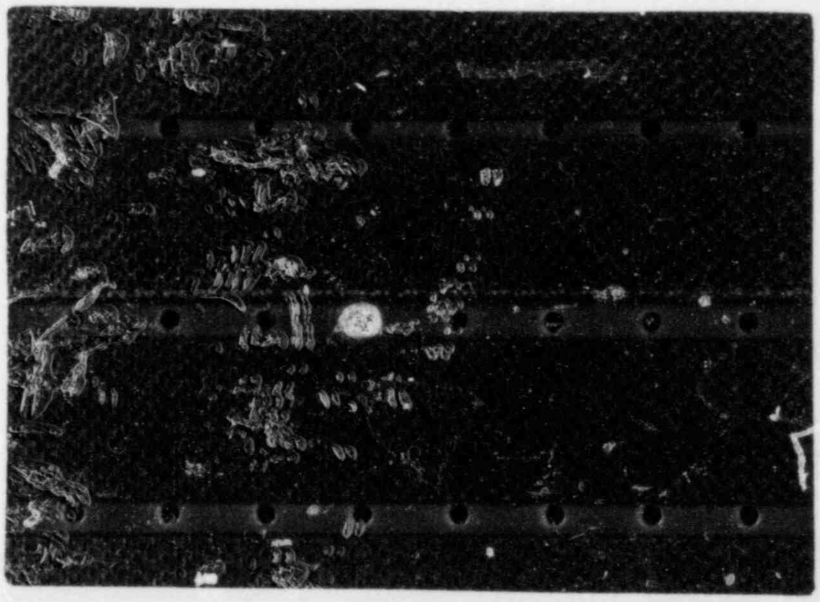
4. Not applicable to Davis-Besse.

Very truly yours

RP Crouse /KDM

RPC:GAB

cj a/9



Engineering Services

Dupe
~~8302220423~~
PDR 70pp.

Babcock & Wilcox
a McDermott company

BABCOCK & WILCOX
177 FUEL ASSEMBLY OWNER'S GROUP
SAFE END TASK FORCE REPORT
ON
GENERIC INVESTIGATION OF
HPI/MU NOZZLE COMPONENT CRACKING

B&W Document Number: 77-1140611-00

Prepared for

Arkansas Power & Light Company
Consumers Power Company
Duke Power Company
Florida Power Corporation
Sacramento Municipal Utilities District
Toledo Edison Company

by

The Babcock & Wilcox Company
Utility Power Generation Division
Lynchburg, Virginia

TABLE OF CONTENTS

	PAGE
1.0 EXECUTIVE SUMMARY	1
2.0 INTRODUCTION	2
2.1 Background	2
2.2 Scope	5
2.3 Results	6
2.4 Organization	7
3.0 COMPILATON OF FACTS	8
3.1 Failure Analyses	8
3.2 Matrix of Facts	11
4.0 REVIEW OF INDUSTRY EXPERIENCE	14
5.0 CRYSTAL RIVER-3 INSTRUMENTED NOZZLE DATA EVALUATION	17
6.0 ANALYTICAL INVESTIGATION OF EXISTING DESIGN	19
7.0 POSSIBLE ROOT AND CONTRIBUTORY CAUSES	21
8.0 PROBABLE FAILURE SCENARIO	25
9.0 TESTS TO SUBSTANTIATE THE ROOT CAUSE	27
10.0 MODIFIED THERMAL SLEEVE DESIGN	30
10.1 Conceptual Designs	30
10.2 Design Improvements	31

TABLE OF CONTENTS (cont'd)

		PAGE
11.0	MAKEUP SYSTEM OPERATING CONDITIONS	33
12.0	AUGMENTED INSERVICE INSPECTION PLAN	34
13.0	JUSTIFICATION OF LONG TERM OPERATION	36
	13.1 Analytical Justification	36
	13.2 Experimental Justification	38
14.0	CONCLUSIONS	39
15.0	RECOMMENDATIONS	40
16.0	REFERENCES	42

LIST OF FIGURES

Title

1. Typical Elevation View of Reactor Coolant System Arrangement Showing Location of HPI Nozzle

2. Typical Plan View of Reactor Coolant System Arrangement Showing Location of HPI Nozzle

3. Typical HPI and HPI/MU Nozzle

4. Typical Layout of HPI and HPI/MU Line

5. Safe-End Task Force Action Plan

6. Instrumentation Arrangement at Crystal River-3

7. "Goodness of Roll" Results

8. Hard Rolled HPI/MU Nozzle Concept

9. Integral HPI/MU Nozzle Concept

10. Flanged HPI/MU Nozzle Concept

11. Roll Expansion Test Schematic Diagram of Test Fixture

12. HPI/MU Static Test Results

13. HPI/MU Nozzle Test Results - Transient Load Tests (Phase IIA)

14. HPI/MU Nozzle Test Results - Vibration Test (No Free End Restraint)

15. Natural Vibration Frequency Test Schematic Diagram

1.0 EXECUTIVE SUMMARY

The purpose of this report is to summarize the Safe-End Task Force's involvement in the high pressure injection/makeup (HPI/MU) nozzle cracking problems which affected Crystal River-3, Oconee-3, Oconee-2, Arkansas Nuclear One-1, and Rancho Seco. Formed by the Babcock & Wilcox (B&W) 177 Fuel Assembly Owner's Group, the Task Force has identified the root cause of the failures, recommended modifications to eliminate future failures, and identified studies to support these modifications on a long term basis.

Site inspections conducted in February-April 1982 indicated that both the HPI only nozzles and the double-duty HPI/MU nozzles were affected. Loose, out-of-place, and cracked thermal sleeves were observed in 6 of the HPI only nozzles, while 4 of the double-duty nozzles also contained cracked safe-ends. Failure analyses indicated that the cracks were initiated on the inside diameter and were propagated by thermal fatigue. The cracked safe-end at Crystal River also contained mechanically initiated outside diameter cracking which appeared to be unrelated. Previous inspections at two plants (Davis Besse-1 and Three Mile Island-2) under construction revealed that one of the Davis Besse sleeves was loose. All four sleeves were subsequently re-rolled at Davis Besse (hard rolled, instead of contact expanded as originally specified). Recent inspections at Midland have also shown that gaps may be present between the thermal sleeve and safe-end in the contact expanded joint. These findings along with stress analysis and testing have implicated insufficient contact expansion of the thermal sleeves as the most probable root cause of the failures.

With this in mind, B&W has recommended modifications to the design, operation and inspection of the HPI/MU nozzles. A hard rolled thermal sleeve design has been developed which helps prevent thermal shock to the nozzle assembly and helps reduce flow induced vibrations more effectively. An increase in minimum continuous makeup flow has been suggested to help prevent thermal stratification in the MU line and more effectively cool the safe-end. An inservice inspection (ISI) plan has also been developed to provide a means of early problem detection.

2.0 INTRODUCTION

On January 24, 1982, normal monitoring of the Crystal River-3 reactor coolant system (RCS) indicated an unexplained loss of coolant. After an orderly plant shutdown, the double duty high pressure injection makeup (HPI/MU) nozzle check valve-43 was identified as the source. The valve, the valve to the safe-end weld, the safe-end, and the thermal sleeve were cracked as a result of thermal and/or mechanical fatigue. Inspections at other Babcock & Wilcox (B&W) operating plants indicated similar types of cracking, but to a lesser extent. As a result, the Safe-End Task Force (SETF) was formed to compile the pertinent facts and to determine a most probable root cause for the failures. Since the failures were apparently generic in nature, the following report was compiled describing the Task Force's investigation. Specifically, the relevant facts and most probable failure scenario are presented, as well as recommended modifications to the thermal sleeve design, makeup system operating conditons and inservice inspection (ISI) plan.

2.1 Background

On the 145, 177 and 205 fuel assembly (FA) plants, four HPI/MU nozzles (one per cold leg) are used to: (1) provide a coolant source for emergency core cooling, and (2) supply normal makeup (purification flow) to the primary system (see Figures 1 and 2). In general, one or two of the nozzles are used for both HPI and MU, while the remaining nozzles are used for HPI alone.

The incorporation of a thermal sleeve into a nozzle assembly is a common practice in the nuclear industry (See Figure 3). The function of the thermal sleeve is to provide a thermal barrier between the cold HPI/MU fluid and the hot high pressure injection nozzle. This helps prevent thermal shock and fatigue of the nozzle. The purpose of the safe-end is to make the field weld easier (pipe to safe-end) by allowing similar metals to be welded. The dissimilar metal weld between the safe-end and the nozzle can then be made under controlled conditions in the vendor's shop. The use of the safe-end also eliminates the need to do any post-weld heat treating in the field.

While monitoring the Crystal River-3 RCS for unidentified leakage, a notable increase was observed on January 24, 1982. On January 25, a further increase in leakage was observed and the unit was subsequently placed in Hot Standby on January 28. The check valve (MUV-43) to safe-end weld on the double duty HPI/MU nozzle contained a thru-wall circumferential crack which caused the leak. Following removal of the valve, visual inspection of the safe-end and thermal sleeve revealed that both components were cracked and worn (see Figure 3). Inspection of the other three HPI nozzles indicated that no cracking or wear was present, and no sleeve movement had occured.

Following the incident at Crystal River-3, letters were issued to each of the B&W 177 FA utilities informing them of the discoveries at Crystal River-3. Inspections were performed at all 177 FA plants to determine whether the problem was site-specific, or generic in nature.

Oconee-1 was shutdown for refueling when Duke Power received B&W's correspondence. Consequently, Oconee-1 was the first unit to be inspected in detail. Radiographic tests (RT) and ultrasonic tests (UT) of the four suspect nozzles indicated that no abnormal conditions were present in any of the nozzles. These findings suggested that the problem may be site-specific to Crystal River-3.

Oconee-3 was also shutdown at that time for a Once-Through Steam Generator (OTSG) tube leak. Radiography of one of the makeup nozzles (A2) showed that the thermal sleeve was displaced about 5/8 inch upstream from its normal location. The radiographic test also revealed that a gap was present between the outside diameter (OD) of the thermal sleeve and the inside diameter (ID) of the safe-end in the contact expanded region. The weld buttons in the safe-end, which prevent upstream motion of the thermal sleeve, had been worn away (see Figure 3). Weld buttons in the nozzle throat, which prevent downstream motion of the thermal sleeve, were still present, but were worn. A UT of the nozzle also revealed that cracking was present. Given these indications, the HPI/MU piping and warming line were cut

from the safe-end and a dye penetrant test (PT) of the safe-end and associated hardware was conducted (see Figure 4). The safe-end, thermal sleeve, spool piece and warming line were cracked. Subsequent RT's of the remaining nozzles revealed that the other makeup nozzle (A1) and one of the HPI nozzles (B2) were not damaged and the thermal sleeves were in position. However, the other HPI nozzle (B1) had a .030 inch gap between the thermal sleeve OD and the safe-end ID as indicated by the RT.

With the cracking problem substantiated at Oconee-3, Duke quickly inspected their Oconee-2 unit. Three of the Oconee-2 nozzles contained anomalies: (1) the makeup nozzle (A2) had a cracked safe-end and a loose thermal sleeve, (2) the HPI nozzle (B1) had a 1/32 inch gap between the thermal sleeve and safe-end as indicated by the RT, and (3) the HPI nozzle (B2) had a tight thermal sleeve which contained a circumferential crack in the roll expanded region.

Inspections at four other operating plants were also conducted. The thermal sleeves at Davis Besse-1 and Three Mile Island-1 (TMI-1) were in position and tight. No cracking was observed and the weld buttons were not worn. However, inspections at Arkansas Nuclear One-1 (ANO-1) and Rancho Seco indicated that abnormal conditions were present at these sites. At ANO-1, three problems were discovered: (1) one HPI nozzle (A1) had a loose sleeve, (2) one HPI nozzle (A2) had a tight sleeve with a partial gap indicated by radiography between the sleeve and safe-end, and (3) the HPI/MU nozzle (B2) had a tight sleeve which contained a circumferential crack in the roll expanded region (similar to the Oconee-2(B2) failure). At Rancho Seco, two problems were discovered: (1) the HPI nozzle (A1) had a loose sleeve, and (2) the HPI/MU nozzle (A2) had a cracked safe-end and a missing thermal sleeve.

Inspections at two plants under construction, Midland and North Anna, were also conducted to determine the conditions present prior to initial plant startup. Radiographs of the two Midland units indicated that a number of the nozzles may have gaps between the thermal sleeve

and safe-end. Supplemental visual inspections revealed that all 8 sleeves were tight and in place. However, one of the HPI thermal sleeves on Unit 2 was conspicuously skewed relative to the safe-end center line. Visual inspections at North Anna revealed that one sleeve had a partial gap in the rolled region, but the sleeve was tight and in place. The length of the rolled region was also observed to vary between 1 1/2 and 2 inches at North Anna. In addition, the TMI-2 and Davis Besse-1 nozzles were inspected in 1971 while the plants were under construction. At TMI-2, all 4 HPI/MU nozzles were inspected and no defects were observed. However, at Davis Besse-1, one of the sleeves was found to be loose and all 4 sleeves were subsequently re-rolled (hard rolled, instead of contact expanded).

These findings indicate that loose sleeves, or sleeves with gaps between the thermal sleeve and safe-end, may have been present in other plants prior to initial plant startup.

2.2 Scope

Given this background information, the Task Force chose to approach the problem from a generic standpoint (see Figure 5 for the Task Force Action Plan). To do this, a root cause(s) must be first identified, and then a generic solution could be recommended. To determine the root cause(s), the following tasks were performed:

1. reviewed manufacturing data
2. compiled and compared site specific facts and inspection results
3. evaluated metallurgical examinations
4. reviewed industry experience
5. evaluated data from the instrumented Crystal River-3 HPI/MU nozzle
6. evaluated the existing design analytically
7. postulated possible failure scenarios
8. determined a most probable root cause(s)

Having determined a most probable root cause(s), a solution was developed which addressed:

1. modified thermal sleeve design for the damaged nozzles
2. makeup system operating conditions
3. augmented inservice inspection plan

Finally, B&W also proposed studies to demonstrate the adequacy of the recommended fix on a long term basis.

2.3 Results

Results of the investigation indicate the following facts:

1. The thermal sleeve manufacturing installation procedure called for a contact roll of the thermal sleeve, not a hard roll.

2. Varying degrees of contact expansion rolls could be performed even for the same plant.

3. Gaps between the thermal sleeve and safe-end have been found in plants under construction.

4. All cracked safe-ends were associated with loose thermal sleeves. However, not all loose thermal sleeves had safe-ends that were cracked.

5. All cracked safe-ends were associated with the makeup nozzle.

6. A makeup nozzle may be subject to random and continuous makeup flow oscillations.

7. The cracks found were ID initiated (Crystal River-3 OD crack initiation appeared to be unrelated).

8. The cracks were propagated by thermal fatigue.

9. Where controlled hard rolling of the thermal sleeve was accomplished, no failures have occurred.

10. Oconee-1, which has the most operating experience, contained no abnormal conditions when recently inspected. Oconee-1 is the only plant which uses a double thermal sleeve design.

2.4 Organization

This report has been organized to address three primary questions:

1. How did the Task Force determine the root cause of the problem?

2. What modifications (design, operation, inspection) were made to correct the problem?

3. What was done to justify these modifications?

Specifically, sections 3 through 9 describe what was done to determine a most probable root cause, sections 10 through 12 describe what modifications were suggested, and section 13 supplies the justification for these modifications. In addition, sections 14 and 15 summarize the conclusions and recommendations of this investigation.

3.0 COMPILATION OF FACTS

Following the incidents at Crystal River-3 and Oconee, the Safe-End Task Force requested that B&W compile a list of facts concerning the HPI/MU nozzle cracking problem, such that possible correlations between plants could be identified. To accomplish this task, B&W reviewed the manufacturing records and the site specific failure analysis reports, and then developed a matrix of facts.

3.1 Failure Analyses

Failure analyses were performed on four of the units (Crystal River-3, Oconee-3, Oconee-2, and Arkansas Nuclear One-1). These studies were conducted to determine the most probable method of crack initiation and propagation. The results are as follows:

Crystal River-3/Florida Power Corporation

While the repair efforts were being completed on the Crystal River-3 unit, the cracked safe-end and thermal sleeve of the HPI/MU nozzle (A1) were sent to B&W's Lynchburg Research Center (LRC), and the cracked valve and section of pipe near MUV-43 were sent to Battelle Columbus Laboratories for failure analysis.

The results of the LRC study indicated that both the sleeve and the safe-end most likely failed by thermal fatigue. Cracking initiated on the ID of both components and was transgranular. The thermal sleeve cracking was confined to the roll expansion area only. The safe-end was cracked in the valve end down to the seating area of the thermal sleeve. Extensive wear was found on the safe-end ID and the thermal sleeve OD in the region of roll expansion of the sleeve into the safe-end. From this and other surface damage, it was concluded that the sleeve had become unseated and was probably rotating due to flow forces. Evidence to confirm or refute whether the sleeve had been roll expanded on installation was not conclusive.[1]

Battelle's inspection of the pipe section revealed that separate circumferential cracks from the inside diameter (ID) and the outside diameter (OD) on half of the pipe section were present, as well as multiple longitudinal cracks. The circumferential crack on the ID was associated with a machine tool mark, while the crack on the OD was associated with the valve to weld bead discontinuity. Fractographic evidence suggested that fatigue was responsible for both the ID and OD circumferential cracks. Metallography showed that the cracks were transgranular. The ID cracks were believed to have initiated by thermal fatigue caused by (1) turbulent mixing of hot and cold water during makeup system additions, and/or by (2) periodic chilling of not metal during makeup system additions. Crack propagation probably occurred by combined thermal and mechanical loading of the system. The OD crack is believed to have initiated and propagated by mechanical loading of the system.[2]

Oconee-3/Duke Power

The LRC examined the safe-end, thermal sleeve, spool piece, and warming line of the damaged Oconee-3 makeup nozzle (A2) (See Figures 3 and 4). Component failures were due to thermal fatigue as with Crystal River; however, the cracking was not as deep or as widespread. The cracking was transgranular and confined to three regions:

1. the roll expanded end of the thermal sleeve

2. the safe-end ID from the upstream edge of the thermal sleeve seat to the spool piece weld

3. the spool piece from the safe-end to about 2 inches upstream of the warming line tee

In addition, evidence of wear was found on the thermal sleeve OD and the safe-end ID in the area of the contact expansion seat. As with the Crystal River components, this suggests that the thermal sleeve had become unseated and was rotating/vibrating due to flow forces.[3]

Oconee-2/Duke Power

B&W's LRC also peformed the metallurgical examination of the Oconee-2 HPI nozzle (B2) thermal sleeve. This sleeve contained a visually observable crack extending approximately 270° around the circumference located about 1 1/2 inches from the roll expanded end of the sleeve. This large crack was transgranular and at one location was shown to be propagating from ID to OD. A small axial branch of this crack contained some fatigue striations, but the bulk of the fracture surface could not be interpreted due to heavy oxidation and damage incurred during removal. Metallographic examination also revealed shallow (<3 mils) transgranular cracking on the OD near the large crack. This sleeve did not contain a large amount of wear compared to the Oconee-3 and Crystal River sleeves; however, the downstream collar contained a peened surface along a 180° arc (See Figure 3). In general, the basic failure mode appeared to be transgranular fatigue as occurred in the Crystal River and Oconee-3 thermal sleeves, but the arrangement of the cracking pattern and differences in surface damage suggested that the stress state required to create this failure was either different, or more dominant than in the previous failures.[4]

Arkansas Nuclear One-1/Arkansas Power & Light

The Lynchburg Research Center also performed a metallurgical examination of the ANO-1 HPI/MU nozzle (B2) thermal sleeve. The sleeve contained a visible crack extending approximately 270° around the circumference located about 1 1/2 inches from the roll expanded end of the sleeve. The crack was transgranular, had propagated by fatigue, and followed a machining mark. No axial cracking was present. The collar end of the sleeve showed damage to the collar itself approximately 180° around the circumference. Below this damaged area, approximately 90° apart, two gouged out areas were also present. The failure mode of this sleeve appeared to be similar in nature to that suggested for the Oconee-2 thermal sleeve.[5]

3.2 Matrix of Facts

While the failure analysis studies were being conducted, a site specific matrix of facts was compiled. Five major areas were addressed: (1) system characterization, (2) component characterization, (3) operating conditions, (4) unit operation, and (5) inspection results. Within each specific area, the following items were included:

1. System Characterization
   - loop designation
   - nozzle type (HPI/MU)
   - pipe layout
   - pump characterization
     - rotation (CW/CCW)
     - distance from pump discharge
     - number of impeller vanes
     - number of diffuser vanes
   - makeup recirculation control

2. Component Characterization

- thermal sleeve geometry
- safe-end geometry
- thermal sleeve/safe-end interface
- material
- sleeve expansion procedure

3. Operating Conditions

- minimum bypass flow
- total makeup flow
- total HPI flow
- minimum RC pressure to provide net positive suction head (NPSH)
- borated water storage tank (BWST) temperature

4. Unit Operation

- full power years
- reactor trips
- estimated HPI actuations

5. Inspection Results

- gaps between thermal sleeve OD and safe-end ID
- thermal sleeve axial location
- weld button integrity/geometry
- thermal sleeve cracking
- safe-end cracking

Table 1 contains the matrix of facts compiled by B&W. Examination of this table suggests that two possible correlations may exist between HPI/MU nozzle failures and sites.

First, neither of the units operating with RC pumps which contain 7 impeller vanes (Oconee-1 and TMI-1) have ever shown any indications of loosening or cracking of the thermal sleeves. On the other hand, 5 out of 6 units operating with RC pumps which contain 5 impeller vanes have shown indications of loosening or cracking of the thermal sleeves. This implies that the dynamics of the pressure field generated by the RC pumps may lead to flow induced vibration damage. However, these observations may simply reflect design differences among the plants (Oconee-1 uses a double thermal sleeve and TMI-1 uses an Inconel safe-end).

Second, either operating unit which has undergone post-installation inspection or modification (Oconee-1 and Davis Besse-1) has not shown any indications of loosening or cracking when recently inspected. At Oconee-1, a single thermal sleeve was originally installed which extended into the cold leg flowstream approximately 2 1/8 inches less than the sleeves used at the other plants. A number of boiling water reactors (BWR) employing a similar design experienced cracking problems. Consequently, a second longer sleeve was re-rolled inside of the original sleeve. Aside from increasing the overall length of the sleeve assembly, the rolling of the second sleeve may have also resulted in the re-rolling of the original sleeve. The second sleeve also had an interlocking flange which contained 4 axial notches in the flanged region. Weld buttons were placed within these notches to provide additional anti-rotation protection. At Davis Besse-1, an inspection of the HPI/MU nozzles was performed in 1977 prior to operation. One sleeve was found to be loose and all four sleeves were subsequently re-rolled. Consequently, the post-installation modifications and inspections have at least mitigated the problem, and may have completely eliminated the problem.

4.0 REVIEW OF INDUSTRY EXPERIENCE

A literature review of recent nuclear industry experience in cracking problems was performed by B&W. Five events of interest were identified:

Babcock & Wilcox PWR, Indian Point Thermal Sleeve Failure, 1970 [6]

While plugging tubes at the Indian Point-1 facility, fragments of the makeup line thermal sleeve were discovered in the primary side of the steam generator water box. Apparently, the sleeve had failed as a result of thermal fatigue in the sleeve to makeup line welded area. The thermal stresses resulted from the flow and temperature gradients associated with normal plant makeup system operations. The problem was eliminated by (1) using a thermal sleeve assembly made from a solid forging, (2) projecting the thermal sleeve into the RC cold leg an additional 1/2 inch to induce better mixing, and (3) increasing the minimum makeup flow to 5000 lb/hr.

GE - BWR, Feedwater Nozzle/Sparger Cracking, 1974-1980 [7]

From 1974 through 1980, 22 of 23 BWR's inspected had experienced some degree of cracking in their primary system feedwater nozzles. The failures occurred due to thermal fatigue with crack initiation caused by turbulent mixing (high-cycle) and crack propagation caused by intermittent feedwater flow (low-cycle) during startup, shutdown, and hot standby. The "loose sleeve design" was identified as the root cause which allowed bypass flow within the annulus between the sleeve and the nozzle. A tight fitting thermal sleeve to restrict bypass flow was used as an interim fix and a triple thermal sleeve design was recommended as a permanent fix.

GE - BWR, Control Rod Drive Return Line Nozzle Cracking, 1975 [8]

In 1975, 12 BWR's were inspected and found to have cracking in the control rod drive return lines (CRDRL) and the reactor vessel beneath the nozzles. As with the BWR feedwater problem, the failures were attributed to thermal fatigue cracking due to turbulent mixing and intermittent cold water flow. The problem was eliminated by plugging the nozzle and rerouting the CRDRL.

Westinghouse - PWR, Steam Generator Feedwater Line Cracking, 1979 [8-10]

In 1979 cracking was discovered in the steam generator feedwater lines of 5 operating PWR systems. The cracking was attributed to thermal fatigue due to flow stratification in the feedwater lines. Corrosion fatigue was subsequently declared to be the root cause.

Westinghouse - PWR, Loss of Thermal Sleeves in Reactor Coolant System Piping at Certain Westinghouse PWR Power Plants, 1982 [14]

In 1982, 2 Westinghouse PWR's were inspected and found to have missing thermal sleeves in their safety injection (SI) nozzles.

Radiography and ultrasonic examinations confirmed that the 10-inch thermal sleeves were missing from all four SI nozzles at the Trojan nuclear plant. Supplemental inspections of the sleeves in the pressurizer surge line, and normal and alternate charging lines revealed that cracking was present in some of the retaining welds.

At Duke Power's McGuire-1 reactor, radiography and underwater camera inspection revealed that the thermal sleeve in one of the four SI accumulator piping nozzles to RCS cold leg piping was missing. Radiography confirmed that the other three SI sleeves and the pressurizer surge line sleeve were in place. Westinghouse recommended that (1) the loose parts monitoring system be fully operational, and (2) a non-destructive examination be performed to assess the thermal sleeve conditions of the affected systems at the next extended plant outage.

In summary, the following observations can be made:

1. Crack initiation was due to high-cycle thermal fatigue caused by turbulent mixing.

2. Crack propagation was due to low-cycle thermal fatigue caused by intermittent flow of cold water.

3. Tests conducted by Hu et.al. [9] have shown that for loose fitting thermal sleeves, leakage flow (up or down stream) may occur within the annulus between the sleeve and nozzle.

4. Cracking occurs in high stress areas, i.e., counter bore transition, weld discontinuities, nozzles blend radius, etc.

5. All failed components were subjected to a stratified flow caused by low flow rates.

5.0 CRYSTAL RIVER-3 INSTRUMENTED HPI/MU NOZZLE DATA EVALUATION

Following the cracking incident at Crystal River-3, metallurgical examinations of the thermal sleeve, safe-end and spool piece were conducted by the LRC and Battelle as previously discussed. Results of these studies indicated that the cracking was attributable to thermal fatigue. Given this information, qualitative modifications were made to minimize the thermal stresses within the nozzle assembly. Subsequent to this effort, the thermal sleeve was replaced with a modified design, the safe-end was replaced, and the HPI/MU check valve was replaced and relocated approximately 5 inches upstream from its original location.

To verify the structural integrity of the modified HPI/MU nozzle design (see Figure 8) and gain insight into the failures, B&W recommended that the makeup nozzle assembly (A1) be instrumented. Information was required regarding the thermal stresses and vibrational environment associated with normal plant heatup, hot standby, and power operation. To provide this information, 12 thermocouples, 4 welded strain gauges, 4 bonded strain gauges and 2 accelerometers were installed at three axial planes (A, B, and C), as shown in Figure 6.

Evaluation of the data obtained from the instrumented nozzle indicated that:

1. The external temperature of the safe-end (plane B) remains at or near the makeup water temperature, while the thick portion of the nozzle (plane A) tends to follow the RC cold leg temperature.

2. Circumferental temperature gradients were small indicating that no significant "hot spots" or flow stratification was occurring.

3. Several continuous makeup flow rates were tested (1.6, 5.0, 15.0, and 130.0 gallons per minute). In all cases, the safe-end metal temperature did not change, while the nozzle metal temperature changed by a maximum of 20°F.

4. During heatup, the makeup flow cycled approximately every three minutes. The resultant stresses were small.

5. Makeup flow induced vibrations could be detected with the supplemental instrumentation and tended to increase as makeup flow increased. The resultant stresses were small.

6. Nozzle/safe-end stresses due to thermal expansion are smaller than design values.

7. High stresses were recorded while a pipe hanger was being set. This was an isolated occurrence and had no significant influence on the other test results.

For further details, the reader is referred to B&W document 77-1134571-00, "Evaluation of Crystal River-3 HPI/MU Nozzle Testing". [11]

6.0 ANALYTICAL INVESTIGATION OF EXISTING DESIGN

The previous discussion revealed that the thermal stresses in the modified HPI/MU nozzle at Crystal River-3 were within design values. However, no data was obtained for the old nozzle design. Consequently, B&W developed a program to evaluate the original (existing) design. The program consisted of two phases: (1) analytical, and (2) experimental. A discussion of the analytical phase follows, while details of the experimental phase are included in Section 9.

The purpose of the analytical study was two-fold: (1) to determine the relationship between wall thinning of the HPI thermal sleeve during roll expansion and residual stresses at the thermal sleeve to safe-end interface, and (2) to determine if the rolled joint becomes loose during steady-state plant operation, or during the most severe transient (HPI event).

To determine the thermal sleeve thinning to thermal sleeve/safe-end interfacial residual stress relationship, a finite element model was constructed for a radial sector of the assembly in the contact expanded region (See Figure 3). Assuming that a generalized plane strain condition exists within this region and that end effects are negligible, a simple axisymmetric, non-linear, inelastic analysis was performed using the ANSYS Code. [12] Results of this finite element analysis follow; however, these results have not been verified and should be used for information only.

The relationship between thermal sleeve wall thinning and sleeve/safe-end interfacial stress is shown in Figure 7. For wall reductions in the 2-10% range, the resulting interfacial residual stress lies in the 4000-4200 psi range. The residual stress varies in a non-linear fashion which suggests that above a certain degree of wall thinning, probably greater than 5%, the beneficial effects of increased wall thinning are negligible. This non-linear behavior is also characteristic of the axial load carrying capability of the joint (see Figure 12 and Section 9); however, the results cannot be simply correlated due to the number of uncertainties, i.e., coefficient of friction, effective contact area, material properties, etc.

The loosening of the rolled joint during steady-state and most severe transient operation was investigated analytically by imposing appropriate thru-wall temperature variations on the model used to determine interfacial residual stress. The temperature distributions were determined assuming one-dimensional heat transfer. The results show that no gap forms between the sleeve and safe-end during stready-state operation. However, the results indicate that during an HPI event (most severe transient), the thermal sleeve contraction relative to the safe-end causes a small gap to form between the sleeve and safe-end for a short period of time. This characteristic behavior is in agreement with the test results described in Section 9.

7.0 POSSIBLE ROOT AND CONTRIBUTORY CAUSES

Following the discovery of cracking at Crystal River-3, an effort was made to identify possible root and contributory causes. The following causes were hypothesized:

1. Makeup flow conditions maintained outside of design limits - this includes either a low MU temperature, or an incorrect bypass flow rate. In particular, the bypass flow rate may have been set at ambient conditions instead of at operating conditions, or may not have been properly maintained.

2. Excessive cycling of the check valve due to improper valve performance

3. Flow stratification in the MU line due to minimal MU flow

4. Thermal stratification and recirculation in the MU line due to minimal flow

5. Cold working of the thermal sleeve due to roll expansion

6. Stress corrosion cracking of the thermal sleeve due to excessive roll expansion

7. Convective heating of the safe-end due to an air gap in the insulation

8. External loading of the attached piping due to thermal transients

9. Sympathetic vibration of the thermal sleeve due to dynamic pressure field generated by the RC pumps

10. Flow induced vibrations due to cross-flow in the RC cold leg pipe

11. Annular flow between the thermal sleeve OD and the safe-end ID due to insufficient rolling of the thermal sleeves

As additional information was obtained from the failure analysis studies and the site inspections, the validity of these causes could be suitably evaluated. It must also be pointed out that this list was compiled after Crystal River-3; therefore, some of the causes identified are site specific to Crystal River-3 and, thus, do not apply to all of the sites.

Of the 11 postulated causes, the first 4 pertain to the makeup system exclusively. A quick inspection of the matrix of facts, Table 1, reveals that both HPI and MU nozzles were affected. Consequently, any cause(s) which pertain to the MU nozzles alone can only be contributory at best. With this in mind, the validity of each cause was evaluated as follows:

1. Makeup flow control problems due to improper maintenance of minimum bypass flow may have occured at all of the sites. Plant data obtained during heatup and cooldown revealed that makeup flow rates were often unknown to the operators. As such, minimum continuous flow rates may not have been properly maintained which could lead to thermal fatigue of the nozzle components. However, since all of the plants experienced similar flow control problems and only 5 of the operating plants contained anomalies, makeup flow control was probably not the root cause.

2. Excessive cycling of the MU check valve may have contributed to the failure at Crystal River-3, but this was probably an isolated occurrence.

3. Flow stratification in the MU line due to minimal MU flow may have occurred at all of the plants since the same design value (1-3 gpm) was used inclusively. However, the results from the instrumented Crystal River-3 nozzle indicated that no significant circumferential temperature gradients were present, even at the lowest flow rate tested (1.6 gpm). From these findings, it can be inferred that the makeup flow was probably not stratified.

4. Low flow velocities in the MU line could also lead to thermal stratification and recirculation zones in the thermal sleeve. However, since the MU line is predominantly filled with MU flow, the thermal shock to the sleeve should not be too extensive (compared to the flow stratification described in 3). As a result, this can be disregarded as a probable cause.

5. Cold working of the thermal sleeve was not responsible for crack initiation or growth according to the failure analysis reports discussed in section 3.2. Consequently, this cannot be considered a probable cause.

6. Also, stress corrosion cracking due to roll expansion was not observed in the failure analysis studies. Consequently, this too cannot be considered a probable cause.

7. Convective heating of the safe-end via an air gap in the insulation may have contributed to the failure at Crystal River-3; however, since some of the plants are uninsulated, this can be disregarded as a probable cause.

8. Excessive loading of the attached piping due to thermal transients may occur at all of the plants. To ascertain the extent of the thermal transient loading, a structural analysis was performed for the Crystal River-3 piping arrangement. The results indicated that all stresses were well within the allowable design constraints. Therefore, this cause can be disregarded.

9. Sympathetic vibration of the thermal sleeve induced by the motion of the impeller vanes past the discharge port of the RC pumps may have occurred at all of the plants. The matrix of facts, Table 1, indicates that 5 of 6 plants using RC pumps with 5 impeller vanes have shown loosening or damage of the thermal sleeves. In contrast, both plants which use RC pumps with 7 impeller vanes have not shown any signs of failure.

   The results from the instrumented nozzle at Crystal River-3 indicated that the flow induced vibrations (FIV), as measured by strain gauges and accelerometers, were minimal. From these findings, it can be inferred that (1) the modifications made at Crystal River-3 have either substantially reduced or eliminated the FIV problem, and/or (2) the FIV problem is a typical high-cycle fatigue problem which takes a finite amount of time to loosen the rolled joint. Loosening of the joint would allow mixing of hot RC cold leg water and cold MU water in the annular region between the thermal sleeve and safe-end. This, in turn, would lead to thermal fatigue of the thermal sleeve and safe-end as described in the failure analysis reports. Consequently, FIV due to the RC pumps may have contributed to the failures.

10. Similarily, FIV due to cross-flow in the RC cold leg may have loosened the rolled joints. However, all of the plants experienced this form of FIV and were not affected. Therefore, this is probably not a root cause.

11. The thermal sleeves could have been rolled to varying degrees (loose and/or with gaps between the thermal sleeve and safe-end) when originally installed. This would allow mixing of the hot RC cold leg flow and the cold HPI/MU flow in the annular region between the thermal sleeve OD and the safe-end ID. This phenomenon, in turn, would thermally shock the nozzle components and eventually lead to crack initiation and propagation.

8.0 PROBABLE FAILURE SCENARIO

With the foregoing discussion in mind, the Safe End Task Force developed a probable failure scenario based on hypothesis 11 of Section 7.0.

"The most likely scenario for failure is that the thermal sleeve is loose after construction or a minimum contact expansion roll becomes loose during operation due to mechanical vibration and/or thermal cycling of the contact expansion joint. This looseness causes wear of the OD of the thermal sleeve and the ID of the safe-end. This wear in the rolled area allows a larger gap to form between the thermal sleeve and safe-end. Hot reactor coolant flows around the sleeve through this gap. The hot coolant randomly impacts the safe-end and thermal sleeve area because of random motions of the sleeve. The cooler makeup flow cools these heated areas when random motion shuts off the annular flow or makeup flow is increased. This random alternating heating and cooling eventually causes thermal fatigue cracking of the safe-end. This cracking may be aggravated by heating and cooling caused by significant cycling of makeup flow."[13]

Facts to support this hypothesis are as follows:

- Inspections conducted at Davis Besse, Midland and North Anna have shown that loose sleeves, or sleeves with gaps between the thermal sleeve and safe-end were present in plants under construction. In addition, the North Anna inspection indicated that the length of the rolled area varied from nozzle to nozzle between 1-1/2 and 2 inches.

- The thermal sleeve contact expansion process, as defined in the original installation procedure, is ambiguous.

- Since the sleeves were rerolled (hard rolled to 3% wall thinning) at Davis Besse-1 in 1977, no additional problems have been observed.

- When the modified thermal sleeve was meticulously rolled into the HPI/MU nozzle at Crystal River-3, no abnormal conditions were observed.

- When the failure analyses were performed (see section 3.2), thermal fatigue was identified as the mechanism of crack propagation.

9.0 TESTS TO SUBSTANTIATE THE ROOT CAUSE

To substantiate the probable root cause, B&W executed a test program with the following objectives:

1. Quantify the axial force required to loosen a thermal sleeve at ambient conditions as a function of degree of wall thinning achieved during contact expansion.

2. Determine if a gap of sufficient size to loosen a thermal sleeve forms when the thermal sleeve is subjected to a thermal quench transient for various degrees of wall thinning.

3. Determine the natural vibration frequency of a thermal sleeve as a function of roll expansion length and degree of wall thinning.

4. Determine the natural vibration frequency of a thermal sleeve with the collar area in contact with a simulated nozzle.

Given these objectives, the program was conducted in four phases. The test apparatus used for the first and second phases is shown in Figure 11, while the test apparatus used for the third and fourth phases is shown in Figure 15.

The first phase compared, under ambient conditions, the axial force required to move the sleeve versus the degree of thermal sleeve wall thinning. The results of these tests were used as a basis for subsequent tests and analytical evaluations. These results are plotted in Figure 12.

The second phase of testing involved thermal quenching of the simulated nozzle at operating temperature by injecting ambient water through the simulated nozzle and thermal sleeve. A predetermined axial force was applied to the unrestrained sleeve (no weld buttons) as water was injected through the nozzle. This axial force was based on the results of phase one and analytical evaluations of the steady-state hydraulic forces acting on the thermal sleeve. These results are tabulated in Figure 13.

The third phase of testing determined the natural vibration frequency of the thermal sleeve. The natural frequency was established as a function of contact expansion length and degree of wall thinning. The tests used a full-scale thermal sleeve mounted in a simulated safe-end. These results are tabulated in Figure 14.

The fourth phase of testing examined the natural frequency of the thermal sleeve with the collar area in contact with a simulated nozzle. The third phase test apparatus was used along with a simulated nozzle consisting of a retaining collar with adjustable set screws. Adjustment of the set screws was used to simulate the gap between the "downstream" collar of the thermal sleeve and the HPI/MU nozzle.

The tests conducted for the simulated safe-end indicated that:

1. Under static (ambient) conditions, the axial load carrying capability of the rolled joint varies in a non-linear fashion. Load carrying capacities in the 6000-13000 lb. range can be anticipated for wall reductions in the 1-8% range. Analytical predictions of the steady drag load exerted on the sleeve suggest that nominal loads applied perpendicular to the sleeve of about 100 lb. should be experienced in service. Worst case loads of 1300 lb. could occur if the vortex shedding frequency coincides with the natural frequency of the sleeve. Therefore, even the worst case analytical predictions, applied perpendicular to the sleeve, fall far below the limiting axial load carrying capability determined by the test.

2. Under transient (thermally quenched) conditions, the rolled joint loses load carrying capability for roll expansions less than 5% wall thinning as evidenced by the sleeve movement and leakage flow. However, should the joint loosen in actual service conditions, sleeve movement would be precluded by the upstream and downstream weld buttons. Above 5% wall thinning, the integrity of the rolled joint is not compromised (i.e., no sleeve movement or leakage flow) during the thermal quench transient.

3. The natural frequency of the sleeve varies as a function of roll expansion length and degree of wall thinning. Natural frequencies in the 220-250 Hz range can be anticipated for wall reductions in the 1-8% range.

4. When the restrained vibration test was conducted, the displacement of the sleeve was less than the sleeve/restraining collar gap. Therefore, the sleeve did not impact the simulated nozzle and no conclusive data was obtained.

10.0 MODIFIED THERMAL SLEEVE DESIGN

The previous sections of this report have been dedicated to determining the root cause of the HPI/MU nozzle cracking problem. The next three sections address the modifications made to alleviate the problem. Specifically, these modifications affect the design, operation, and inspection of the HPI/MU nozzles.

10.1 Conceptual Designs

In the aftermath of the Crystal River incident, the effectiveness of the contact rolled thermal sleeve design was re-evaluated. Three alternative concepts for shielding the HPI nozzle from cold injection water were developed. Each concept uses a stainless steel thermal sleeve which is secured into the nozzle and projects into the RC cold leg piping. The approaches are as follows:

Hard Rolled Thermal Sleeve Concept

A hard rolled thermal sleeve design was developed (see Figure 8), which requires a hard roll of the upstream end of the thermal sleeve, instead of a contact roll. Since the same concept was used in the original design, the hard rolled concept should be easy to implement. However, the problem of loosening of the rolled joints may still exist.

Integral Thermal Sleeve Concept

An integral thermal sleeve concept was developed which incorporates the thermal sleeve and the safe-end into a single component (see Figure 9). This design eliminates the possibility of the sleeve loosening and also eliminates the concern about annular flow

between the thermal sleeve and the safe-end. However, disadvantages of this concept include: (1) increased pressure drop due to reduced thermal sleeve ID, (2) fabrication problems, (3) welding problems, (4) excessive cost, and (5) an inability to meet fatigue design requirements as specified in code B31.7, 1968 draft.

Flanged Thermal Sleeve Concept

B&W's flanged thermal sleeve concept is shown in Figure 10. The flanged connections allow easy access to the thermal sleeves for inspection and replacement. The concept also provides a positive seal against water flow in the annular region. The disadvantages of this concept, on the other hand, include: (1) re-routing of piping, (2) thermal shock to the gasket, and (3) reliability of the gasket.

B&W engineers concluded that the hard rolled thermal sleeve concept represented the optimum choice from a cost, licensing, and leakage standpoint.

10.2 Design Improvements

The redesigned hard rolled thermal sleeve (See Figure 8) was developed with some notable improvements:

1. Bell shaped upstream end on the thermal sleeve - This should prevent movement of the sleeve towards the RC cold leg piping.

2. Increased length and width of the upstream end of the thermal sleeve - This feature provides more roll surface contact area and more metal to be cold worked during the rolling process.

3. Hard roll of the thermal sleeve shoulder - The original thermal sleeve was only contact rolled. The increased compression and subsequent deformation of the thermal sleeve material should provide a more secure bond with the safe-end. Also, the additional wall thinning should mitigate sleeve to safe-end separation during HPI events.

4. Contact roll at the thermal sleeve collar - The effects of possible flow induced vibration will be reduced with the sleeve surface in contact with the nozzle ID.

5. Axially notched upstream end of the thermal sleeve - The 4 notches allow the placement of weld beads to provide additional anti-rotation protection.

In summary, the thermal sleeve has been redesigned to eliminate the causes which contributed to the failures at Crystal River, Oconee, ANO, and Rancho Seco.

11.0 MAKEUP SYSTEM OPERATING CONDITIONS

Aside from the redesign of the thermal sleeve, modifications to the makeup system operating conditions were also suggested following the Crystal River incident. The original design specification called for a minimum continuous makeup flow of 1-3 gpm. It was believed that at this limited flow rate, flow and thermal stratification could occur in the makeup line which may lead to thermal fatigue of the nozzle assembly. Similar flow conditions at 5 Westinghouse PWR's [8-10] in 1979 lead to cracking of the steam generator feedwater lines. Consequently, a minimum bypass flow of 15 gpm was suggested to eliminate, or at least mitigate this potential problem.

As additional information was obtained, the recommended 15 gpm minimum makeup flow rate was re-evaluated. The results from the instrumented Crystal River-3 nozzle indicated that the new design achieved all design requirements even at the lowest flow rate tested (1.6 gpm). The safe-end remained cool, while the outer surface of the nozzle varied by at most 20°F. The circumferential temperature gradients were small indicating that no significant "hot spots" or flow stratification was occurring. Also, as the makeup flow rate was increased to a maximum of 130 gpm, the nozzle thermal stresses tended to decrease.

In light of these findings, a minimum continuous makeup flow of 1-3 gpm (as originally specified) should adequately maintain all design parameters within analyzed limits and prevent thermal stratification. However, it must also be pointed out that increasing continuous makeup flow may decrease the nozzle thermal stresses.

12.0 AUGMENTED INSERVICE INSPECTION PLAN

Along with the thermal sleeve redesign and the MU system operating changes, an augmented inservice inspection (ISI) plan was also developed. An ISI provides a means of early problem detection, such that repairs can be effected before extensive damage occurs. Prior to Crystal River, no HPI/MU nozzle assembly inspection was required.

B&W and the Safe-End Task Force developed an augmented ISI for the 177 FA Owner's Group. Specifically, the plan calls for:

Makeup Nozzles

1. Unrepaired Nozzles

   - RT during the next five refueling outages to ensure that the thermal sleeve is in the proper location and no gap exists between the thermal sleeve and safe end. Ensure RT is comparable with "baseline" first RT taken. Perform RT every fifth refueling outage thereafter.

   - UT the safe end and some length of adjacent pipe/valve during the next five refueling outages to ensure no cracking. Perform UT every fifth refueling outage thereafter.

2. Repaired Nozzles (New Sleeve Design)

   - RT during the first refueling outage to ensure that the thermal sleeve is in the proper location and no gap has formed.

   - UT safe end, cold leg ID nozzle knuckle transition, and adjacent piping/valve during the first refueling outage to ensure no cracking exists.

   - RT and UT again at third and fifth refueling outages after repair and every fifth refueling outage thereafter.

3. Repaired Nozzles (with re-rolling)

- RT during the next five refueling outages to ensure that the thermal sleeve is in the proper location and no gap exists between the thermal sleeve and safe end. Ensure RT is comparable with "baseline" first RT taken. Perform RT every fifth refueling outage thereafter.

High Pressure Injection Nozzles

1. Unrepaired

- RT during the next five refueling outages to ensure that the thermal sleeve is in the proper location and no gap exists. Ensure RT is comparable with "baseline" first RT taken. Perform RT every fifth refueling outage thereafter.

2. Repaired (New Sleeve Design)

- RT during first refueling outage to ensure that the thermal sleeve is in the proper location and no gap has formed. RT during third and fifth refueling outages and every fifth refueling outage thereafter.

- UT the ID nozzle/cold leg transition knuckle area during the first refueling outage to assure that no cracking is present. UT during third and fifth refueling outages thereafter.

3. Repaired (with re-rolling)

- RT during the next five refueling outages and every fifth refueling outage thereafter to ensure a gap does not form.

13.0 JUSTIFICATION OF LONG TERM OPERATION

Finally, having described the modifications (design, operation, inspection) made to correct the problem, we must now consider the steps taken to support these changes. Specifically, continued operation on a long term basis will be justified analytically, experimentally, and by inspections of nozzles in service.

13.1 Analytical Justification

After the repair efforts were completed at the damaged sites, the NRC staff required that the new design be proven safe for operation in the near term. In response to this request, B&W provided certified field change authorizations (FCA) to the utilities. These FCA's were predicated on simple, yet conservative stress analysis, worst case operational histories, and the consideration of continued nozzle usage through the next fuel cycle only. As such, these studies were only valid in the short term.

In order to justify long term use, B&W recommended a more extensive stress analysis. The stress information required for more detailed evaluation of makeup and HPI nozzle design changes can be obtained most accurately through the use of the finite element method of structural analysis. This analysis technique will determine, in detail, the stresses in the critical areas and will provide the means to assess the impact of unanticipated operating transients on the makeup and HPI nozzles. Such an analytical capability will be invaluable at some later date if, for example, an HPI nozzle that had a loose thermal sleeve was subjected to more HPI flow cycles than can presently be shown to be acceptable using conservative techniques. In addition, evaluation of thermal sleeve/safe-end interface stresses may be required, at a later date, for unanticipated makeup nozzle flow transients. Inservice inspection (ISI) detected flaws could also be less conservatively evaluated if the new detailed stress profiles were available for use in determining the number of cycles for thru-wall crack propagation.

B&W's modified nozzle design is currently being used for both the double-duty HPI/MU nozzles and the HPI only nozzles. However, design differences in service conditions between the two nozzle functions lead to radically different stress distributions.

For the HPI/MU nozzle with continuous 95°F makeup flow, injection of HPI water at 40°F (design temperature) is normally not considered to be a severe transient. The highest stresses for this nozzle are at the point where the HPI/MU pipe penetrates the RC pipe (nozzle "knuckle" region) and are due to the steady axial temperature gradient between the relatively cool safe-end and the hot RC pipe.

On the other hand, the insulated HPI only nozzle is kept hot through heat conduction from the RC pipe under conditions of no HPI flow. When HPI is actuated, the sudden flow of 40°F water (design conditions) causes severe thermal stresses at the thin walled portion of the upstream end of the safe-end. Contributing to the stresses in this region are a severe radial temperature gradient and a local axial temperature gradient.

Although the HPI/MU and HPI only nozzles see different service conditions and experience different stress distributions, a single finite element model will suffice for both nozzle functions. The only exception will be substructured regions where a refined mesh is required to investigate highly stressed locations (e.g., near the wide collar for the makeup nozzle and in the safe-end for the HPI nozzle).

Ultimately, the stress analysis using this model will quantify the usable lifetime of the modified design.

13.2 Experimental Justification

To substantiate the results of the analytical study, an experimental study was conducted (see Section 9.0 for details). The thermal sleeve/safe-end geometry was simulated using the test apparatus shown in Figure 11. The results indicated that under static conditions, the axial load carrying capability of the rolled joint varies in a non-linear manner with nominal values in the 6000-13000 lb. range (1-8% range). Thermal transient characteristics were obtained by injecting cold water through a heated simulated nozzle. During these thermal quench tests, the rolled joint lost load carrying capability (i.e., sleeve movement and leakage flow) for roll expansions less than 5% wall thinning. The natural vibration frequency of the thermal sleeves was also quantified in another segment of the test program. These tests showed that the natural frequency of the sleeve varies as a function of roll expansion length and degree of wall thinning with nominal values in the 220-250 Hz range.

14.0 CONCLUSIONS

Based upon the information presented, the following conclusions can be drawn:

1. Variations in contact expansion of the thermal sleeves is the most probable root cause of the failures.

2. Continued operation in the short term is acceptable with the modified design.

3. If continued inspections show that the sleeves are properly in place, it is not expected that the sleeves will loosen during plant operation prior to subsequent inspections.

15.0 RECOMMENDATIONS

As a result of the Safe End Task Force's investigation into the HPI/MU nozzle component failures, the following recommendations are made:

1. In terms of future repairs, it is recommended that:

   Nozzles with Original Design Thermal Sleeves

   Reroll the upstream end of the thermal sleeve when inspections indicate that a gap exists. A 5.0% wall reduction is suggested to achieve an adequate interfacial residual stress and avoid stress corrosion cracking of the thermal sleeve.

   Nozzles with Modified Design Thermal Sleeve

   Repair and/or replace the damaged components if inspections reveal that abnormal conditions are present.

   In either case, the affected utility should also verify that the components attached to the safe-end meet the design constraints used in the stress analysis.

2. In order to ensure proper HPI/MU system operation, it is recommended that:
   - A continuous makeup flow via bypass of the Pressurizer Level Control Valve should be maintained.

   - A known amount of bypass flow which is greater than 1.5 gpm should be maintained and checked frequently (increased flows of up to about 10-15 gpm may be preferable depending upon plant configuration and operating practices).

- There should be a consistent set of procedures to initiate continuous bypass flow
    - RCS temperature
    - RCS pressure
    - Bypass flow rate
    - Frequency of adjustment and calibration

- The makeup tank temperature should be maintained within the proper control band as determined by other plant parameters.

- In the event that future anomalies are discovered, proper logging of HPI initiations will be invaluable. This procedure should include:
    - Nozzles used
    - Temperature of BWST
    - Temperature of cold leg before and after HPI initiation
    - Pressure
    - Flow rate
    - Duration of HPI flow

3. An augmented inservice inspection plan as stated in Section 12.0 should be implemented.

4. A detailed stress analysis of a nozzle with a modified thermal sleeve design should be performed to justify long term operation.

REFERENCES

1. Lynchburg Research Center, "Examination of Normal Makeup Nozzle Thermal Sleeve and Safe-End", No. 77-1131543-00.

2. Sykes, J. F., Hoch, G. H., Beavers, J. A. and Berry, W. E. of Battelle Columbus Laboratories, "Failure Analysis of Safe-End to Check Valve Pipe Weld in the Crystal River-3 Makeup Water System", March 1, 1982.

3. D. L. Baty of Lynchburg Research Center, "Examination of Oconee-3 HPI Thermal Sleeve, Safe-End", LR:82:5463-08:01, March 26, 1982.

4. D. L. Baty of Lynchburg Research Center, "Examination of HPI Thermal Sleeve from Oconee-2", RDD:83:5492-08:01, June 2, 1982.

5. M. R. Dietrich of Lynchburg Research Center, "Examination of Thermal Sleeve from ANO", RDD:83:5032-08:01, June 28, 1982.

6. A. Flynn, et al., "Thermal Sleeve Failure and Repairs - Indian Point #1 Nuclear Unit (285 MW)", Nuclear Technology, Vol. 25, January 1975.

7. R. Snaider, "BWR Feedwater Nozzle and Control Rod Drive Return Line Nozzle Cracking", NUREG-0619, November 1980.

8. R. W. Klecker, "Thermal Fatigue Cracking in Pressurized Water Reactor Feedwater Lines", Pipe Crack Study Group Supporting Document, June 18, 1980.

9. M. H. Hu, J. L. Houtman and D. H. White, "Flow Model Test for the Investigation of Feedwater Line Cracking for PWR Steam Generators", ASME Conference, Denver, Colorado, June 21-25, 1981.

10. W. H. Bamford, A. Thurman and M. Mahlab, "Fatigue Crack Growth in Pressurized Water Reactor Feedwater Lines", ASME Conference, Denver, Colorado, June 21-25, 1981.

11. "Evaluation of Crystal River-3 HPI/MU Nozzle Testing", B&W Document ID 77-1134571-00, May 1982.

12. "ANSYS Engineering Analysis System - User's Manual", Swanson Analysis Systems, Inc., 1978 Edition, Revision 3, (Update 67L).

13. "Evaluation of Preliminary Cause of HPI/MU Nozzle Thermal Sleeve and Safe-End Failures", Minutes from the Safe End Task Force Meeting, Bethesda, Maryland, May 7, 1982.

14. <u>Loss of Thermal Sleeves in Reactor Coolant System Piping at Certain Westinghouse PWR Power Plants</u>, Nuclear Regulatory Commission Office of Inspection and Enforcement, IN 82-30, Washington, D.C. (1982), pp 1-2.

Figure 1. TYPICAL ELEVATION VIEW OF REACTOR COOLANT SYSTEM ARRANGEMENT SHOWING LOCATION OF HPI NOZZLE

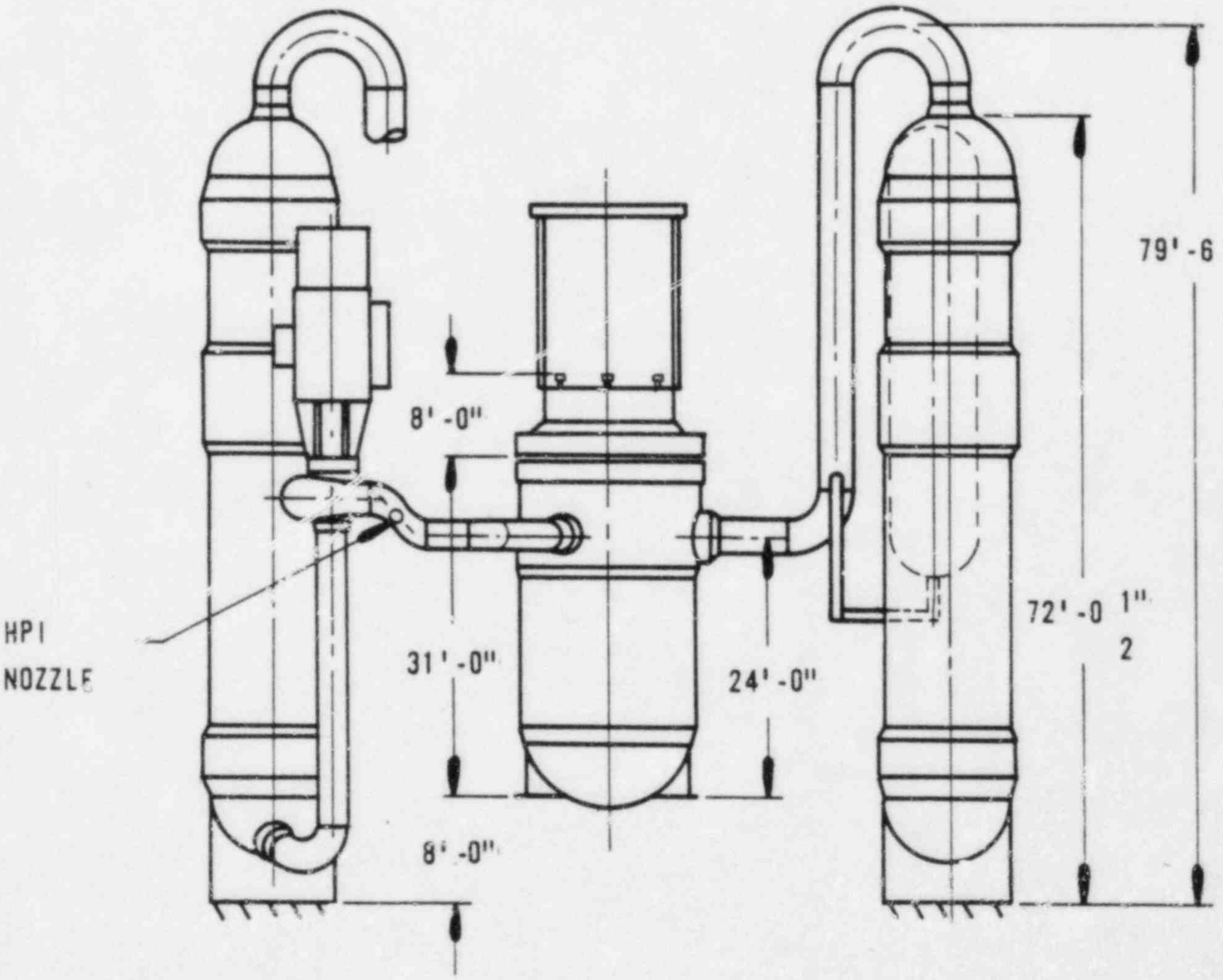


Figure 2 TYPICAL PLAN VIEW OF REACTOR COOLANT SYSTEM ARRANGEMENT SHOWING LOCATION OF HPI NOZZLE

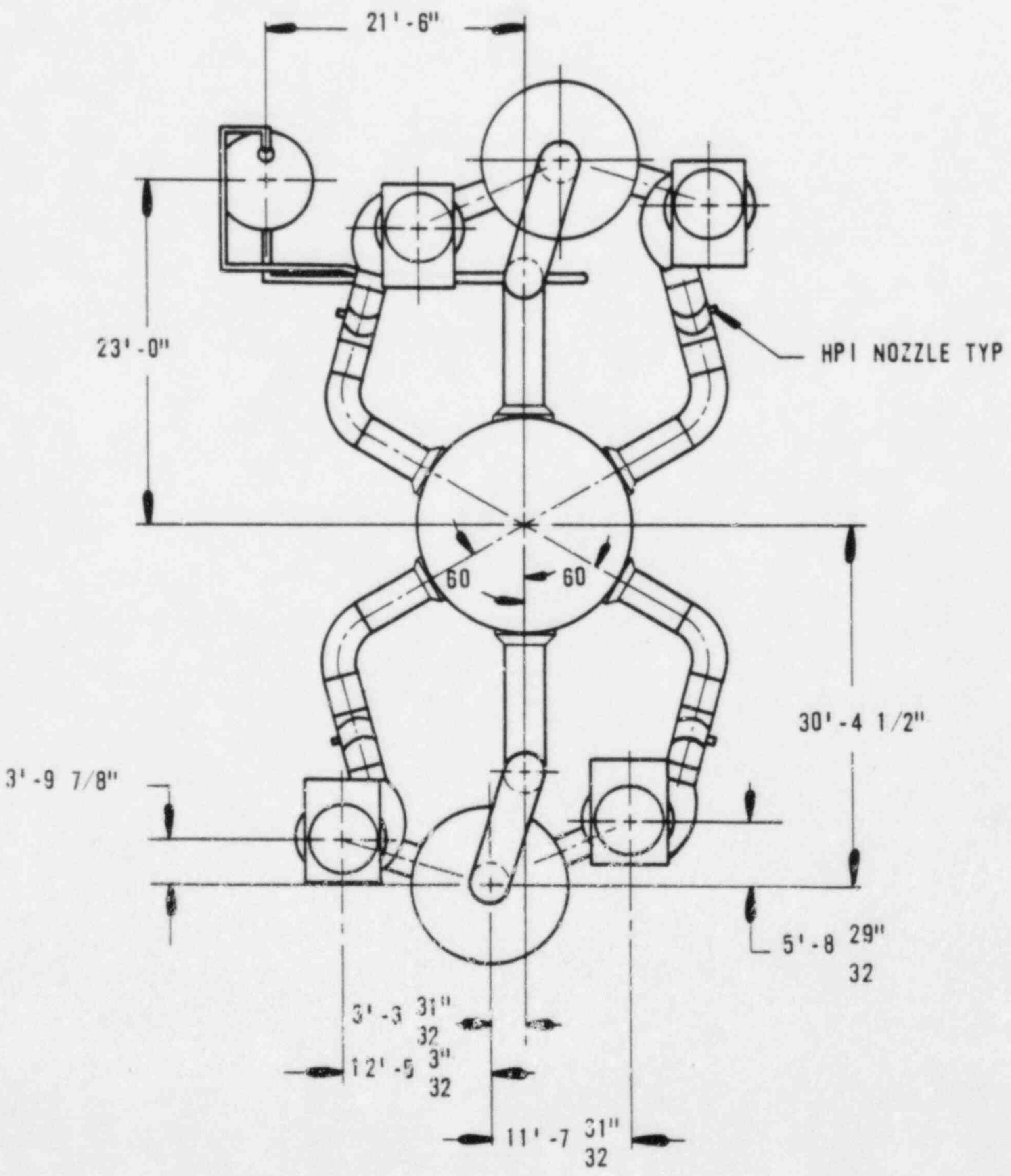


Figure 3

TYPICAL HPI AND HPI/MU NOZZLE

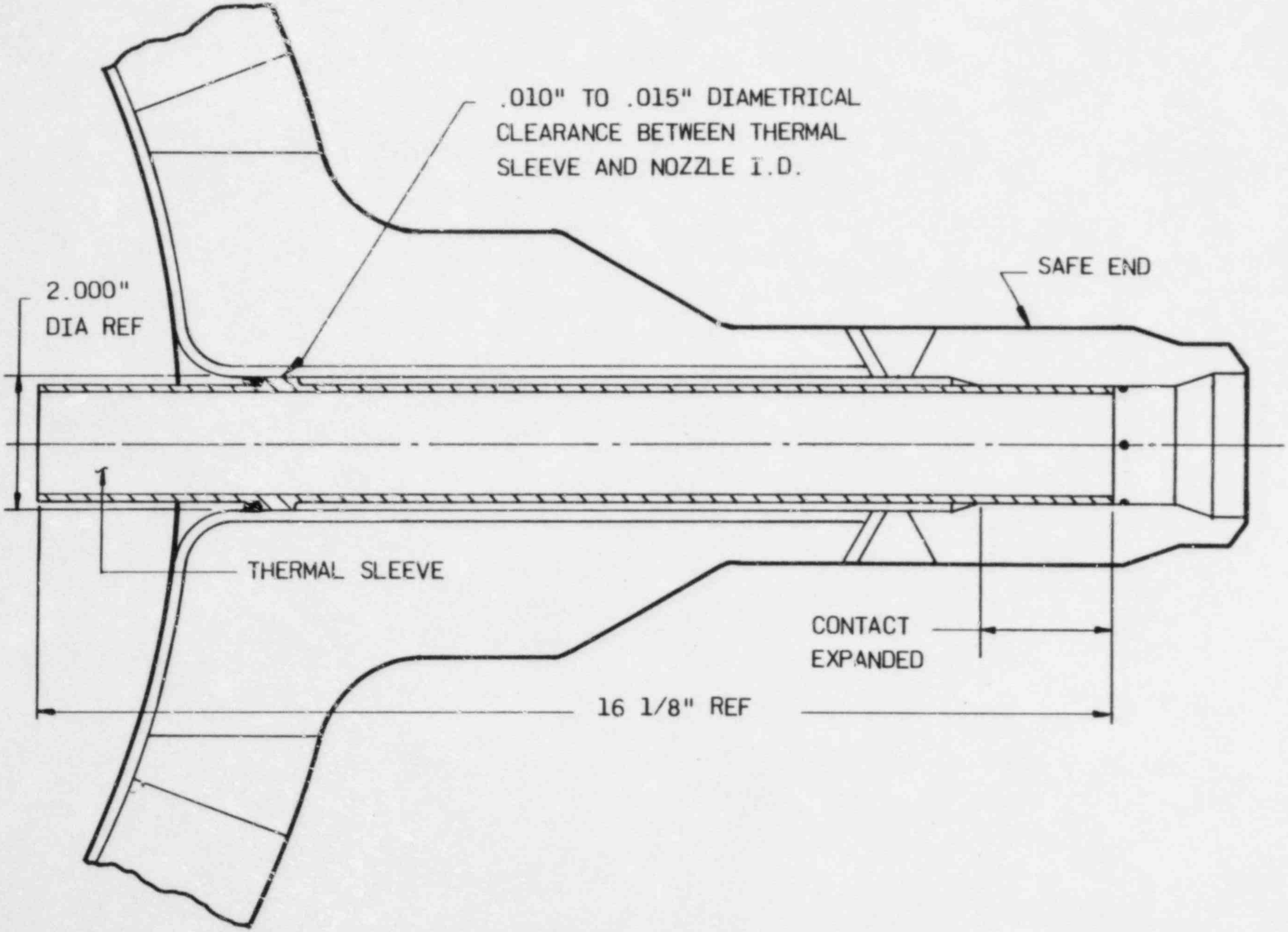


Figure 4

TYPICAL LAYOUT OF HPI OR HPI/MU LINE

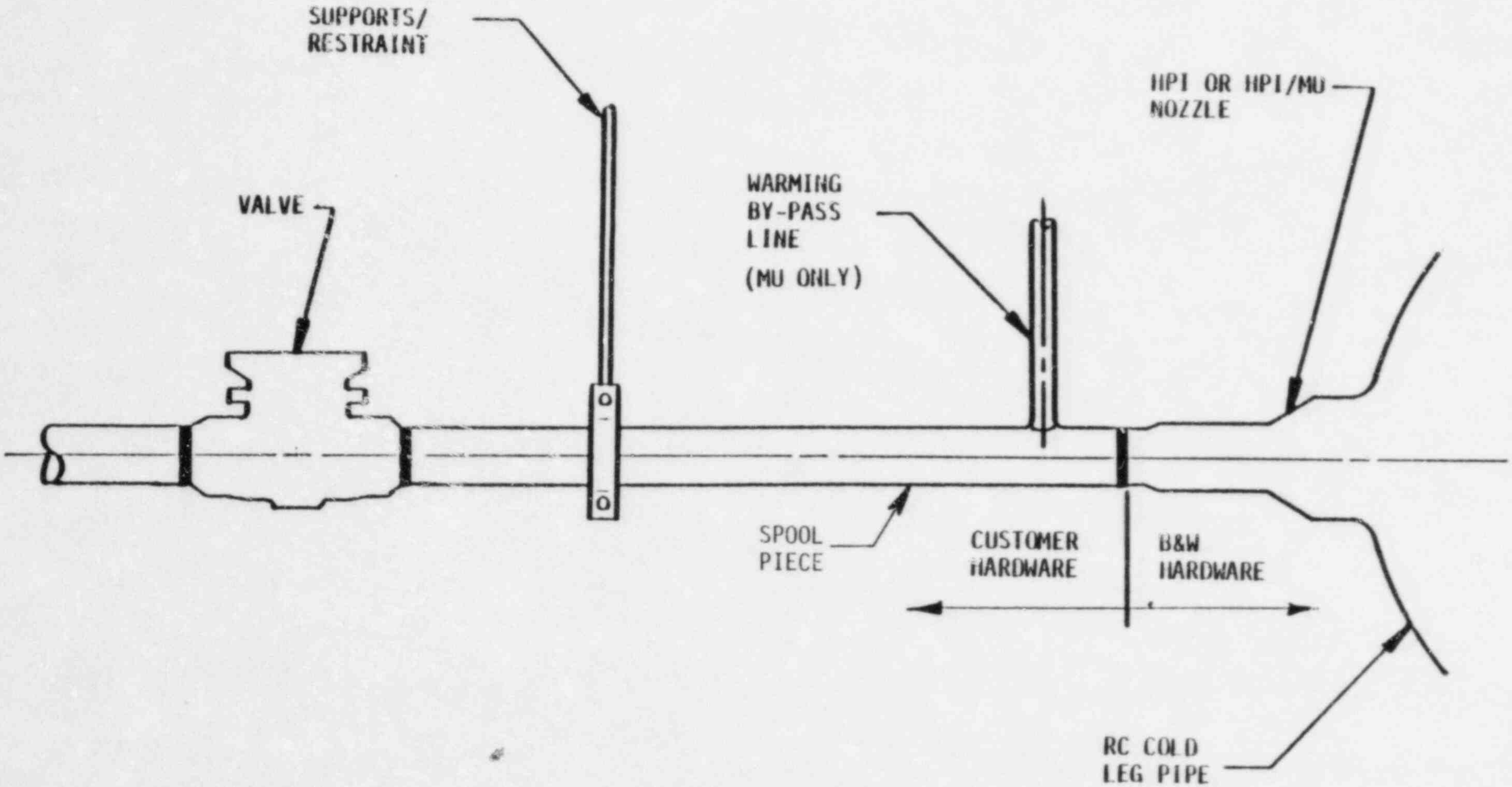


Figure 5

SAFE END TASK FORCE ACTION PLAN - REV 02

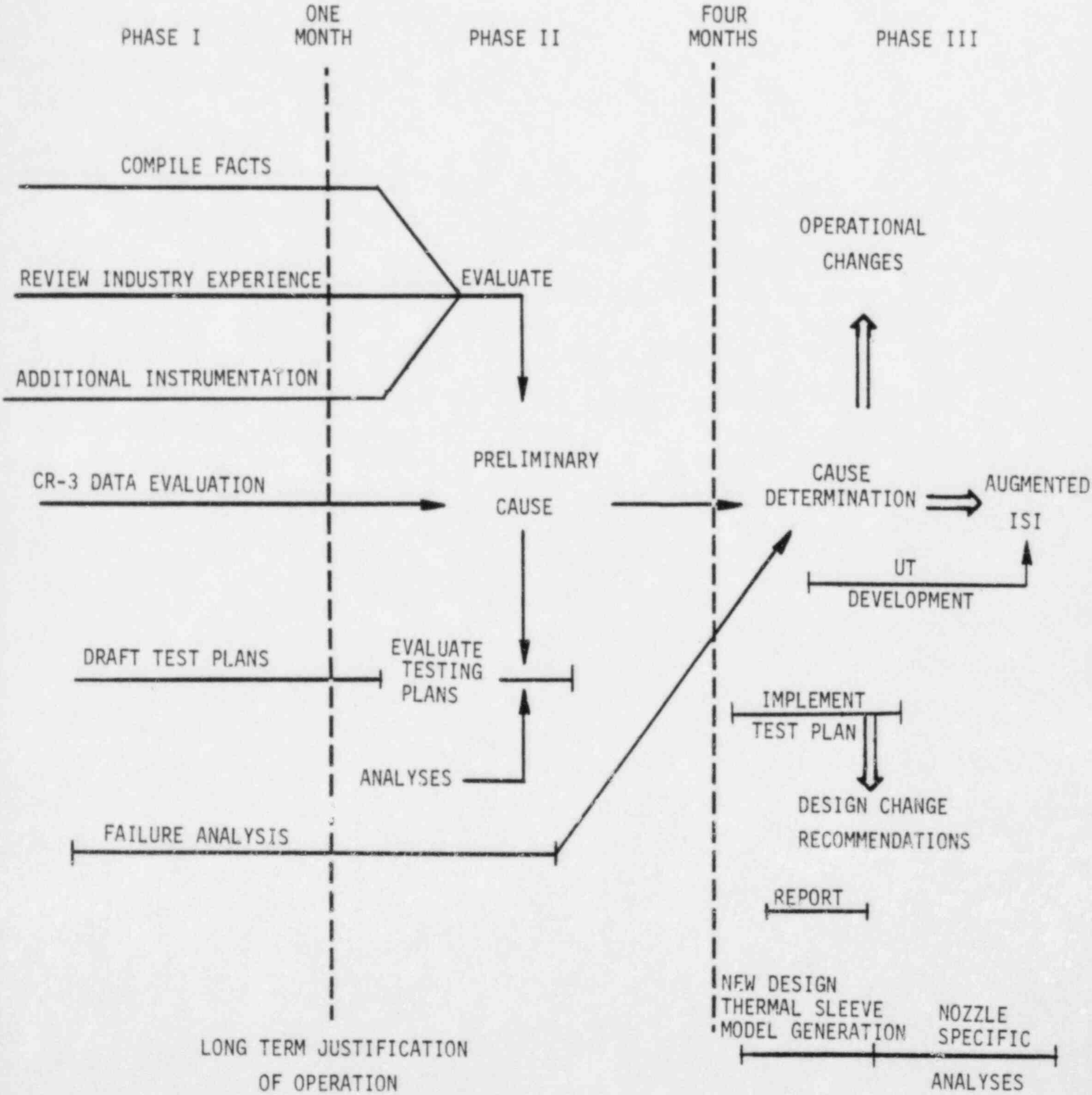


Figure 6

INSTRUMENTATION ARRANGEMENT AT CRYSTAL RIVER-3

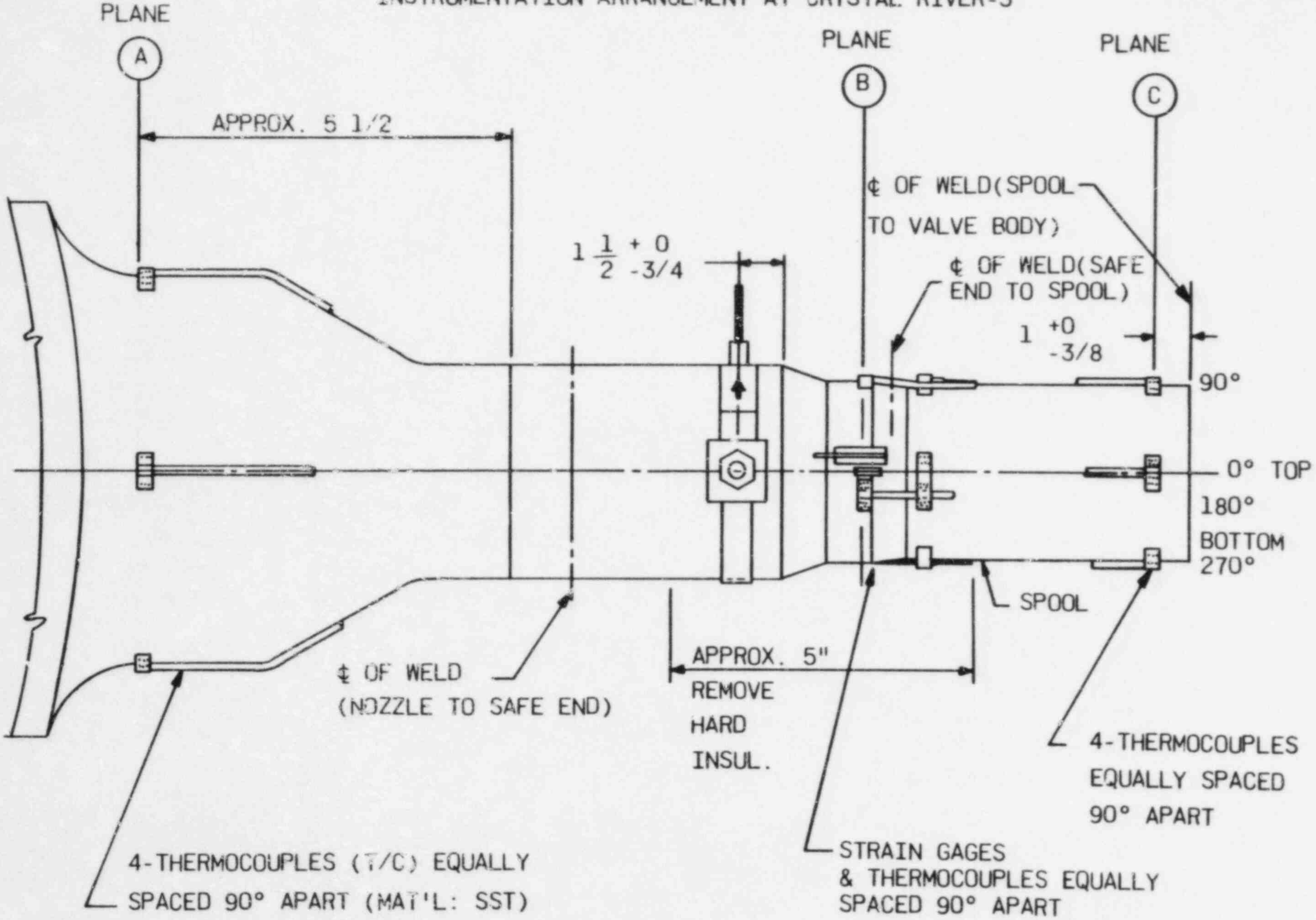


Figure 7 "GOODNESS OF ROLL" RESULTS

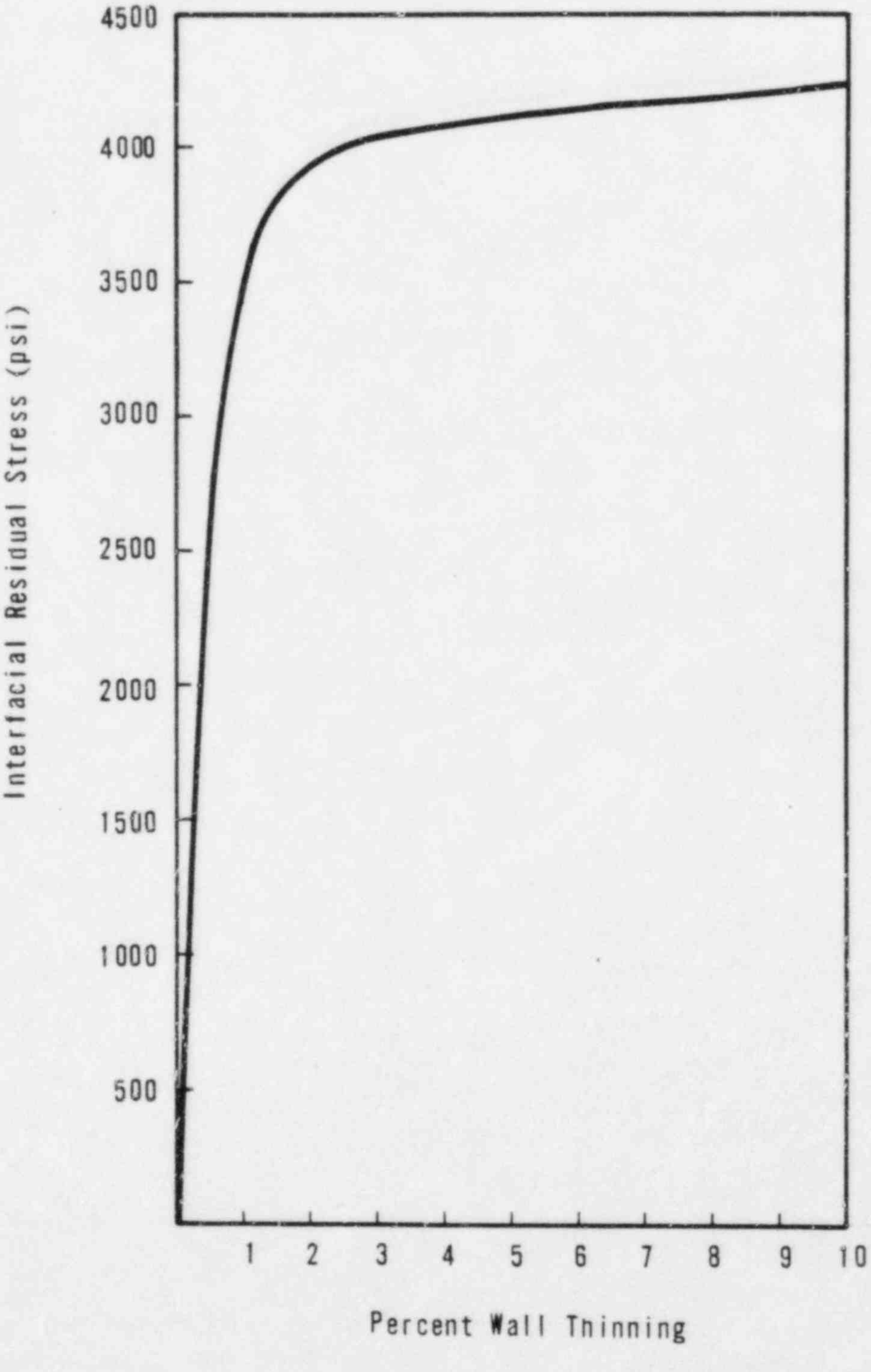


Figure 8

HARD ROLLED HPI/MU NOZZLE

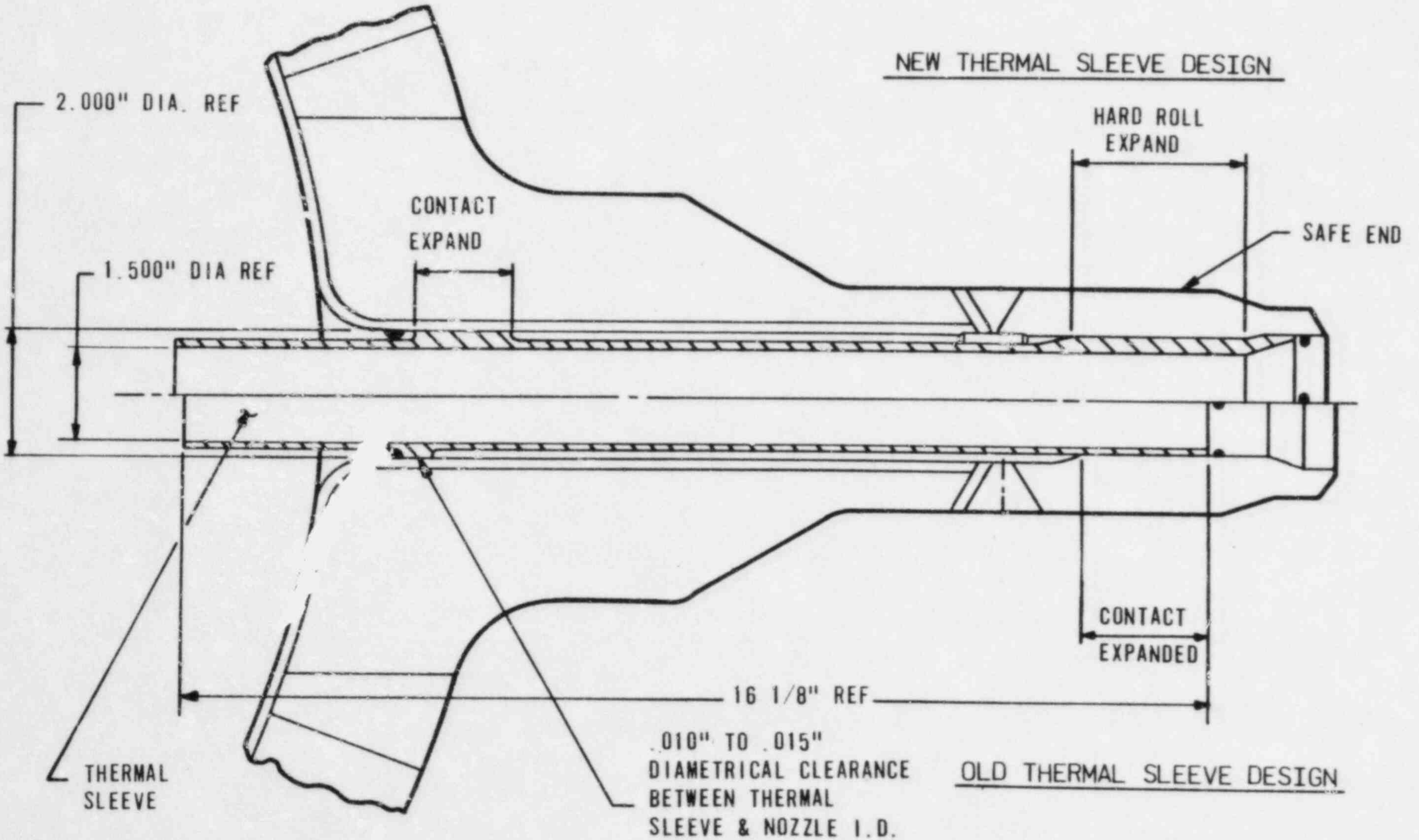


Figure 9 INTEGRAL HPI/MU NOZZLE MODIFICATION

HPI/MU NOZZLE
CONCEPTUAL DESIGN
FOR INTEGRAL SAFE-END/
THERMAL SLEEVE

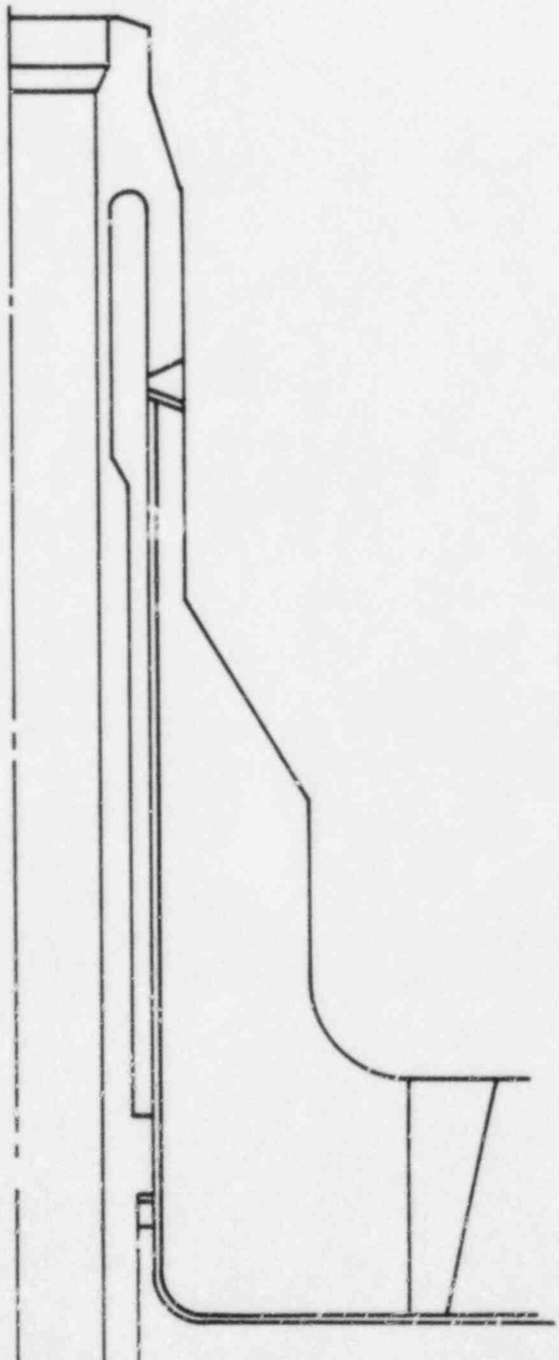
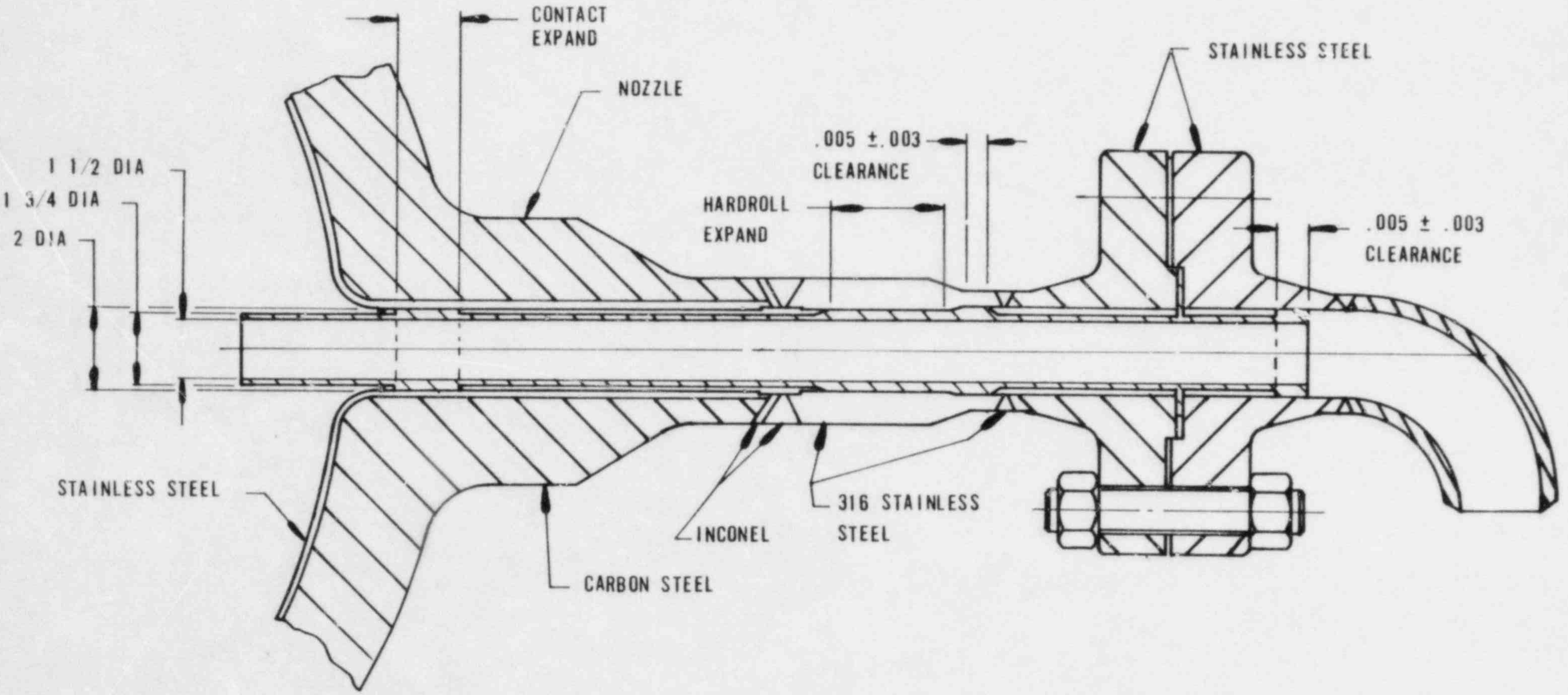


Figure 10 FLANGED MAKE-UP/HPI NOZZLE



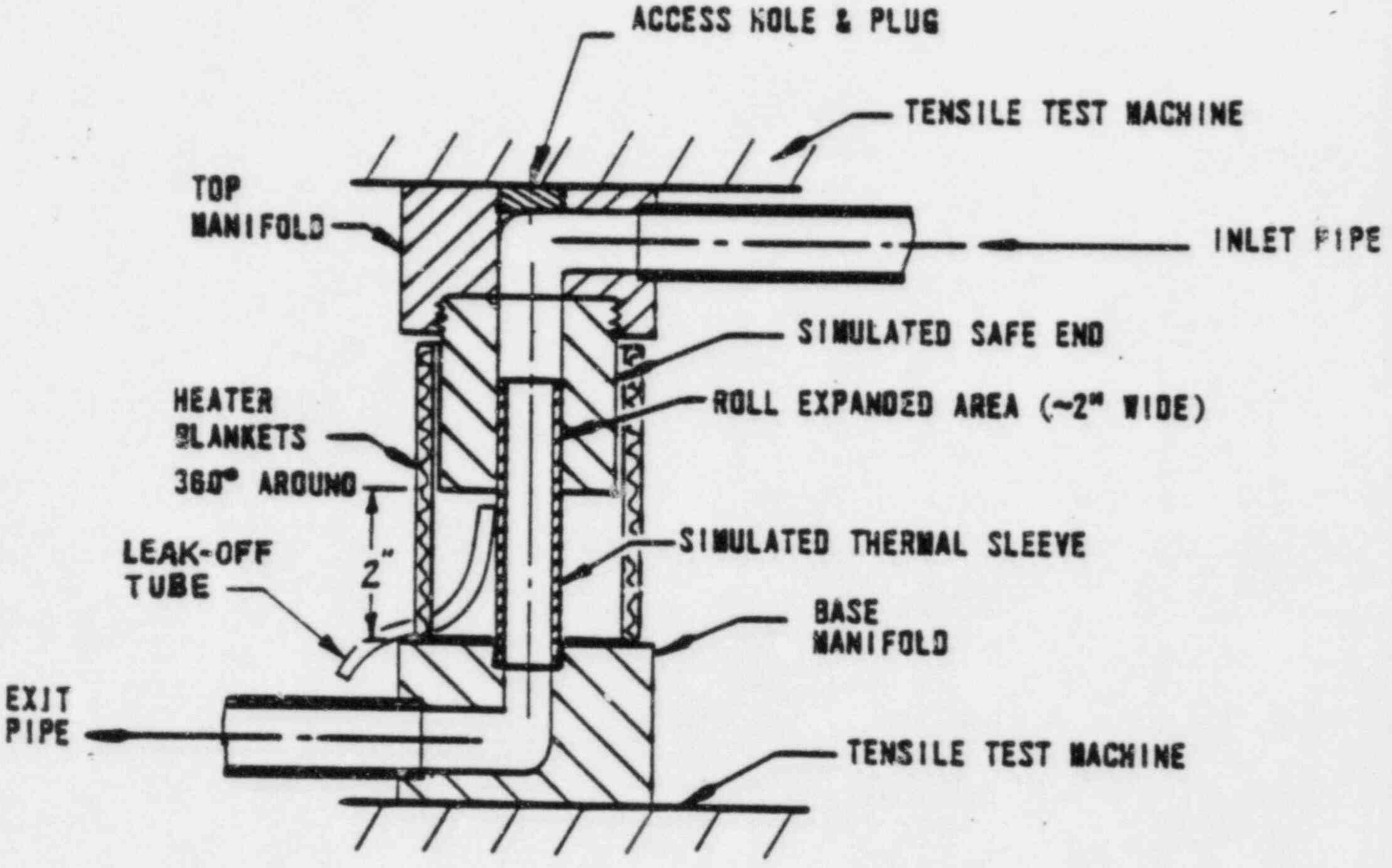


FIGURE 11. - ROLL EXPANSION TEST SCHEMATIC
DIAGRAM OF TEST FIXTURE

Figure 12 HPI/MU STATIC TEST RESULTS

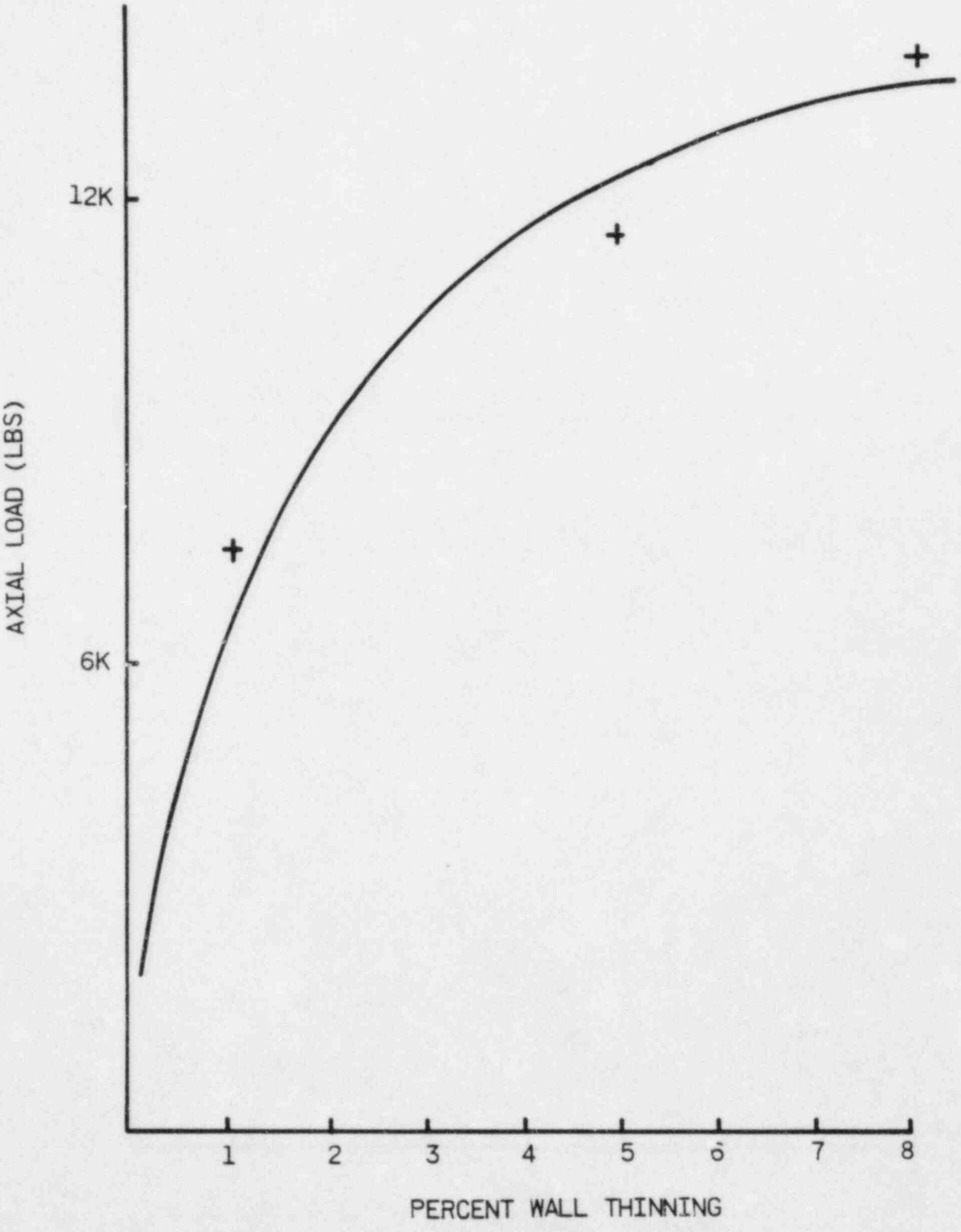


FIGURE 13

HPI/MU NOZZLE TEST RESULTS

TRANSIENT LOAD TESTS (PHASE II A)

	THERMAL SLEEVE WALL REDUCTION			
	0%	2%	4%	5%
DISPLACEMENT AFTER QUENCH (IN.)	1.053*	1.251	0.841	0
LEAKAGE (FL. OZ.)	~8	~4	0	0

POSITIVE DOWNWARD EQUIVALENT LOAD: 86 LBS.

TEMPERATURE: MAX: 550^{O}F, MIN: 200^{O}F

QUENCH FLOW: 275 GPM AT 65^{O}F

*THE MOTION OF THE SLEEVE WAS STOPPED PREMATURELY BY JAMMING THE LEAK-OFF TUBE IN THE GAP.

FIGURE 14

HPI/MU NOZZLE TEST RESULTS

VIBRATION TEST (NO FREE END RESTRAINT)

	THERMAL SLEEVE WALL REDUCTION			
	1%	1%	5%	8%
CONTACT LENGTH (IN.)	1 1/2	2	2	2
NATURAL FREQUENCY (H_Z)	221.8	236.0	237.5	237.5
NATURAL FREQUENCY AT (H_Z) 90° FROM ABOVE	239.0	250.1	251.6	253.1
DAMPING(%)	1.86	1.79	1.59	1.39

Figure 15 NATURAL VIBRATION FREQUENCY TEST SCHEMATIC DIAGRAM

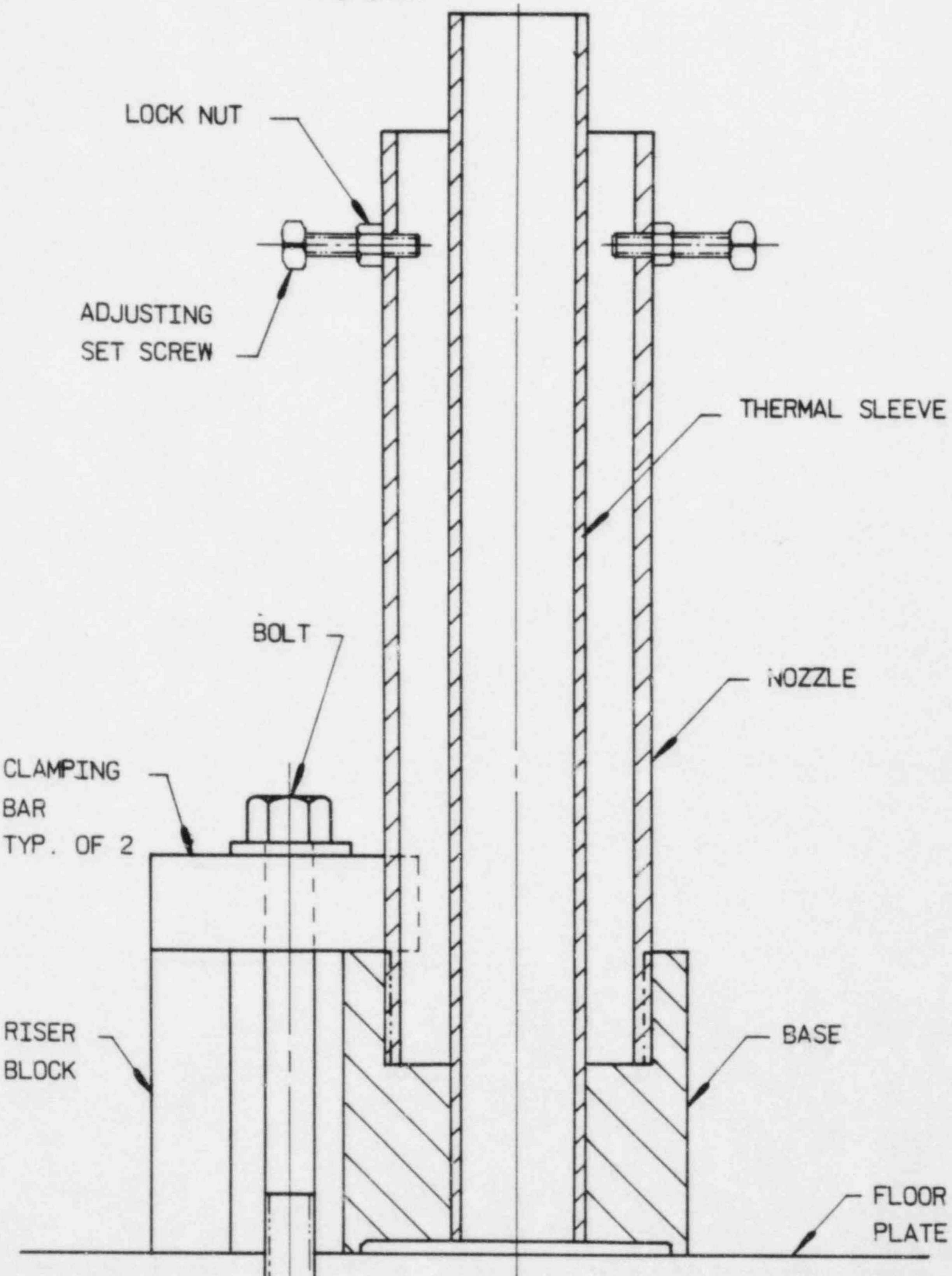


TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	INSPECTION RESULTS (See Note 2)	TH.SLEEVE COLLAR OD	NOZZLE ID IN COLLAR AREA	DIAMETRICAL GAP BETWEEN TH.SL.COL.& NOZ. (MIL)	THERMAL SLEEVE ID/OD	SAFE END ID
OCONEE 1	WX		A1	MU/HPI	OK					
	XY		A2	MU/HPI	"					
	YZ		B2	HPI	"					
	ZW		B1	HPI	"					
OCONEE 2	WX	B44	B1	HPI	B					1.762
	XY	B41	B2	HPI	C		2.031			1.763
	YZ	B40	A2	MU/HPI	A					1.763
	ZW	B46	A1	MU/HPI	OK					1.763
OCONEE 3	WX	B44	B1	HPI	B	2.003	2.015	12	1.500/1.754	1.762
	XY	(See Note 4)	B2	HPI	OK					
	YZ	B40	A2	MU/HPI	A	1.992	2.003	11	1.500/1.752	1.762
	ZW	(See Note 4)	A1	MU/HPI	OK					
TMI 1	WX	B44		HPI	OK					
	XY	B41		MU/HPI	"					
	YZ	B40		HPI	"					
	ZW	B46		HPI	"					
TMI 2	WX									
	XY									
	YZ									
	ZW									
CR 3	WX	B44	A2	HPI	OK	1.993	2.004	11	1.498/1.754	1.763
	XY	B41	A1	MU/HPI	A	1.994	2.004	10	1.498/1.752	1.764
	YZ	B40	B1	HPI	OK	1.992	2.003	11	1.497/1.753	1.762
	ZW	B46	B2	HPI	OK	2.003	2.013	10	1.502/1.754	1.763
ANO 1	WX	B44	C	HPI	OK	1.991	2.002	11	1.500/1.754	1.762
	XY	B41	D	MU/HPI	C	1.989	2.002	13	1.499/1.754	1.762
	YZ	B40	B	HPI	B	1.982	1.994	12	1.500/1.754	1.762
	ZW	B41	A	HPI	B	1.993	2.003	10	1.499/1/754	1.764
RANCHO SECO	WX	B44	D	HPI	OK	1.989	2.000	11	?/?	1.762
	XY	B46	C	HPI	OK	1.992	2.003	11	1.500/1.754	1.762
	YZ	B40	A	MU/HPI	A	1.981	1.992	11	1.500/1.753	1.761
	ZW	B41	B	HPI	B	1.990	2.003	13	1.498/1.754	1.764
MIDLAND 1	WX	B44	A	HPI		1.993	2.005	12		1.762
	XY	B41	B	MU/HPI		1.993	2.006	13		1.762
	YZ	B40	C	HPI		1.990	2.002	12		1.762
	ZW	B41	D	HPI		2.008	2.020	12		1.762
MIDLAND 2	WX	B44	C	HPI		1.998	2.010	12		
	XY	B41	D	HPI		1.993	2.006	13		
	YZ	B40	A	MU/HPI		1.997	2.010	13		
	ZW	B41	B	HPI		1.994	2.006	12		
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	OK	2.004	2.016	12	1.500/1.753	1.762
	XY	B61	A1	HPI	"	2.003	2.015	12	1.498/1.754	"
	YZ	B59	B1	MU/HPI	"	1.985	1.997	12		"
	ZW	B44	B2	HPI	"	2.003	2.018	15	1.500/1.750	"

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	THERMAL SLEEVE HT. NO. AND MAT'L. SPEC.	SAFE END HT. NO. AND MAT'L. SPEC.	EXPANSION INFO. LOC.	DATE	TOOL NO.	SOURCE REFERENCE DOC. REFERENCE DRAWINGS	SHOP RECORDS IDENTIFIED BY PIPE SER.NO.
OCONEE 1	WX		A1	MU/HPI							
	XY		A2	MU/HPI							
	YZ		B2	HPI							
	ZW		B1	HPI							
OCONEE 2	WX	B44	B1	HPI	-A336F8M	43116-A336F8M	SITE	(See Note 3)	(See Note 3)	146614E-5	B44-204-50-1
	XY	B41	B2	HPI	"	" "	"			146629E-7	B41-204-50-1
	YZ	B40	A2	MU/HPI	"	" "	"				B40-204-50-1
	ZW	B46	A1	MU/HPI	"	" "	"				B46-204-50-1
OCONEE 3	WX	B44	B1	HPI	05477-A336F8M	65047-A336F8M	MTV			150141E-7	B44-209-50-1
	XY	(See Note 4)	B2	HPI	" "	" "	"			150156E-7	
	YZ	B40	A2	MU/HPI	" "	" "	"	11-18-71	7573-1		B40-209-50-1
	ZW	(See Note 4)	A1	MU/HPI	" "	" "	"				
TMI 1	WX	B44		HPI		-SB 166	SITE	(See Note 3)	(See Note 3)	131956E-7	
	XY	B41		MU/HPI		"	"			160493E-0	
	YZ	B40		HPI		"	"			131960E-9	
	ZW	B46		HPI		"	"				
TMI 2	WX									141578E-9	
	XY									141576E-13	
	YZ										
	ZW										
CR 3	WX	B44	A2	HPI	05477-A336F8M	810906-A336F8M	MTV	9-7-71	7573-1	141599E-5	B44-207-50-1
	XY	B41	A1	MU/HPI	" "	" "	"			141597E-5	B41-207-50-1
	YZ	B40	B1	HPI	" "	" "	"	9-8-71	7573-1		B40-207-50-1
	ZW	B46	B2	HPI	" "	" "	"	9-11-71	7573-1		B46-207-50-1
ANO 1	WX	B44	C	HPI	05477-A336F8M	811236-A336F8M	MTV	3-7-72	7573-1	131998E-4	B44-208-50-1
	XY	B41	D	MU/HPI	" "	" "	"	3-15-72	"	131996E-6	B41-208-50-2
	YZ	B40	B	HPI	" "	81564- "	"	11-12-71	"		B40-208-50-1
	ZW	B41	A	HPI	" "	811236- "	"	12-1-71	"		B41-208-50-1
RANCHO SECO	WX	B44	D	HPI	05477-A336F8M	129186-A336F8M	MTV	1-8-72	7573-1	143491E-7	B44-2011-50-1
	XY	B46	C	HPI	" "	" "	"	12-30-71	"	143509E-8	B46-2011-50-1
	YZ	B40	A	MU/HPI	" "	" "	"	12-30-71	"		B40-2011-50-1
	ZW	B41	B	HPI	" "	" "	"	1-6-72	"		B41-2011-50-1
MIDLAND 1	WX	B44	A	HPI	818442-A336F8M	43116-A336F8M	MTV	9-20-74	7573-1	150176E-6	B44-2012-50-1
	XY	B41	B	MU/HPI	" "	" "	"	12-9-74	"	150191E-1	B41-2012-50-1
	YZ	B40	C	HPI	" "	" "	"	10-16-74	"		B40-2012-50-1
	ZW	B41	D	HPI	" "	" "	"	9-27-74	"		B41-2012-50-2
MIDLAND 2	WX	B44	C	HPI	121294-A336F8M	817962-A336F8M	MTV	10-15-75	7573-1	150206E-4	B44-2013-50-1
	XY	B41	D	HPI	" "	29006- "	"	9-28-75	"	150221E-2	B41-2013-50-1
	YZ	B40	A	MU/HPI	" "	817962- "	"	10-16-75	"		B40-2013-50-1
	ZW	B41	B	HPI	" "	43116- "	"	9-23-75	"		B41-2013-50-2
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	05477-A336F8M	811584-A336F8M	MTV & SITE (See Note 5)	6-27-72	7673-1	152027E-4	B56-2014-50-1
	XY	B61	A1	HPI	" "	" "		7-6-72	"	152042E-4	B61-2014-50-1
	YZ	B59	B1	MU/HPI	" "	" "		6-16-72	"		B59-2014-50-1
	ZW	B44	B2	HPI	" "	48417- "		7-3-72	"		B44-2014-50-1

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	PUMP ROTATION	FLOW LENGTH FROM RC PUMP	COLD LEG GEOM. & NOZZLE DATE ORIENTATION (a)	2/2 RC FLOW (% of 131.3 x 10 lbm/hr)	NO. OF RC PUMP IMPELLER VANES	NO. OF RC PUMP DIFFUSER VANES
OCONEE 1	WX		A1	MU/HPI	2 CCW/LOOP	5.2 ft.	Type A	109%	7	12
	XY		A2	MU/HPI	"	"	"	"	"	"
	YZ		B2	HPI	"	"	"	"	"	"
	ZW		B1	HPI	"	"	"	"	"	"
OCONEE 2	WX	B44	B1	HPI	2 CCW/LOOP	5.2 ft.	Type A	112%	5	4
	XY	B41	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	B46	A1	MU/HPI	"	"	"	"	"	"
OCONEE 3	WX	B44	B1	HPI	2 CCW/LOOP	5.2 ft.	Type A	112%	5	4
	XY	(See Note 4)	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	(See Note 4)	A1	MU/HPI	"	"	"	"	"	"
TMI 1	WX	B44		HPI	2 CCW/LOOP	5.2 ft.	Type A	109%	7	12
	XY	B41		MU/HPI	"	"	"	"	"	"
	YZ	B40		HP	"	"	"	"	"	"
	ZW	B46		HP	"	"	"	"	"	"
TMI 2	WX									
	XY									
	YZ									
	ZW									
CR 3	WX	B44	A2	HP	2 CCW/LOOP	5.2 ft.	Type B	112%	5	9
	XY	B41	A1	MU/HP	"	"	"	"	"	"
	YZ	B40	B1	HP	"	"	"	"	"	"
	ZW	B46	B2	HP	"	"	"	"	"	"
ANO 1	WX	B44	C	HP	2 CCW/LOOP	5.2 ft.	Type B	112%	5	9
	XY	B41	D	MU/HP	"	"	"	"	"	"
	YZ	B40	B	HP	"	"	"	"	"	"
	ZW	B41	A	HP	"	"	"	"	"	"
RANCHO SECO	WX	B44	D	HP	2 CCW/LOOP	5.2 ft.	Type A	116%	5	4
	XY	B16	C	HPI	"	"	"	"	"	"
	YZ	340	A	MU/HPI	"	"	"	"	"	"
	ZW	B41	B	HPI	"	"	"	"	"	"
MIDLAND 1	WX		A	HPI	*2 CCW/LOOP	5.2 ft.	Type B	*100%	*5	*9
	XY		B	MU/HPI		"	"			
	YZ		C	HPI		"	"			
	ZW		D	HPI		"	"			
MIDLAND 2	WX		C	HPI	*2 CCW/LOOP	5.2 ft.	Type B	*100%	*5	*9
	XY		D	HPI		"	"			
	YZ		A	MU/HPI		"	"			
	ZW		B	HPI		"	"			
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	1 CW & 1 CCW per LOOP	9.1 ft	Type C	114%	5	9
	XY	B61	A1	HP	"	"	"	"	"	"
	YZ	B59	B1	MU/HP	"	"	"	"	"	"
	ZW	B44	B2	HP	"	"	"	"	"	"

(a) See Attachments

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	MINIMUM ALLOWABLE RC PRESSURE TO PROVIDE NPSH FOR RC PUMPS AT 160° F (2/2)	TOTAL MAKEUP FLOW WITH 1 MU PUMP OPERATION AT 2150 PSIG	TOTAL MAKEUP FLOW WITH 2 MU PUMP OPERATION AT 2150 PSIG	TOTAL HPI FLOW WITH 1 PUMP OPERATION AT 1500 PSIG
OCONEE 1	WX		A1	MU/HPI	300 PSIG	157 GPM	186 GPM	360 GPM
	XY		A2	MU/HPI	"	"	"	"
	YZ		B2	HPI	"	"	"	"
	ZW		B1	HPI	"	"	"	"
OCONEE 2	WX	B44	B1	HPI	170 PSIG	157 GPM	186 GPM	360 GPM
	XY	B41	B2	HPI	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"
	ZW	B46	A1	MU/HPI	"	"	"	"
OCONEE 3	WX	B44	B1	HPI	215 PSIG	157 GPM	186 GPM	360 GPM
	XY	(See Note 4)	B2	HPI	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"
	ZW	(See Note 4)	A1	MU/HPI	"	"	"	"
TMI 1	WX	B44		HPI	290 PSIG	145 GPM	165 GPM	405 GPM
	XY	B41		MU/HPI	"	"	"	"
	YZ	B40		HPI	"	"	"	"
	ZW	B46		HPI	"	"	"	"
TMI 2	WX							
	XY							
	YZ							
	ZW							
CR 3	WX	B44	A2	HPI	(c) 230 PSIG	147 GPM	185 GPM	410 GPM
	XY	B41	A1	MU/HPI	"	"	"	"
	YZ	B40	B1	HPI	"	"	"	"
	ZW	B46	B2	HPI	"	"	"	"
ANO 1	WX	B44	C	HPI		142 GPM	180 GPM	405 GPM
	XY	B41	D	MU/HPI		"	"	"
	YZ	B40	B	HPI		"	"	"
	ZW	B4[illegible]	A	HPI		"	"	"
RANCHO SECO	WX	B44	D	HPI	102 PSIG	192 GPM	288 GPM	405 GPM
	XY	B46	C	HPI	"	"	"	"
	YZ	B40	A	MU/HPI	"	"	"	"
	ZW	B41	B	HPI	"	"	"	"
MIDLAND 1	WX		A	HPI	*265 PSIG for minimum seal staging	140 GPM	NOT AVAILABLE	*420 GPM TOTAL
	XY		B	MU/HPI				
	YZ		C	HPI				
	ZW		D	HPI				
MIDLAND 2	WX		C	HPI	*265 PSIG for minimum seal staging	140 GPM	NOT AVAILABLE	*420 GPM TOTAL
	XY		D	HPI				
	YZ		A	MU/HPI				
	ZW		B	HPI				
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	(c) 190 PSIG	164 GPM	264 GPM	300 GPM
	XY	B61	A1	HPI	"	"	"	"
	YZ	B59	B1	MU/HPI	"	"	"	"
	ZW	B44	B2	HPI	"	"	"	"

(c) at 260°F

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	TOTAL HPI FLOW WITH 2 PUMP OPERATION AT 1500 PSIG	TOTAL HPI FLOW WITH 3 PUMP OPERATION AT 1500 PSIG	RECIRCULATION CONTROL MEANS	BWST TEMPERATURE (NORMAL OPERATION)	FULL POWER YEARS	REACTOR TRIPS
OCONEE 1	WX		A1	MU/HPI	(b) 720/540 GPM	900 GPM	BLOCK ORIFICE (NO ESFAS ISOL.)	80° F	5.1	87
	XY		A2	MU/HPI	"	"	"	"	"	"
	YZ		B2	HPI	"	"	"	"	"	"
	ZW		B1	HPI	"	"	"	"	"	"
OCONEE 2	WX	B44	B1	HPI	(b) 720/540 GPM	900 GPM	BLOCK ORIFICE (NO ESFAS ISOL.)	80° F	4.82	53
	XY	B41	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	B46	A1	MU/HPI	"	"	"	"	"	"
OCONEE 3	WX	B44	B1	HPI	(b) 720/540 GPM	900 GPM	BLOCK ORIFICE (NO ESFAS ISOL.)	80° F	4.99	47
	XY	(See Note 4)	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	(See Note 4)	A1	MU/HPI	"	"	"	"	"	"
TMI 1	WX	B44		HPI	810 GPM		FLOW ORIFICE	70°F	3.51	18
	XY	B41		MU/HPI	"		"	"	"	"
	YZ	340		HPI	"		"	"	"	"
	ZW	B46		HPI	"		"	"	"	"
TMI 2	WX									
	XY									
	YZ									
	ZW									
CR 3	WX	B44	A2	HPI	790 GPM	1130 GPM	FLOW ORIFICE		2.66	56
	XY	B41	A1	MU/HPI	"	"	"		"	"
	YZ	B40	B1	HPI	"	"	"		"	"
	ZW	B46	B2	HPI	"	"	"		"	"
ANO 1	WX	B44	C	HP	780 GPM		FLOW ORIFICE		4.63	56
	XY	B41	D	MU/HPI	"		"		"	"
	YZ	B40	B	HPI	"		"		"	"
	ZW	B41	A	HPI	"		"		"	"
RANCHO SECO	WX	B14	D	HPI	585 GPM	650 GPM	FLOW ORIFICE		3.87	52
	XY	B46	C	HPI	"	"	"		"	"
	YZ	B40	A	MU/HPI	"	"	"		"	"
	ZW	B41	B	HP	"	"	"		"	"
MIDLAND 1	WX		A	HPI	*675 GPM TOTAL	NOT AVAILABLE	*FLOW ORIFICE	40°F-110°F (DEPENDING ON THE WEATHER)	0	0
	XY		B	MU/HPI					"	"
	YZ		C	HPI					"	"
	ZW		D	HPI					"	"
MIDLAND 2	WX		C	HPI	*675 GPM TOTAL	NOT AVAILABLE	*FLOW ORIFICE	40°F-110°F (DEPENDING ON THE WEATHER)	0	0
	XY		D	HPI					"	"
	YZ		A	MU/HPI					"	"
	ZW		B	HPI					"	"
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	600 GPM		FLOW ORIFICE		2.01	46
	XY	B61	A1	HPI	"		"		"	"
	YZ	B59	B1	MU/HPI	"		"		"	"
	ZW	B44	B2	HPI	"		"		"	"

(b) 2 pump operation for ONS-III can either be:

1 HPI Train with 2 pumps
or 1 HPI Train with 1 pump and 1 HPI Train with 1 pump

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	EST. MAX. HPI NOZZLE ACT.	EST. HPI TO NOZZLE	MU/HPI CONNECTION
OCONEE 1	WX		A1	MU/HPI	(20)	87	PIPE/PIPE
	XY		A2	MU/HPI		87	"
	YZ		B2	HPI			"
	ZW		B1	HPI			"
OCONEE 2	WX	B44	B1	HPI	(13)		PIPE/PIPE
	XY	B41	B2	HPI			"
	YZ	B40	A2	MU/HPI		53	"
	ZW	B46	A1	MU/HPI		53	"
OCONEE 3	WX	B44	B1	HPI	(17)		PIPE/PIPE
	XY	(See Note 4)	B2	HPI			"
	YZ	B40	A2	MU/HPI		47	"
	ZW	(See Note 4)	A1	MU/HPI		47	"
TMI 1	WX	B44		HPI	-	-	CHECK VALVE
	XY	B41		MU/HPI			"
	YZ	B40		HPI			"
	ZW	B46		HPI			"
TMI 2	WX						
	XY						
	YZ						
	ZW						
CR 3	WX	B44	A2	HPI	39		CHECK VALVE
	XY	B41	A1	MU/HPI		49	"
	YZ	B40	B1	HPI	36		"
	ZW	B46	B2	HPI	37		"
ANO 1	WX	B44	C	HPI	(17)		ELBOW
	XY	B41	D	MU/HPI		56	"
	YZ	B40	B	HPI			"
	ZW	B41	A	HPI			"
RANCHO SECO	WX	B44	D	HPI	(31)		ELBOW
	XY	B46	C	HPI			"
	YZ	B40	A	MU/HPI		52	"
	ZW	B41	B	HPI			"
MIDLAND 1	WX		A	HPI	*0	*0	SEVERAL FEET
	XY		B	MU/HPI			" "
	YZ		C	HPI			" "
	ZW		D	HPI			" "
MIDLAND 2	WX		C	HPI	*0	*0	SEVERAL FEET
	XY		D	HPI			" "
	YZ		A	MU/HPI			" "
	ZW		B	HPI			" "
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	(3)		ELBOW
	XY	B61	A1	HPI			"
	YZ	B59	B1	MU/HPI		46	"
	ZW	B44	B2	HPI			"

NOTES: 1. SHOP ASSEMBLIES WERE CLEANED TO CLASS C PER SPECIFICATION S-107 E.

2. INSPECTION RESULTS NOMENCLATURE

A. SAFE END CRACKED, SLEEVE LOOSE/WORN/MISSING
B. SLEEVE INDICATED SOME LOOSENESS/WEAR - NO SAFE END CRACKING
C. CIRCUMFERENTIAL CRACK OR MARK

OK - NO ABNORMAL INDICATIONS

3. INFORMATION MUST BE OBTAINED FROM SITE RECORDS

4. INFORMATION FOR THIS MATRIX CONCERNING COLD LEG PIPE ASSEMBLY SERIAL NO'S. B41-209-50-1 AND B41-209-50-2 IS AVAILABLE BUT WHICH ASSEMBLY IS LOCATED IN THE B2 LEG AND A1 LEG MUST BE OBTAINED FROM SITE RECORDS.

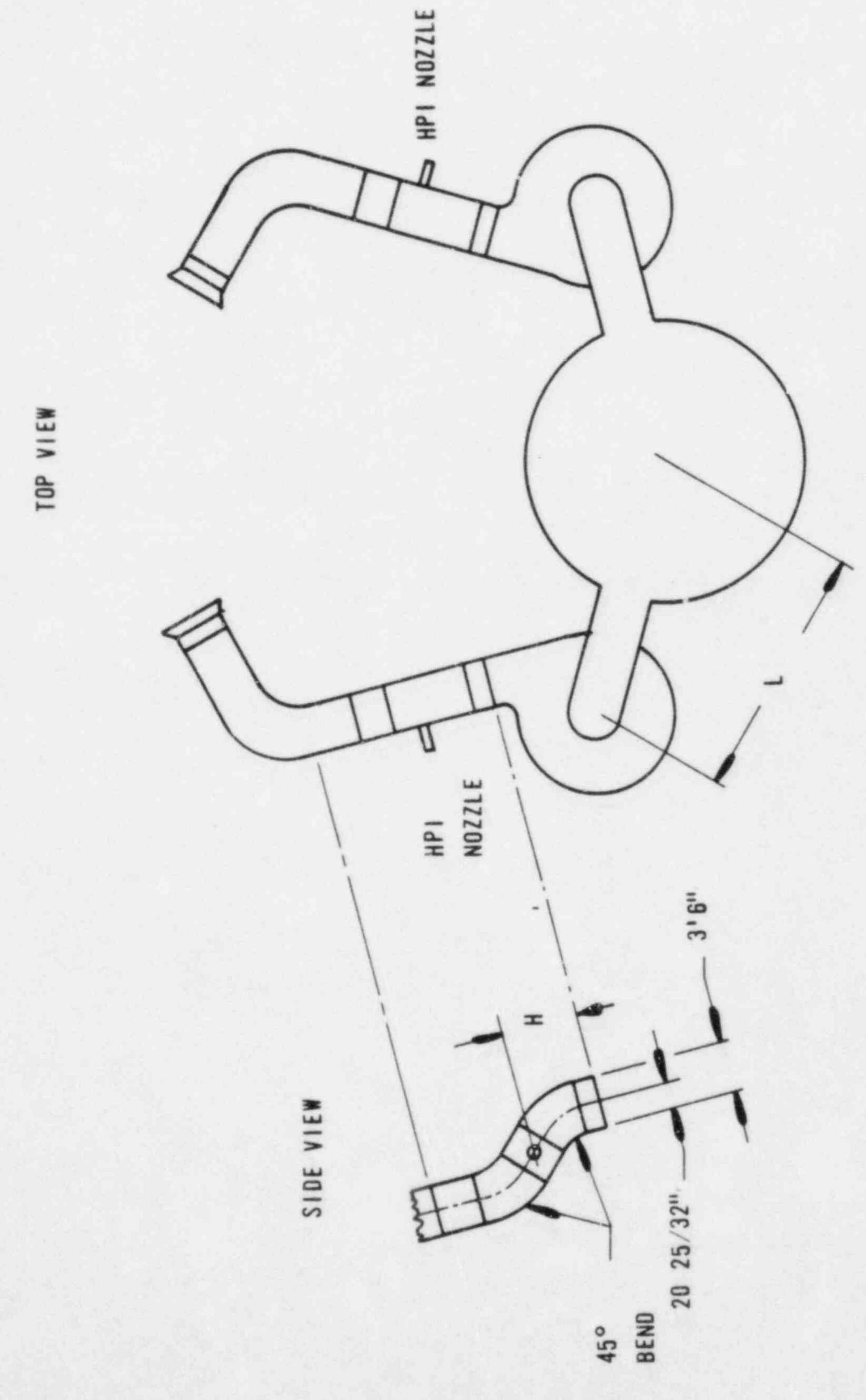
5. WHILE TAKING MEASUREMENTS OF THE A-1 RC PUMP FIXED VANES, IT WAS DISCOVERED THAT THE THERMAL SLEEVE IN THE HPI LINE NOZZLES WAS LOOSE. ALL THERMAL SLEEVES WERE REROLLED. THE FOLLOWING INFORMATION WAS RECORDED AT THE SITE.

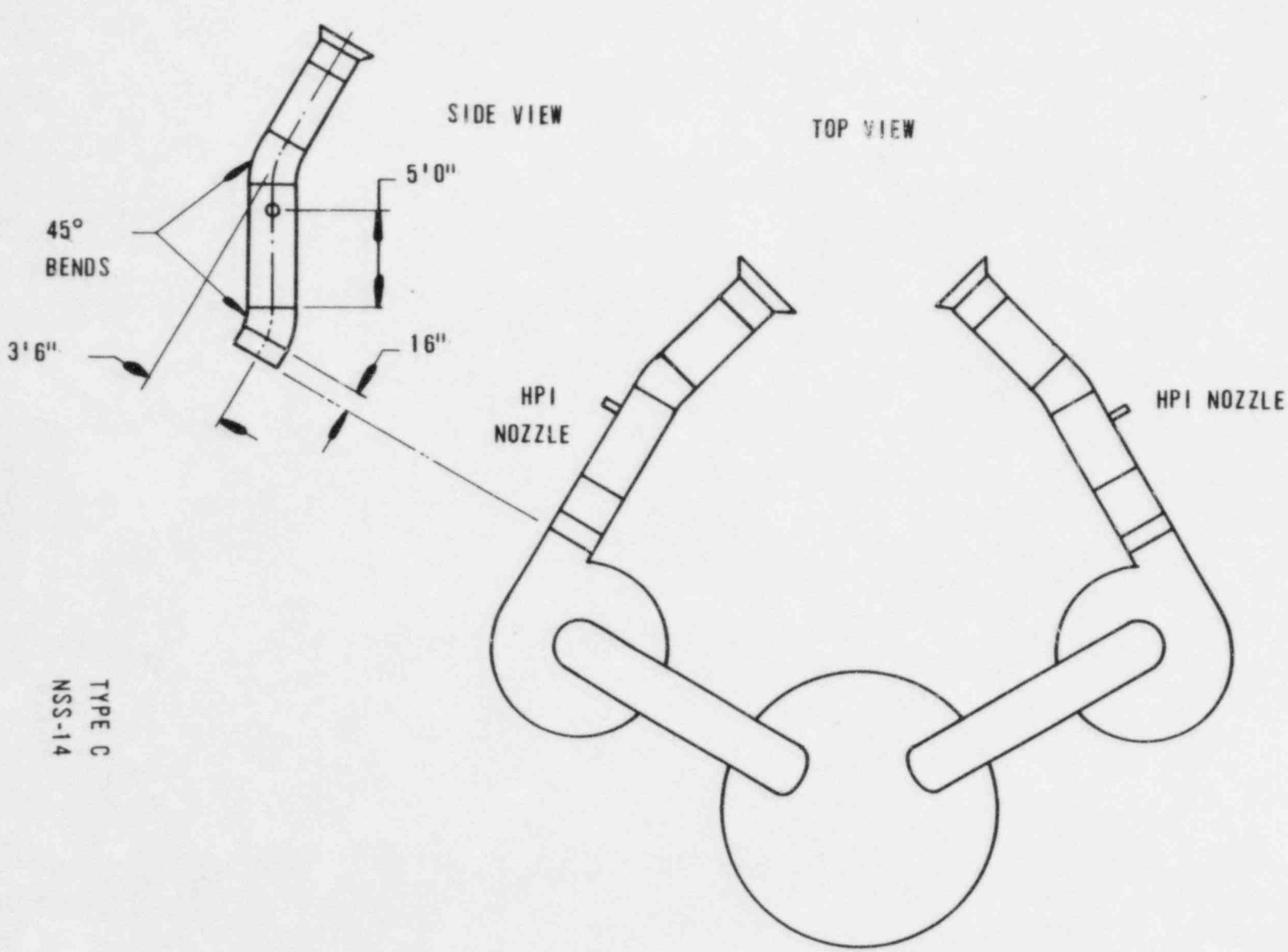
CUST. IDENTIFICATION		THERMAL SLEEVE ID IN EXPANDED AREA
A2	TH. SLEEVE TIGHT	1.5086
A1	TH. SLEEVE LOOSE	1.5060
B1	TH. SLEEVE TIGHT	1.5178
B2	TH. SLEEVE TIGHT	1.5162

	AFTER REROLLING	THERMAL SLEEVE ID IN EXPANDED AREA
A2	TH. SLEEVE TIGHT	1.5162
A1	TH. SLEEVE TIGHT	1.5190
B1	TH. SLEEVE TIGHT	1.5178
B2	TH. SLEEVE TIGHT	1.5183

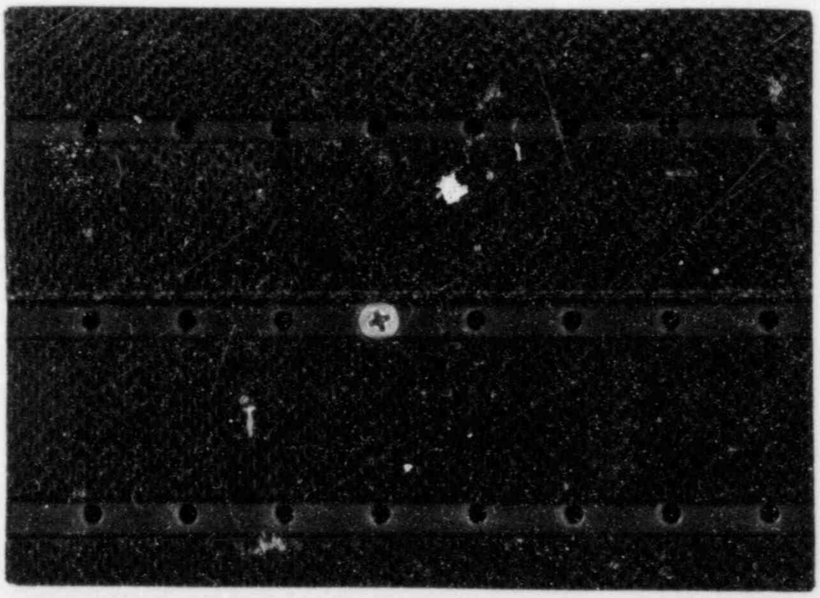
TYPE A H = 4'5 3/16" L = 12'6"
FOR NSS 3, 4, 5, 9, 11

TYPE B H = 4'9 3/16" L = 13'
FOR NSS 7, 8





TYPE C
NSS-14



Engineering Services

Babcock & Wilcox
a McDermott company

BABCOCK & WILCOX
177 FUEL ASSEMBLY OWNER'S GROUP
SAFE END TASK FORCE REPORT
ON
GENERIC INVESTIGATION OF
HPI/MU NOZZLE COMPONENT CRACKING

B&W Document Number: 77-1140611-00

Prepared for

Arkansas Power & Light Company
Consumers Power Company
Duke Power Company
Florida Power Corporation
Sacramento Municipal Utilities District
Toledo Edison Company

by

The Babcock & Wilcox Company
Utility Power Generation Division
Lynchburg, Virginia

TABLE OF CONTENTS

		PAGE
1.0	EXECUTIVE SUMMARY	1
2.0	INTRODUCTION	2
	2.1 Background	2
	2.2 Scope	5
	2.3 Results	6
	2.4 Organization	7
3.0	COMPILATON OF FACTS	8
	3.1 Failure Analyses	8
	3.2 Matrix of Facts	11
4.0	REVIEW OF INDUSTRY EXPERIENCE	14
5.0	CRYSTAL RIVER-3 INSTRUMENTED NOZZLE DATA EVALUATION	17
6.0	ANALYTICAL INVESTIGATION OF EXISTING DESIGN	19
7.0	POSSIBLE ROOT AND CONTRIBUTORY CAUSES	21
8.0	PROBABLE FAILURE SCENARIO	25
9.0	TESTS TO SUBSTANTIATE THE ROOT CAUSE	27
10.0	MODIFIED THERMAL SLEEVE DESIGN	30
	10.1 Conceptual Designs	30
	10.2 Design Improvements	31

TABLE OF CONTENTS (cont'd)

	PAGE
11.0 MAKEUP SYSTEM OPERATING CONDITIONS	33
12.0 AUGMENTED INSERVICE INSPECTION PLAN	34
13.0 JUSTIFICATION OF LONG TERM OPERATION	36
13.1 Analytical Justification	36
13.2 Experimental Justification	38
14.0 CONCLUSIONS	39
15.0 RECOMMENDATIONS	40
16.0 REFERENCES	42

LIST OF FIGURES

Title

1. Typical Elevation View of Reactor Coolant System Arrangement Showing Location of HPI Nozzle
2. Typical Plan View of Reactor Coolant System Arrangement Showing Location of HPI Nozzle
3. Typical HPI and HPI/MU Nozzle
4. Typical Layout of HPI and HPI/MU Line
5. Safe-End Task Force Action Plan
6. Instrumentation Arrangement at Crystal River-3
7. "Goodness of Roll" Results
8. Hard Rolled HPI/MU Nozzle Concept
9. Integral HPI/MU Nozzle Concept
10. Flanged HPI/MU Nozzle Concept
11. Roll Expansion Test Schematic Diagram of Test Fixture
12. HPI/MU Static Test Results
13. HPI/MU Nozzle Test Results - Transient Load Tests (Phase IIA)
14. HPI/MU Nozzle Test Results - Vibration Test (No Free End Restraint)
15. Natural Vibration Frequency Test Schematic Diagram

1.0 EXECUTIVE SUMMARY

The purpose of this report is to summarize the Safe-End Task Force's involvement in the high pressure injection/makeup (HPI/MU) nozzle cracking problems which affected Crystal River-3, Oconee-3, Oconee-2, Arkansas Nuclear One-1, and Rancho Seco. Formed by the Babcock & Wilcox (B&W) 177 Fuel Assembly Owner's Group, the Task Force has identified the root cause of the failures, recommended modifications to eliminate future failures, and identified studies to support these modifications on a long term basis.

Site inspections conducted in February-April 1982 indicated that both the HPI only nozzles and the double-duty HPI/MU nozzles were affected. Loose, out-of-place, and cracked thermal sleeves were observed in 6 of the HPI only nozzles, while 4 of the double-duty nozzles also contained cracked safe-ends. Failure analyses indicated that the cracks were initiated on the inside diameter and were propagated by thermal fatigue. The cracked safe-end at Crystal River also contained mechanically initiated outside diameter cracking which appeared to be unrelated. Previous inspections at two plants (Davis Besse-1 and Three Mile Island-2) under construction revealed that one of the Davis Besse sleeves was loose. All four sleeves were subsequently re-rolled at Davis Besse (hard rolled, instead of contact expanded as originally specified). Recent inspections at Midland have also shown that gaps may be present between the thermal sleeve and safe-end in the contact expanded joint. These findings along with stress analysis and testing have implicated insufficient contact expansion of the thermal sleeves as the most probable root cause of the failures.

With this in mind, B&W has recommended modifications to the design, operation and inspection of the HPI/MU nozzles. A hard rolled thermal sleeve design has been developed which helps prevent thermal shock to the nozzle assembly and helps reduce flow induced vibrations more effectively. An increase in minimum continuous makeup flow has been suggested to help prevent thermal stratification in the MU line and more effectively cool the safe-end. An inservice inspection (ISI) plan has also been developed to provide a means of early problem detection.

2.0 INTRODUCTION

On January 24, 1982, normal monitoring of the Crystal River-3 reactor coolant system (RCS) indicated an unexplained loss of coolant. After an orderly plant shutdown, the double duty high pressure injection makeup (HPI/MU) nozzle check valve-43 was identified as the source. The valve, the valve to the safe-end weld, the safe-end, and the thermal sleeve were cracked as a result of thermal and/or mechanical fatigue. Inspections at other Babcock & Wilcox (B&W) operating plants indicated similar types of cracking, but to a lesser extent. As a result, the Safe-End Task Force (SETF) was formed to compile the pertinent facts and to determine a most probable root cause for the failures. Since the failures were apparently generic in nature, the following report was compiled describing the Task Force's investigation. Specifically, the relevant facts and most probable failure scenario are presented, as well as recommended modifications to the thermal sleeve design, makeup system operating conditons and inservice inspection (ISI) plan.

2.1 Background

On the 145, 177 and 205 fuel assembly (FA) plants, four HPI/MU nozzles (one per cold leg) are used to: (1) provide a coolant source for emergency core cooling, and (2) supply normal makeup (purification flow) to the primary system (see Figures 1 and 2). In general, one or two of the nozzles are used for both HPI and MU, while the remaining nozzles are used for HPI alone.

The incorporation of a thermal sleeve into a nozzle assembly is a common practice in the nuclear industry (See Figure 3). The function of the thermal sleeve is to provide a thermal barrier between the cold HPI/MU fluid and the hot high pressure injection nozzle. This helps prevent thermal shock and fatigue of the nozzle. The purpose of the safe-end is to make the field weld easier (pipe to safe-end) by allowing similar metals to be welded. The dissimilar metal weld between the safe-end and the nozzle can then be made under controlled conditions in the vendor's shop. The use of the safe-end also eliminates the need to do any post-weld heat treating in the field.

While monitoring the Crystal River-3 RCS for unidentified leakage, a notable increase was observed on January 24, 1982. On January 25, a further increase in leakage was observed and the unit was subsequently placed in Hot Standby on January 28. The check valve (MUV-43) to safe-end weld on the double duty HPI/MU nozzle contained a thru-wall circumferential crack which caused the leak. Following removal of the valve, visual inspection of the safe-end and thermal sleeve revealed that both components were cracked and worn (see Figure 3). Inspection of the other three HPI nozzles indicated that no cracking or wear was present, and no sleeve movement had occured.

Following the incident at Crystal River-3, letters were issued to each of the B&W 177 FA utilities informing them of the discoveries at Crystal River-3. Inspections were performed at all 177 FA plants to determine whether the problem was site-specific, or generic in nature.

Oconee-1 was shutdown for refueling when Duke Power received B&W's correspondence. Consequently, Oconee-1 was the first unit to be inspected in detail. Radiographic tests (RT) and ultrasonic tests (UT) of the four suspect nozzles indicated that no abnormal conditions were present in any of the nozzles. These findings suggested that the problem may be site-specific to Crystal River-3.

Oconee-3 was also shutdown at that time for a Once-Through Steam Generator (OTSG) tube leak. Radiography of one of the makeup nozzles (A2) showed that the thermal sleeve was displaced about 5/8 inch upstream from its normal location. The radiographic test also revealed that a gap was present between the outside diameter (OD) of the thermal sleeve and the inside diameter (ID) of the safe-end in the contact expanded region. The weld buttons in the safe-end, which prevent upstream motion of the thermal sleeve, had been worn away (see Figure 3). Weld buttons in the nozzle throat, which prevent downstream motion of the thermal sleeve, were still present, but were worn. A UT of the nozzle also revealed that cracking was present. Given these indications, the HPI/MU piping and warming line were cut

from the safe-end and a dye penetrant test (PT) of the safe-end and associated hardware was conducted (see Figure 4). The safe-end, thermal sleeve, spool piece and warming line were cracked. Subsequent RT's of the remaining nozzles revealed that the other makeup nozzle (A1) and one of the HPI nozzles (B2) were not damaged and the thermal sleeves were in position. However, the other HPI nozzle (B1) had a .030 inch gap between the thermal sleeve OD and the safe-end ID as indicated by the RT.

With the cracking problem substantiated at Oconee-3, Duke quickly inspected their Oconee-2 unit. Three of the Oconee-2 nozzles contained anomalies: (1) the makeup nozzle (A2) had a cracked safe-end and a loose thermal sleeve, (2) the HPI nozzle (B1) had a 1/32 inch gap between the thermal sleeve and safe-end as indicated by the RT, and (3) the HPI nozzle (B2) had a tight thermal sleeve which contained a circumferential crack in the roll expanded region.

Inspections at four other operating plants were also conducted. The thermal sleeves at Davis Besse-1 and Three Mile Island-1 (TMI-1) were in position and tight. No cracking was observed and the weld buttons were not worn. However, inspections at Arkansas Nuclear One-1 (ANO-1) and Rancho Seco indicated that abnormal conditions were present at these sites. At ANO-1, three problems were discovered: (1) one HPI nozzle (A1) had a loose sleeve, (2) one HPI nozzle (A2) had a tight sleeve with a partial gap indicated by radiography between the sleeve and safe-end, and (3) the HPI/MU nozzle (B2) had a tight sleeve which contained a circumferential crack in the roll expanded region (similar to the Oconee-2(B2) failure). At Rancho Seco, two problems were discovered: (1) the HPI nozzle (A1) had a loose sleeve, and (2) the HPI/MU nozzle (A2) had a cracked safe-end and a missing thermal sleeve.

Inspections at two plants under construction, Midland and North Anna, were also conducted to determine the conditions present prior to initial plant startup. Radiographs of the two Midland units indicated that a number of the nozzles may have gaps between the thermal sleeve

and safe-end. Supplemental visual inspections revealed that all 8 sleeves were tight and in place. However, one of the HPI thermal sleeves on Unit 2 was conspicuously skewed relative to the safe-end center line. Visual inspections at North Anna revealed that one sleeve had a partial gap in the rolled region, but the sleeve was tight and in place. The length of the rolled region was also observed to vary between 1 1/2 and 2 inches at North Anna. In addition, the TMI-2 and Davis Besse-1 nozzles were inspected in 1971 while the plants were under construction. At TMI-2, all 4 HPI/MU nozzles were inspected and no defects were observed. However, at Davis Besse-1, one of the sleeves was found to be loose and all 4 sleeves were subsequently re-rolled (hard rolled, instead of contact expanded).

These findings indicate that loose sleeves, or sleeves with gaps between the thermal sleeve and safe-end, may have been present in other plants prior to initial plant startup.

2.2 Scope

Given this background information, the Task Force chose to approach the problem from a generic standpoint (see Figure 5 for the Task Force Action Plan). To do this, a root cause(s) must be first identified, and then a generic solution could be recommended. To determine the root cause(s), the following tasks were performed:

1. reviewed manufacturing data
2. compiled and compared site specific facts and inspection results
3. evaluated metallurgical examinations
4. reviewed industry experience
5. evaluated data from the instrumented Crystal River-3 HPI/MU nozzle
6. evaluated the existing design analytically
7. postulated possible failure scenarios
8. determined a most probable root cause(s)

Having determined a most probable root cause(s), a solution was developed which addressed:

1. modified thermal sleeve design for the damaged nozzles
2. makeup system operating conditions
3. augmented inservice inspection plan

Finally, B&W also proposed studies to demonstrate the adequacy of the recommended fix on a long term basis.

2.3 Results

Results of the investigation indicate the following facts:

1. The thermal sleeve manufacturing installation procedure called for a contact roll of the thermal sleeve, not a hard roll.

2. Varying degrees of contact expansion rolls could be performed even for the same plant.

3. Gaps between the thermal sleeve and safe-end have been found in plants under construction.

4. All cracked safe-ends were associated with loose thermal sleeves. However, not all loose thermal sleeves had safe-ends that were cracked.

5. All cracked safe-ends were associated with the makeup nozzle.

6. A makeup nozzle may be subject to random and continuous makeup flow oscillations.

7. The cracks found were ID initiated (Crystal River-3 OD crack initiation appeared to be unrelated).

8. The cracks were propagated by thermal fatigue.

9. Where controlled hard rolling of the thermal sleeve was accomplished, no failures have occurred.

10. Oconee-1, which has the most operating experience, contained no abnormal conditions when recently inspected. Oconee-1 is the only plant which uses a double thermal sleeve design.

2.4 Organization

This report has been organized to address three primary questions:

1. How did the Task Force determine the root cause of the problem?

2. What modifications (design, operation, inspection) were made to correct the problem?

3. What was done to justify these modifications?

Specifically, sections 3 through 9 describe what was done to determine a most probable root cause, sections 10 through 12 describe what modifications were suggested, and section 13 supplies the justification for these modifications. In addition, sections 14 and 15 summarize the conclusions and recommendations of this investigation.

3.0 COMPILATION OF FACTS

Following the incidents at Crystal River-3 and Oconee, the Safe-End Task Force requested that B&W compile a list of facts concerning the HPI/MU nozzle cracking problem, such that possible correlations between plants could be identified. To accomplish this task, B&W reviewed the manufacturing records and the site specific failure analysis reports, and then developed a matrix of facts.

3.1 Failure Analyses

Failure analyses were performed on four of the units (Crystal River-3, Oconee-3, Oconee-2, and Arkansas Nuclear One-1). These studies were conducted to determine the most probable method of crack initiation and propagation. The results are as follows:

Crystal River-3/Florida Power Corporation

While the repair efforts were being completed on the Crystal River-3 unit, the cracked safe-end and thermal sleeve of the HPI/MU nozzle (A1) were sent to B&W's Lynchburg Research Center (LRC), and the cracked valve and section of pipe near MUV-43 were sent to Battelle Columbus Laboratories for failure analysis.

The results of the LRC study indicated that both the sleeve and the safe-end most likely failed by thermal fatigue. Cracking initiated on the ID of both components and was transgranular. The thermal sleeve cracking was confined to the roll expansion area only. The safe-end was cracked in the valve end down to the seating area of the thermal sleeve. Extensive wear was found on the safe-end ID and the thermal sleeve OD in the region of roll expansion of the sleeve into the safe-end. From this and other surface damage, it was concluded that the sleeve had become unseated and was probably rotating due to flow forces. Evidence to confirm or refute whether the sleeve had been roll expanded on installation was not conclusive.[1]

Battelle's inspection of the pipe section revealed that separate circumferential cracks from the inside diameter (ID) and the outside diameter (OD) on half of the pipe section were present, as well as multiple longitudinal cracks. The circumferential crack on the ID was associated with a machine tool mark, while the crack on the OD was associated with the valve to weld bead discontinuity. Fractographic evidence suggested that fatigue was responsible for both the ID and OD circumferential cracks. Metallography showed that the cracks were transgranular. The ID cracks were believed to have initiated by thermal fatigue caused by (1) turbulent mixing of hot and cold water during makeup system additions, and/or by (2) periodic chilling of hot metal during makeup system additions. Crack propagation probably occurred by combined thermal and mechanical loading of the system. The OD crack is believed to have initiated and propagated by mechanical loading of the system.[2]

Oconee-3/Duke Power

The LRC examined the safe-end, thermal sleeve, spool piece, and warming line of the damaged Oconee-3 makeup nozzle (A2) (See Figures 3 and 4). Component failures were due to thermal fatigue as with Crystal River; however, the cracking was not as deep or as widespread. The cracking was transgranular and confined to three regions:

1. the roll expanded end of the thermal sleeve
2. the safe-end ID from the upstream edge of the thermal sleeve seat to the spool piece weld
3. the spool piece from the safe-end to about 2 inches upstream of the warming line tee

In addition, evidence of wear was found on the thermal sleeve OD and the safe-end ID in the area of the contact expansion seat. As with the Crystal River components, this suggests that the thermal sleeve had become unseated and was rotating/vibrating due to flow forces.[3]

Oconee-2/Duke Power

B&W's LRC also peformed the metallurgical examination of the Oconee-2 HPI nozzle (B2) thermal sleeve. This sleeve contained a visually observable crack extending approximately 270° around the circumference located about 1 1/2 inches from the roll expanded end of the sleeve. This large crack was transgranular and at one location was shown to be propagating from ID to OD. A small axial branch of this crack contained some fatigue striations, but the bulk of the fracture surface could not be interpreted due to heavy oxidation and damage incurred during removal. Metallographic examination also revealed shallow (<3 mils) transgranular cracking on the OD near the large crack. This sleeve did not contain a large amount of wear compared to the Oconee-3 and Crystal River sleeves; however, the downstream collar contained a peened surface along a 180° arc (See Figure 3). In general, the basic failure mode appeared to be transgranular fatigue as occurred in the Crystal River and Oconee-3 thermal sleeves, but the arrangement of the cracking pattern and differences in surface damage suggested that the stress state required to create this failure was either different, or more dominant than in the previous failures.[4]

Arkansas Nuclear One-1/Arkansas Power & Light

The Lynchburg Research Center also performed a metallurgical examination of the ANO-1 HPI/MU nozzle (B2) thermal sleeve. The sleeve contained a visible crack extending approximately 270° around the circumference located about 1 1/2 inches from the roll expanded end of the sleeve. The crack was transgranular, had propagated by fatigue, and followed a machining mark. No axial cracking was present. The collar end of the sleeve showed damage to the collar itself approximately 180° around the circumference. Below this damaged area, approximately 90° apart, two gouged out areas were also present. The failure mode of this sleeve appeared to be similar in nature to that suggested for the Oconee-2 thermal sleeve.[5]

3.2 Matrix of Facts

While the failure analysis studies were being conducted, a site specific matrix of facts was compiled. Five major areas were addressed: (1) system characterization, (2) component characterization, (3) operating conditions, (4) unit operation, and (5) inspection results. Within each specific area, the following items were included:

1. System Characterization
   - loop designation
   - nozzle type (HPI/MU)
   - pipe layout
   - pump characterization
     - rotation (CW/CCW)
     - distance from pump discharge
     - number of impeller vanes
     - number of diffuser vanes
   - makeup recirculation control

2. Component Characterization
   - thermal sleeve geometry
   - safe-end geometry
   - thermal sleeve/safe-end interface
   - [illegible]
   - sleeve expansion procedure

3. Operating Conditions
   - minimum bypass flow
   - total makeup flow
   - total HPI flow
   - minimum RC pressure to provide net positive suction head (NPSH)
   - borated water storage tank (BWST) temperature

4. Unit Operation
   - full power years
   - reactor trips
   - estimated HPI actuations

5. Inspection Results
   - gaps between thermal sleeve OD and safe-end ID
   - thermal sleeve axial location
   - weld button integrity/geometry
   - thermal sleeve cracking
   - safe-end cracking

Table 1 contains the matrix of facts compiled by B&W. Examination of this table suggests that two possible correlations may exist between HPI/MU nozzle failures and sites.

First, neither of the units operating with RC pumps which contain 7 impeller vanes (Oconee-1 and TMI-1) have ever shown any indications of loosening or cracking of the thermal sleeves. On the other hand, 5 out of 6 units operating with RC pumps which contain 5 impeller vanes have shown indications of loosening or cracking of the thermal sleeves. This implies that the dynamics of the pressure field generated by the RC pumps may lead to flow induced vibration damage. However, these observations may simply reflect design differences among the plants (Oconee-1 uses a double thermal sleeve and TMI-1 uses an Inconel safe-end).

Second, either operating unit which has undergone post-installation inspection or modification (Oconee-1 and Davis Besse-1) has not shown any indications of loosening or cracking when recently inspected. At Oconee-1, a single thermal sleeve was originally installed which extended into the cold leg flowstream approximately 2 1/8 inches less than the sleeves used at the other plants. A number of boiling water reactors (BWR) employing a similar design experienced cracking problems. Consequently, a second longer sleeve was re-rolled inside of the original sleeve. Aside from increasing the overall length of the sleeve assembly, the rolling of the second sleeve may have also resulted in the re-rolling of the original sleeve. The second sleeve also had an interlocking flange which contained 4 axial notches in the flanged region. Weld buttons were placed within these notches to provide additional anti-rotation protection. At Davis Besse-1, an inspection of the HPI/MU nozzles was performed in 1977 prior to operation. One sleeve was found to be loose and all four sleeves were subsequently re-rolled. Consequently, the post-installation modifications and inspections have at least mitigated the problem, and may have completely eliminated the problem.

4.0 REVIEW OF INDUSTRY EXPERIENCE

A literature review of recent nuclear industry experience in cracking problems was performed by B&W. Five events of interest were identified:

Babcock & Wilcox PWR, Indian Point Thermal Sleeve Failure, 1970 [6]

While plugging tubes at the Indian Point-1 facility, fragments of the makeup line thermal sleeve were discovered in the primary side of the steam generator water box. Apparently, the sleeve had failed as a result of thermal fatigue in the sleeve to makeup line welded area. The thermal stresses resulted from the flow and temperature gradients associated with normal plant makeup system operations. The problem was eliminated by (1) using a thermal sleeve assembly made from a solid forging, (2) projecting the thermal sleeve into the RC cold leg an additional 1/2 inch to induce better mixing, and (3) increasing the minimum makeup flow to 5000 lb/hr.

GE - BWR, Feedwater Nozzle/Sparger Cracking, 1974-1980 [7]

From 1974 through 1980, 22 of 23 BWR's inspected had experienced some degree of cracking in their primary system feedwater nozzles. The failures occurred due to thermal fatigue with crack initiation caused by turbulent mixing (high-cycle) and crack propagation caused by intermittent feedwater flow (low-cycle) during startup, shutdown, and hot standby. The "loose sleeve design" was identified as the root cause which allowed bypass flow within the annulus between the sleeve and the nozzle. A tight fitting thermal sleeve to restrict bypass flow was used as an interim fix and a triple thermal sleeve design was recommended as a permanent fix.

GE - BWR, Control Rod Drive Return Line Nozzle Cracking, 1975 [8]

In 1975, 12 BWR's were inspected and found to have cracking in the control rod drive return lines (CRDRL) and the reactor vessel beneath the nozzles. As with the BWR feedwater problem, the failures were attributed to thermal fatigue cracking due to turbulent mixing and intermittent cold water flow. The problem was eliminated by plugging the nozzle and rerouting the CRDRL.

Westinghouse - PWR, Steam Generator Feedwater Line Cracking, 1979 [8-10]

In 1979 cracking was discovered in the steam generator feedwater lines of 5 operating PWR systems. The cracking was attributed to thermal fatigue due to flow stratification in the feedwater lines. Corrosion fatigue was subsequently declared to be the root cause.

Westinghouse - PWR, Loss of Thermal Sleeves in Reactor Coolant System Piping at Certain Westinghouse PWR Power Plants, 1982 [14]

In 1982, 2 Westinghouse PWR's were inspected and found to have missing thermal sleeves in their safety injection (SI) nozzles.

Radiography and ultrasonic examinations confirmed that the 10-inch thermal sleeves were missing from all four SI nozzles at the Trojan nuclear plant. Supplemental inspections of the sleeves in the pressurizer surge line, and normal and alternate charging lines revealed that cracking was present in some of the retaining welds.

At Duke Power's McGuire-1 reactor, radiography and underwater camera inspection revealed that the thermal sleeve in one of the four SI accumulator piping nozzles to RCS cold leg piping was missing. Radiography confirmed that the other three SI sleeves and the pressurizer surge line sleeve were in place. Westinghouse recommended that (1) the loose parts monitoring system be fully operational, and (2) a non-destructive examination be performed to assess the thermal sleeve conditions of the affected systems at the next extended plant outage.

In summary, the following observations can be made:

1. Crack initiation was due to high-cycle thermal fatigue caused by turbulent mixing.

2. Crack propagation was due to low-cycle thermal fatigue caused by intermittent flow of cold water.

3. Tests conducted by Hu et.al. [9] have shown that for loose fitting thermal sleeves, leakage flow (up or down stream) may occur within the annulus between the sleeve and nozzle.

4. Cracking occurs in high stress areas, i.e., counter bore transition, weld discontinuities, nozzles blend radius, etc.

5. All failed components were subjected to a stratified flow caused by low flow rates.

5.0 CRYSTAL RIVER-3 INSTRUMENTED HPI/MU NOZZLE DATA EVALUATION

Following the cracking incident at Crystal River-3, metallurgical examinations of the thermal sleeve, safe-end and spool piece were conducted by the LRC and Battelle as previously discussed. Results of these studies indicated that the cracking was attributable to thermal fatigue. Given this information, qualitative modifications were made to minimize the thermal stresses within the nozzle assembly. Subsequent to this effort, the thermal sleeve was replaced with a modified design, the safe-end was replaced, and the HPI/MU check valve was replaced and relocated approximately 5 inches upstream from its original location.

To verify the structural integrity of the modified HPI/MU nozzle design (see Figure 8) and gain insight into the failures, B&W recommended that the makeup nozzle assembly (A1) be instrumented. Information was required regarding the thermal stresses and vibrational environment associated with normal plant heatup, hot standby, and power operation. To provide this information, 12 thermocouples, 4 welded strain gauges, 4 bonded strain gauges and 2 accelerometers were installed at three axial planes (A, B, and C), as shown in Figure 6.

Evaluation of the data obtained from the instrumented nozzle indicated that:

1. The external temperature of the safe-end (plane B) remains at or near the makeup water temperature, while the thick portion of the nozzle (plane A) tends to follow the RC cold leg temperature.

2. Circumferental temperature gradients were small indicating that no significant "hot spots" or flow stratification was occurring.

3. Several continuous makeup flow rates were tested (1.6, 5.0, 15.0, and 130.0 gallons per minute). In all cases, the safe-end metal temperature did not change, while the nozzle metal temperature changed by a maximum of 20°F.

4. During heatup, the makeup flow cycled approximately every three minutes. The resultant stresses were small.

5. Makeup flow induced vibrations could be detected with the supplemental instrumentation and tended to increase as makeup flow increased. The resultant stresses were small.

6. Nozzle/safe-end stresses due to thermal expansion are smaller than design values.

7. High stresses were recorded while a pipe hanger was being set. This was an isolated occurrence and had no significant influence on the other test results.

For further details, the reader is referred to B&W document 77-1134571-00, "Evaluation of Crystal River-3 HPI/MU Nozzle Testing". [11]

6.0 ANALYTICAL INVESTIGATION OF EXISTING DESIGN

The previous discussion revealed that the thermal stresses in the modified HPI/MU nozzle at Crystal River-3 were within design values. However, no data was obtained for the old nozzle design. Consequently, B&W developed a program to evaluate the original (existing) design. The program consisted of two phases: (1) analytical, and (2) experimental. A discussion of the analytical phase follows, while details of the experimental phase are included in Section 9.

The purpose of the analytical study was two-fold: (1) to determine the relationship between wall thinning of the HPI thermal sleeve during roll expansion and residual stresses at the thermal sleeve to safe-end interface, and (2) to determine if the rolled joint becomes loose during steady-state plant operation, or during the most severe transient (HPI event).

To determine the thermal sleeve thinning to thermal sleeve/safe-end interfacial residual stress relationship, a finite element model was constructed for a radial sector of the assembly in the contact expanded region (See Figure 3). Assuming that a generalized plane strain condition exists within this region and that end effects are negligible, a simple axisymmetric, non-linear, inelastic analysis was performed using the ANSYS Code. [12] Results of this finite element analysis follow; however, these results have not been verified and should be used for information only.

The relationship between thermal sleeve wall thinning and sleeve/safe-end interfacial stress is shown in Figure 7. For wall reductions in the 2-10% range, the resulting interfacial residual stress lies in the 4000-4200 psi range. The residual stress varies in a non-linear fashion which suggests that above a certain degree of wall thinning, probably greater than 5%, the beneficial effects of increased wall thinning are negligible. This non-linear behavior is also characteristic of the axial load carrying capability of the joint (see Figure 12 and Section 9); however, the results cannot be simply correlated due to the number of uncertainties, i.e., coefficient of friction, effective contact area, material properties, etc.

The loosening of the rolled joint during steady-state and most severe transient operation was investigated analytically by imposing appropriate thru-wall temperature variations on the model used to determine interfacial residual stress. The temperature distributions were determined assuming one-dimensional heat transfer. The results show that no gap forms between the sleeve and safe-end during stready-state operation. However, the results indicate that during an HPI event (most severe transient), the thermal sleeve contraction relative to the safe-end causes a small gap to form between the sleeve and safe-end for a short period of time. This characteristic behavior is in agreement with the test results described in Section 9.

7.0 POSSIBLE ROOT AND CONTRIBUTORY CAUSES

Following the discovery of cracking at Crystal River-3, an effort was made to identify possible root and contributory causes. The following causes were hypothesized:

1. Makeup flow conditions maintained outside of design limits - this includes either a low MU temperature, or an incorrect bypass flow rate. In particular, the bypass flow rate may have been set at ambient conditions instead of at operating conditions, or may not have been properly maintained.

2. Excessive cycling of the check valve due to improper valve performance

3. Flow stratification in the MU line due to minimal MU flow

4. Thermal stratification and recirculation in the MU line due to minimal flow

5. Cold working of the thermal sleeve due to roll expansion

6. Stress corrosion cracking of the thermal sleeve due to excessive roll expansion

7. Convective heating of the safe-end due to an air gap in the insulation

8. External loading of the attached piping due to thermal transients

9. Sympathetic vibration of the thermal sleeve due to dynamic pressure field generated by the RC pumps

10. Flow induced vibrations due to cross-flow in the RC cold leg pipe

11. Annular flow between the thermal sleeve OD and the safe-end ID due to insufficient rolling of the thermal sleeves

As additional information was obtained from the failure analysis studies and the site inspections, the validity of these causes could be suitably evaluated. It must also be pointed out that this list was compiled after Crystal River-3; therefore, some of the causes identified are site specific to Crystal River-3 and, thus, do not apply to all of the sites.

Of the 11 postulated causes, the first 4 pertain to the makeup system exclusively. A quick inspection of the matrix of facts, Table 1, reveals that both HPI and MU nozzles were affected. Consequently, any cause(s) which pertain to the MU nozzles alone can only be contributory at best. With this in mind, the validity of each cause was evaluated as follows:

1. Makeup flow control problems due to improper maintenance of minimum bypass flow may have occured at all of the sites. Plant data obtained during heatup and cooldown revealed that makeup flow rates were often unknown to the operators. As such, minimum continuous flow rates may not have been properly maintained which could lead to thermal fatigue of the nozzle components. However, since all of the plants experienced similar flow control problems and only 5 of the operating plants contained anomalies, makeup flow control was probably not the root cause.

2. Excessive cycling of the MU check valve may have contributed to the failure at Crystal River-3, but this was probably an isolated occurrence.

3. Flow stratification in the MU line due to minimal MU flow may have occurred at all of the plants since the same design value (1-3 gpm) was used inclusively. However, the results from the instrumented Crystal River-3 nozzle indicated that no significant circumferential temperature gradients were present, even at the lowest flow rate tested (1.6 gpm). From these findings, it can be inferred that the makeup flow was probably not stratified.

4. Low flow velocities in the MU line could also lead to thermal stratification and recirculation zones in the thermal sleeve. However, since the MU line is predominantly filled with MU flow, the thermal shock to the sleeve should not be too extensive (compared to the flow stratification described in 3). As a result, this can be disregarded as a probable cause.

5. Cold working of the thermal sleeve was not responsible for crack initiation or growth according to the failure analysis reports discussed in section 3.2. Consequently, this cannot be considered a probable cause.

6. Also, stress corrosion cracking due to roll expansion was not observed in the failure analysis studies. Consequently, this too cannot be considered a probable cause.

7. Convective heating of the safe-end via an air gap in the insulation may have contributed to the failure at Crystal River-3; however, since some of the plants are uninsulated, this can be disregarded as a probable cause.

8. Excessive loading of the attached piping due to thermal transients may occur at all of the plants. To ascertain the extent of the thermal transient loading, a structural analysis was performed for the Crystal River-3 piping arrangement. The results indicated that all stresses were well within the allowable design constraints. Therefore, this cause can be disregarded.

9. Sympathetic vibration of the thermal sleeve induced by the motion of the impeller vanes past the discharge port of the RC pumps may have occurred at all of the plants. The matrix of facts, Table 1, indicates that 5 of 6 plants using RC pumps with 5 impeller vanes have shown loosening or damage of the thermal sleeves. In contrast, both plants which use RC pumps with 7 impeller vanes have not shown any signs of failure.

   The results from the instrumented nozzle at Crystal River-3 indicated that the flow induced vibrations (FIV), as measured by strain gauges and accelerometers, were minimal. From these findings, it can be inferred that (1) the modifications made at Crystal River-3 have either substantially reduced or eliminated the FIV problem, and/or (2) the FIV problem is a typical high-cycle fatigue problem which takes a finite amount of time to loosen the rolled joint. Loosening of the joint would allow mixing of hot RC cold leg water and cold MU water in the annular region between the thermal sleeve and safe-end. This, in turn, would lead to thermal fatigue of the thermal sleeve and safe-end as described in the failure analysis reports. Consequently, FIV due to the RC pumps may have contributed to the failures.

10. Similarily, FIV due to cross-flow in the RC cold leg may have loosened the rolled joints. However, all of the plants experienced this form of FIV and were not affected. Therefore, this is probably not a root cause.

11. The thermal sleeves could have been rolled to varying degrees (loose and/or with gaps between the thermal sleeve and safe-end) when originally installed. This would allow mixing of the hot RC cold leg flow and the cold HPI/MU flow in the annular region between the thermal sleeve OD and the safe-end ID. This phenomenon, in turn, would thermally shock the nozzle components and eventually lead to crack initiation and propagation.

8.0 PROBABLE FAILURE SCENARIO

With the foregoing discussion in mind, the Safe End Task Force developed a probable failure scenario based on hypothesis 11 of Section 7.0.

"The most likely scenario for failure is that the thermal sleeve is loose after construction or a minimum contact expansion roll becomes loose during operation due to mechanical vibration and/or thermal cycling of the contact expansion joint. This looseness causes wear of the OD of the thermal sleeve and the ID of the safe-end. This wear in the rolled area allows a larger gap to form between the thermal sleeve and safe-end. Hot reactor coolant flows around the sleeve through this gap. The hot coolant randomly impacts the safe-end and thermal sleeve area because of random motions of the sleeve. The cooler makeup flow cools these heated areas when random motion shuts off the annular flow or makeup flow is increased. This random alternating heating and cooling eventually causes thermal fatigue cracking of the safe-end. This cracking may be aggravated by heating and cooling caused by significant cycling of makeup flow."[13]

Facts to support this hypothesis are as follows:

- Inspections conducted at Davis Besse, Midland and North Anna have shown that loose sleeves, or sleeves with gaps between the thermal sleeve and safe-end were present in plants under construction. In addition, the North Anna inspection indicated that the length of the rolled area varied from nozzle to nozzle between 1-1/2 and 2 inches.

- The thermal sleeve contact expansion process, as defined in the original installation procedure, is ambiguous.

- Since the sleeves were rerolled (hard rolled to 3% wall thinning) at Davis Besse-1 in 1977, no additional problems have been observed.

- When the modified thermal sleeve was meticulously rolled into the HPI/MU nozzle at Crystal River-3, no abnormal conditions were observed.

- When the failure analyses were performed (see section 3.2), thermal fatigue was identified as the mechanism of crack propagation.

9.0 TESTS TO SUBSTANTIATE THE ROOT CAUSE

To substantiate the probable root cause, B&W executed a test program with the following objectives:

1. Quantify the axial force required to loosen a thermal sleeve at ambient conditions as a function of degree of wall thinning achieved during contact expansion.

2. Determine if a gap of sufficient size to loosen a thermal sleeve forms when the thermal sleeve is subjected to a thermal quench transient for various degrees of wall thinning.

3. Determine the natural vibration frequency of a thermal sleeve as a function of roll expansion length and degree of wall thinning.

4. Determine the natural vibration frequency of a thermal sleeve with the collar area in contact with a simulated nozzle.

Given these objectives, the program was conducted in four phases. The test apparatus used for the first and second phases is shown in Figure 11, while the test apparatus used for the third and fourth phases is shown in Figure 15.

The first phase compared, under ambient conditions, the axial force required to move the sleeve versus the degree of thermal sleeve wall thinning. The results of these tests were used as a basis for subsequent tests and analytical evaluations. These results are plotted in Figure 12.

The second phase of testing involved thermal quenching of the simulated nozzle at operating temperature by injecting ambient water through the simulated nozzle and thermal sleeve. A predetermined axial force was applied to the unrestrained sleeve (no weld buttons) as water was injected through the nozzle. This axial force was based on the results of phase one and analytical evaluations of the steady-state hydraulic forces acting on the thermal sleeve. These results are tabulated in Figure 13.

The third phase of testing determined the natural vibration frequency of the thermal sleeve. The natural frequency was established as a function of contact expansion length and degree of wall thinning. The tests used a full-scale thermal sleeve mounted in a simulated safe-end. These results are tabulated in Figure 14.

The fourth phase of testing examined the natural frequency of the thermal sleeve with the collar area in contact with a simulated nozzle. The third phase test apparatus was used along with a simulated nozzle consisting of a retaining collar with adjustable set screws. Adjustment of the set screws was used to simulate the gap between the "downstream" collar of the thermal sleeve and the HPI/MU nozzle.

The tests conducted for the simulated safe-end indicated that:

1. Under static (ambient) conditions, the axial load carrying capability of the rolled joint varies in a non-linear fashion. Load carrying capacities in the 6000-13000 lb. range can be anticipated for wall reductions in the 1-8% range. Analytical predictions of the steady drag load exerted on the sleeve suggest that nominal loads applied perpendicular to the sleeve of about 100 lb. should be experienced in service. Worst case loads of 1300 lb. could occur if the vortex shedding frequency coincides with the natural frequency of the sleeve. Therefore, even the worst case analytical predictions, applied perpendicular to the sleeve, fall far below the limiting axial load carrying capability determined by the test.

2. Under transient (thermally quenched) conditions, the rolled joint loses load carrying capability for roll expansions less than 5% wall thinning as evidenced by the sleeve movement and leakage flow. However, should the joint loosen in actual service conditions, sleeve movement would be precluded by the upstream and downstream weld buttons. Above 5% wall thinning, the integrity of the rolled joint is not compromised (i.e., no sleeve movement or leakage flow) during the thermal quench transient.

3. The natural frequency of the sleeve varies as a function of roll expansion length and degree of wall thinning. Natural frequencies in the 220-250 Hz range can be anticipated for wall reductions in the 1-8% range.

4. When the restrained vibration test was conducted, the displacement of the sleeve was less than the sleeve/restraining collar gap. Therefore, the sleeve did not impact the simulated nozzle and no conclusive data was obtained.

10.0 MODIFIED THERMAL SLEEVE DESIGN

The previous sections of this report have been dedicated to determining the root cause of the HPI/MU nozzle cracking problem. The next three sections address the modifications made to alleviate the problem. Specifically, these modifications affect the design, operation, and inspection of the HPI/MU nozzles.

10.1 Conceptual Designs

In the aftermath of the Crystal River incident, the effectiveness of the contact rolled thermal sleeve design was re-evaluated. Three alternative concepts for shielding the HPI nozzle from cold injection water were developed. Each concept uses a stainless steel thermal sleeve which is secured into the nozzle and projects into the RC cold leg piping. The approaches are as follows:

Hard Rolled Thermal Sleeve Concept

A hard rolled thermal sleeve design was developed (see Figure 8), which requires a hard roll of the upstream end of the thermal sleeve, instead of a contact roll. Since the same concept was used in the original design, the hard rolled concept should be easy to implement. However, the problem of loosening of the rolled joints may still exist.

Integral Thermal Sleeve Concept

An integral thermal sleeve concept was developed which incorporates the thermal sleeve and the safe-end into a single component (see Figure 9). This design eliminates the possibility of the sleeve loosening and also eliminates the concern about annular flow

between the thermal sleeve and the safe-end. However, disadvantages of this concept include: (1) increased pressure drop due to reduced thermal sleeve ID, (2) fabrication problems, (3) welding problems, (4) excessive cost, and (5) an inability to meet fatigue design requirements as specified in code B31.7, 1968 draft.

Flanged Thermal Sleeve Concept

B&W's flanged thermal sleeve concept is shown in Figure 10. The flanged connections allow easy access to the thermal sleeves for inspection and replacement. The concept also provides a positive seal against water flow in the annular region. The disadvantages of this concept, on the other hand, include: (1) re-routing of piping, (2) thermal shock to the gasket, and (3) reliability of the gasket.

B&W engineers concluded that the hard rolled thermal sleeve concept represented the optimum choice from a cost, licensing, and leakage standpoint.

10.2 Design Improvements

The redesigned hard rolled thermal sleeve (See Figure 8) was developed with some notable improvements:

1. Bell shaped upstream end on the thermal sleeve - This should prevent movement of the sleeve towards the RC cold leg piping.

2. Increased length and width of the upstream end of the thermal sleeve - This feature provides more roll surface contact area and more metal to be cold worked during the rolling process.

3. Hard roll of the thermal sleeve shoulder - The original thermal sleeve was only contact rolled. The increased compression and subsequent deformation of the thermal sleeve material should provide a more secure bond with the safe-end. Also, the additional wall thinning should mitigate sleeve to safe-end separation during HPI events.

4. Contact roll at the thermal sleeve collar - The effects of possible flow induced vibration will be reduced with the sleeve surface in contact with the nozzle ID.

5. Axially notched upstream end of the thermal sleeve - The 4 notches allow the placement of weld beads to provide additional anti-rotation protection.

In summary, the thermal sleeve has been redesigned to eliminate the causes which contributed to the failures at Crystal River, Oconee, ANO, and Rancho Seco.

11.0 MAKEUP SYSTEM OPERATING CONDITIONS

Aside from the redesign of the thermal sleeve, modifications to the makeup system operating conditions were also suggested following the Crystal River incident. The original design specification called for a minimum continuous makeup flow of 1-3 gpm. It was believed that at this limited flow rate, flow and thermal stratification could occur in the makeup line which may lead to thermal fatigue of the nozzle assembly. Similar flow conditions at 5 Westinghouse PWR's [8-10] in 1979 lead to cracking of the steam generator feedwater lines. Consequently, a minimum bypass flow of 15 gpm was suggested to eliminate, or at least mitigate this potential problem.

As additional information was obtained, the recommended 15 gpm minimum makeup flow rate was re-evaluated. The results from the instrumented Crystal River-3 nozzle indicated that the new design achieved all design requirements even at the lowest flow rate tested (1.6 gpm). The safe-end remained cool, while the outer surface of the nozzle varied by at most 20°F. The circumferential temperature gradients were small indicating that no significant "hot spots" or flow stratification was occurring. Also, as the makeup flow rate was increased to a maximum of 130 gpm, the nozzle thermal stresses tended to decrease.

In light of these findings, a minimum continuous makeup flow of 1-3 gpm (as originally specified) should adequately maintain all design parameters within analyzed limits and prevent thermal stratification. However, it must also be pointed out that increasing continuous makeup flow may decrease the nozzle thermal stresses.

12.0 AUGMENTED INSERVICE INSPECTION PLAN

Along with the thermal sleeve redesign and the MU system operating changes, an augmented inservice inspection (ISI) plan was also developed. An ISI provides a means of early problem detection, such that repairs can be effected before extensive damage occurs. Prior to Crystal River, no HPI/MU nozzle assembly inspection was required.

B&W and the Safe-End Task Force developed an augmented ISI for the 177 FA Owner's Group. Specifically, the plan calls for:

Makeup Nozzles

1. Unrepaired Nozzles

   - RT during the next five refueling outages to ensure that the thermal sleeve is in the proper location and no gap exists between the thermal sleeve and safe end. Ensure RT is comparable with "baseline" first RT taken. Perform RT every fifth refueling outage thereafter.

   - UT the safe end and some length of adjacent pipe/valve during the next five refueling outages to ensure no cracking. Perform UT every fifth refueling outage thereafter.

2. Repaired Nozzles (New Sleeve Design)

   - RT during the first refueling outage to ensure that the thermal sleeve is in the proper location and no gap has formed.

   - UT safe end, cold leg ID nozzle knuckle transition, and adjacent piping/valve during the first refueling outage to ensure no cracking exists.

   - RT and UT again at third and fifth refueling outages after repair and every fifth refueling outage thereafter.

3. Repaired Nozzles (with re-rolling)

- RT during the next five refueling outages to ensure that the thermal sleeve is in the proper location and no gap exists between the thermal sleeve and safe end. Ensure RT is comparable with "baseline" first RT taken. Perform RT every fifth refueling outage thereafter.

High Pressure Injection Nozzles

1. Unrepaired

- RT during the next five refueling outages to ensure that the thermal sleeve is in the proper location and no gap exists. Ensure RT is comparable with "baseline" first RT taken. Perform RT every fifth refueling outage thereafter.

2. Repaired (New Sleeve Design)

- RT during first refueling outage to ensure that the thermal sleeve is in the proper location and no gap has formed. RT during third and fifth refueling outages and every fifth refueling outage thereafter.

- UT the ID nozzle/cold leg transition knuckle area during the first refueling outage to assure that no cracking is present. UT during third and fifth refueling outages thereafter.

3. Repaired (with re-rolling)

- RT during the next five refueling outages and every fifth refueling outage thereafter to ensure a gap does not form.

13.0 JUSTIFICATION OF LONG TERM OPERATION

Finally, having described the modifications (design, operation, inspection) made to correct the problem, we must now consider the steps taken to support these changes. Specifically, continued operation on a long term basis will be justified analytically, experimentally, and by inspections of nozzles in service.

13.1 Analytical Justification

After the repair efforts were completed at the damaged sites, the NRC staff required that the new design be proven safe for operation in the near term. In response to this request, B&W provided certified field change authorizations (FCA) to the utilities. These FCA's were predicated on simple, yet conservative stress analysis, worst case operational histories, and the consideration of continued nozzle usage through the next fuel cycle only. As such, these studies were only valid in the short term.

In order to justify long term use, B&W recommended a more extensive stress analysis. The stress information required for more detailed evaluation of makeup and HPI nozzle design changes can be obtained most accurately through the use of the finite element method of structural analysis. This analysis technique will determine, in detail, the stresses in the critical areas and will provide the means to assess the impact of unanticipated operating transients on the makeup and HPI nozzles. Such an analytical capability will be invaluable at some later date if, for example, an HPI nozzle that had a loose thermal sleeve was subjected to more HPI flow cycles than can presently be shown to be acceptable using conservative techniques. In addition, evaluation of thermal sleeve/safe-end interface stresses may be required, at a later date, for unanticipated makeup nozzle flow transients. Inservice inspection (ISI) detected flaws could also be less conservatively evaluated if the new detailed stress profiles were available for use in determining the number of cycles for thru-wall crack propagation.

B&W's modified nozzle design is currently being used for both the double-duty HPI/MU nozzles and the HPI only nozzles. However, design differences in service conditions between the two nozzle functions lead to radically different stress distributions.

For the HPI/MU nozzle with continuous 95°F makeup flow, injection of HPI water at 40°F (design temperature) is normally not considered to be a severe transient. The highest stresses for this nozzle are at the point where the HPI/MU pipe penetrates the RC pipe (nozzle "knuckle" region) and are due to the steady axial temperature gradient between the relatively cool safe-end and the hot RC pipe.

On the other hand, the insulated HPI only nozzle is kept hot through heat conduction from the RC pipe under conditions of no HPI flow. When HPI is actuated, the sudden flow of 40°F water (design conditions) causes severe thermal stresses at the thin walled portion of the upstream end of the safe-end. Contributing to the stresses in this region are a severe radial temperature gradient and a local axial temperature gradient.

Although the HPI/MU and HPI only nozzles see different service conditions and experience different stress distributions, a single finite element model will suffice for both nozzle functions. The only exception will be substructured regions where a refined mesh is required to investigate highly stressed locations (e.g., near the wide collar for the makeup nozzle and in the safe-end for the HPI nozzle).

Ultimately, the stress analysis using [illegible] will quantify the usable lifetime of the modified design.

13.2 Experimental Justification

To substantiate the results of the analytical study, an experimental study was conducted (see Section 9.0 for details). The thermal sleeve/safe-end geometry was simulated using the test apparatus shown in Figure 11. The results indicated that under static conditions, the axial load carrying capability of the rolled joint varies in a non-linear manner with nominal values in the 6000-13000 lb. range (1-8% range). Thermal transient characteristics were obtained by injecting cold water through a heated simulated nozzle. During these thermal quench tests, the rolled joint lost load carrying capability (i.e., sleeve movement and leakage flow) for roll expansions less than 5% wall thinning. The natural vibration frequency of the thermal sleeves was also quantified in another segment of the test program. These tests showed that the natural frequency of the sleeve varies as a function of roll expansion length and degree of wall thinning with nominal values in the 220-250 Hz range.

14.0 CONCLUSIONS

Based upon the information presented, the following conclusions can be drawn:

1. Variations in contact expansion of the thermal sleeves is the most probable root cause of the failures.

2. Continued operation in the short term is acceptable with the modified design.

3. If continued inspections show that the sleeves are properly in place, it is not expected that the sleeves will loosen during plant operation prior to subsequent inspections.

15.0 RECOMMENDATIONS

As a result of the Safe End Task Force's investigation into the HPI/MU nozzle component failures, the following recommendations are made:

1. In terms of future repairs, it is recommended that:

   Nozzles with Original Design Thermal Sleeves

   Reroll the upstream end of the thermal sleeve when inspections indicate that a gap exists. A 5.0% wall reduction is suggested to achieve an adequate interfacial residual stress and avoid stress corrosion cracking of the thermal sleeve.

   Nozzles with Modified Design Thermal Sleeve

   Repair and/or replace the damaged components if inspections reveal that abnormal conditions are present.

   In either case, the affected utility should also verify that the components attached to the safe-end meet the design constraints used in the stress analysis.

2. In order to ensure proper HPI/MU system operation, it is recommended that:
   - A continuous makeup flow via bypass of the Pressurizer Level Control Valve should be maintained.
   - A known amount of bypass flow which is greater than 1.5 gpm should be maintained and checked frequently (increased flows of up to about 10-15 gpm may be preferable depending upon plant configuration and operating practices).

- There should be a consistent set of procedures to initiate continuous bypass flow
    - RCS temperature
    - RCS pressure
    - Bypass flow rate
    - Frequency of adjustment and calibration

- The makeup tank temperature should be maintained within the proper control band as determined by other plant parameters.

- In the event that future anomalies are discovered, proper logging of HPI initiations will be invaluable. This procedure should include:
    - Nozzles used
    - Temperature of BWST
    - Temperature of cold leg before and after HPI initiation
    - Pressure
    - Flow rate
    - Duration of HPI flow

3. An augmented inservice inspection plan as stated in Section 12.0 should be implemented.

4. A detailed stress analysis of a nozzle with a modified thermal sleeve design should be performed to justify long term operation.

REFERENCES

1. Lynchburg Research Center, "Examination of Normal Makeup Nozzle Thermal Sleeve and Safe-End", No. 77-1131543-00.

2. Sykes, J. F., Hoch, G. H., Beavers, J. A. and Berry, W. E. of Battelle Columbus Laboratories, "Failure Analysis of Safe-End to Check Valve Pipe Weld in the Crystal River-3 Makeup Water System", March 1, 1982.

3. D. L. Baty of Lynchburg Research Center, "Examination of Oconee-3 HPI Thermal Sleeve, Safe-End", LR:82:5463-08:01, March 26, 1982.

4. D. L. Baty of Lynchburg Research Center, "Examination of HPI Thermal Sleeve from Oconee-2", RDD:83:5492-08:01, June 2, 1982.

5. M. R. Dietrich of Lynchburg Research Center, "Examination of Thermal Sleeve from ANO", RDD:83:5032-08:01, June 28, 1982.

6. A. Flynn, et al., "Thermal Sleeve Failure and Repairs - Indian Point #1 Nuclear Unit (285 MW)", Nuclear Technology, Vol. 25, January 1975.

7. R. Snaider, "BWR Feedwater Nozzle and Control Rod Drive Return Line Nozzle Cracking", NUREG-0619, November 1980.

8. R. W. Klecker, "Thermal Fatigue Cracking in Pressurized Water Reactor Feedwater Lines", Pipe Crack Study Group Supporting Document, June 18, 1980.

9. M. H. Hu, J. L. Houtman and D. H. White, "Flow Model Test for the Investigation of Feedwater Line Cracking for PWR Steam Generators", ASME Conference, Denver, Colorado, June 21-25, 1981.

10. W. H. Bamford, A. Thurman and M. Mahlab, "Fatigue Crack Growth in Pressurized Water Reactor Feedwater Lines", ASME Conference, Denver, Colorado, June 21-25, 1981.

11. "Evaluation of Crystal River-3 HPI/MU Nozzle Testing", B&W Document ID 77-1134571-00, May 1982.

12. "ANSYS Engineering Analysis System - User's Manual", Swanson Analysis Systems, Inc., 1978 Edition, Revision 3, (Update 67L).

13. "Evaluation of Preliminary Cause of HPI/MU Nozzle Thermal Sleeve and Safe-End Failures", Minutes from the Safe End Task Force Meeting, Bethesda, Maryland, May 7, 1982.

14. <u>Loss of Thermal Sleeves in Reactor Coolant System Piping at Certain Westinghouse PWR Power Plants</u>, Nuclear Regulatory Commission Office of Inspection and Enforcement, IN 82-30, Washington, D.C. (1982), pp 1-2.

Figure 1. TYPICAL ELEVATION VIEW OF REACTOR COOLANT SYSTEM ARRANGEMENT SHOWING LOCATION OF HPI NOZZLE

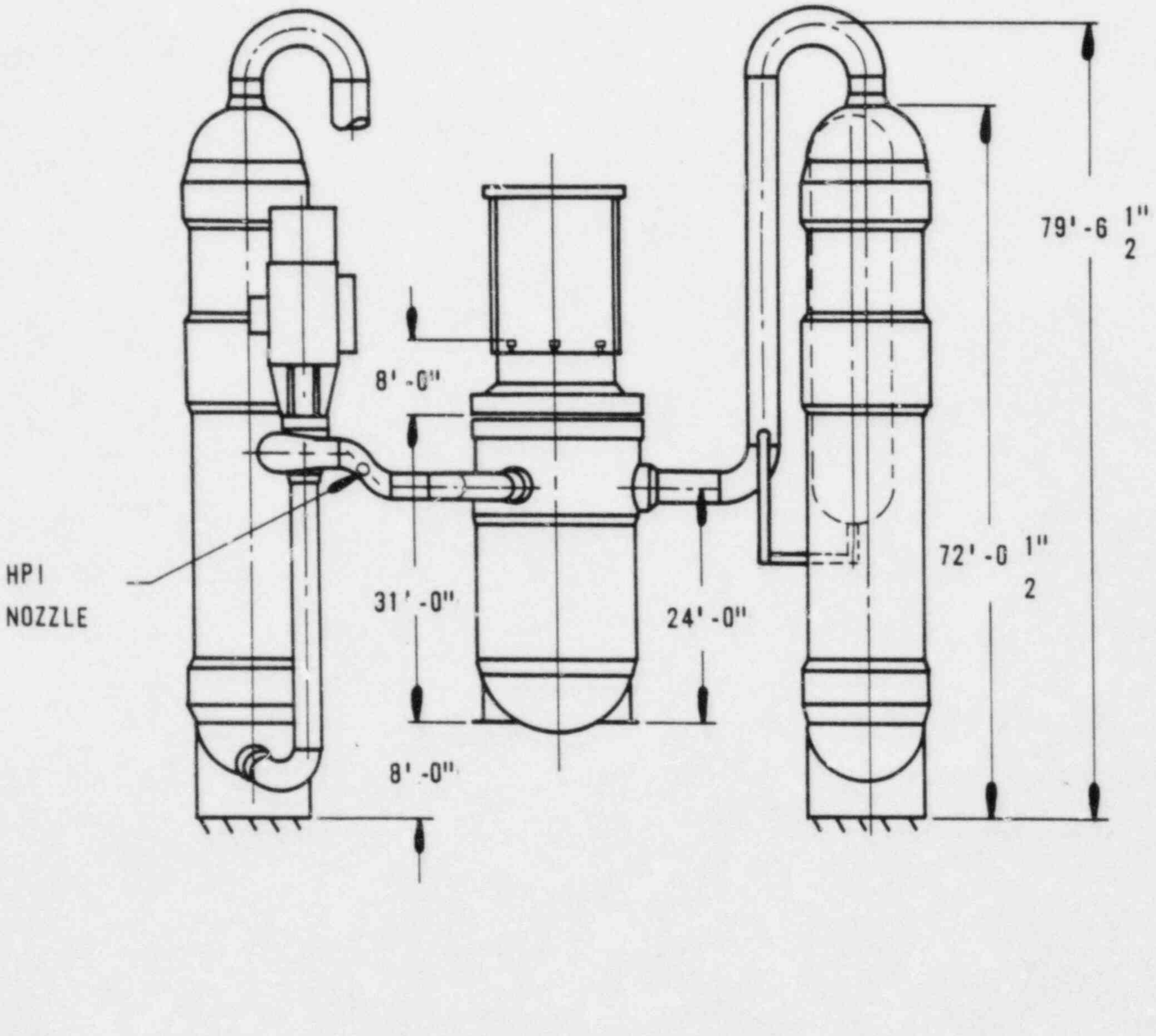


Figure 2 TYPICAL PLAN VIEW OF REACTOR COOLANT SYSTEM ARRANGEMENT SHOWING LOCATION OF HPI NOZZLE

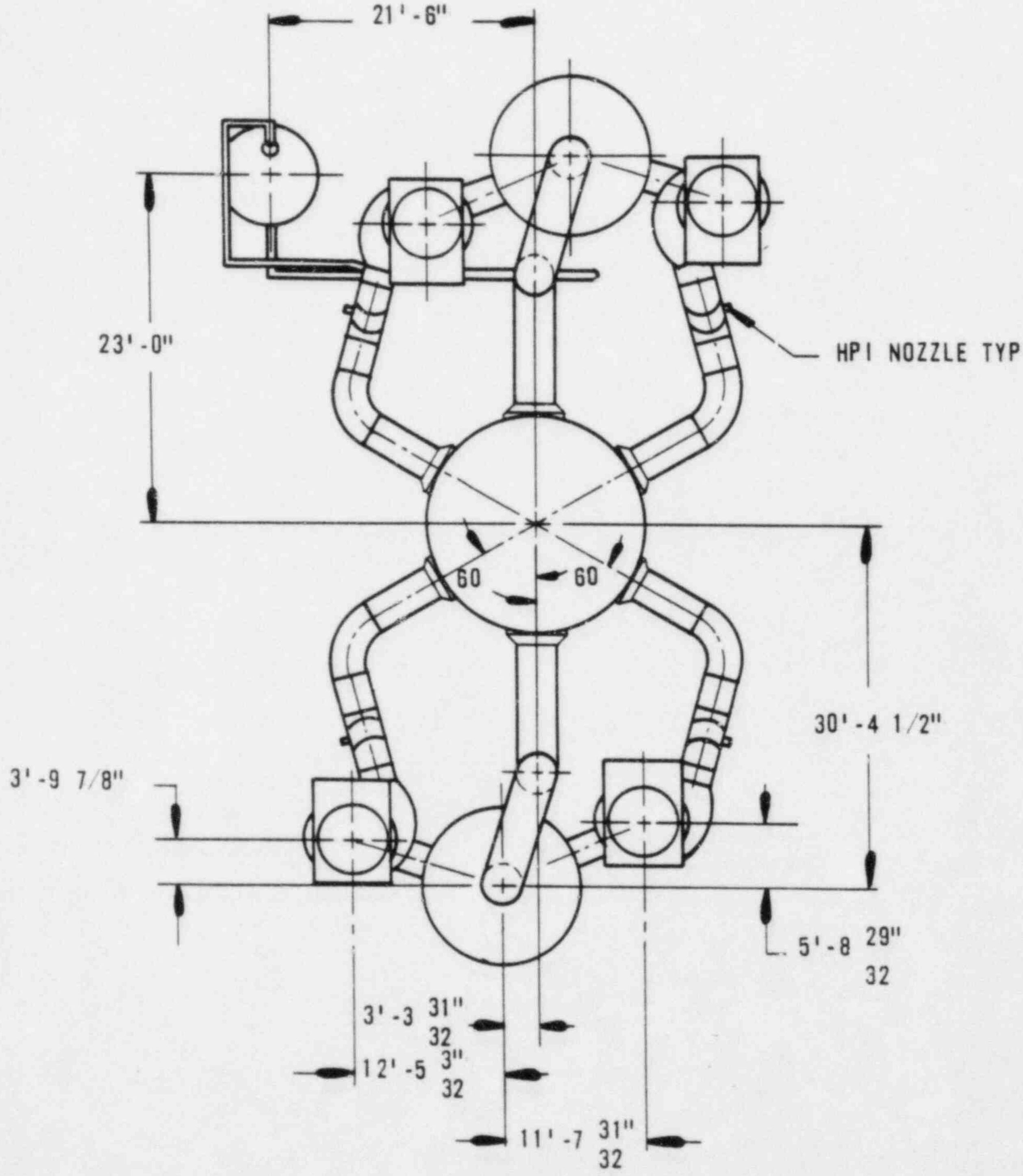


Figure 3

TYPICAL HPI AND HPI/MU NOZZLE

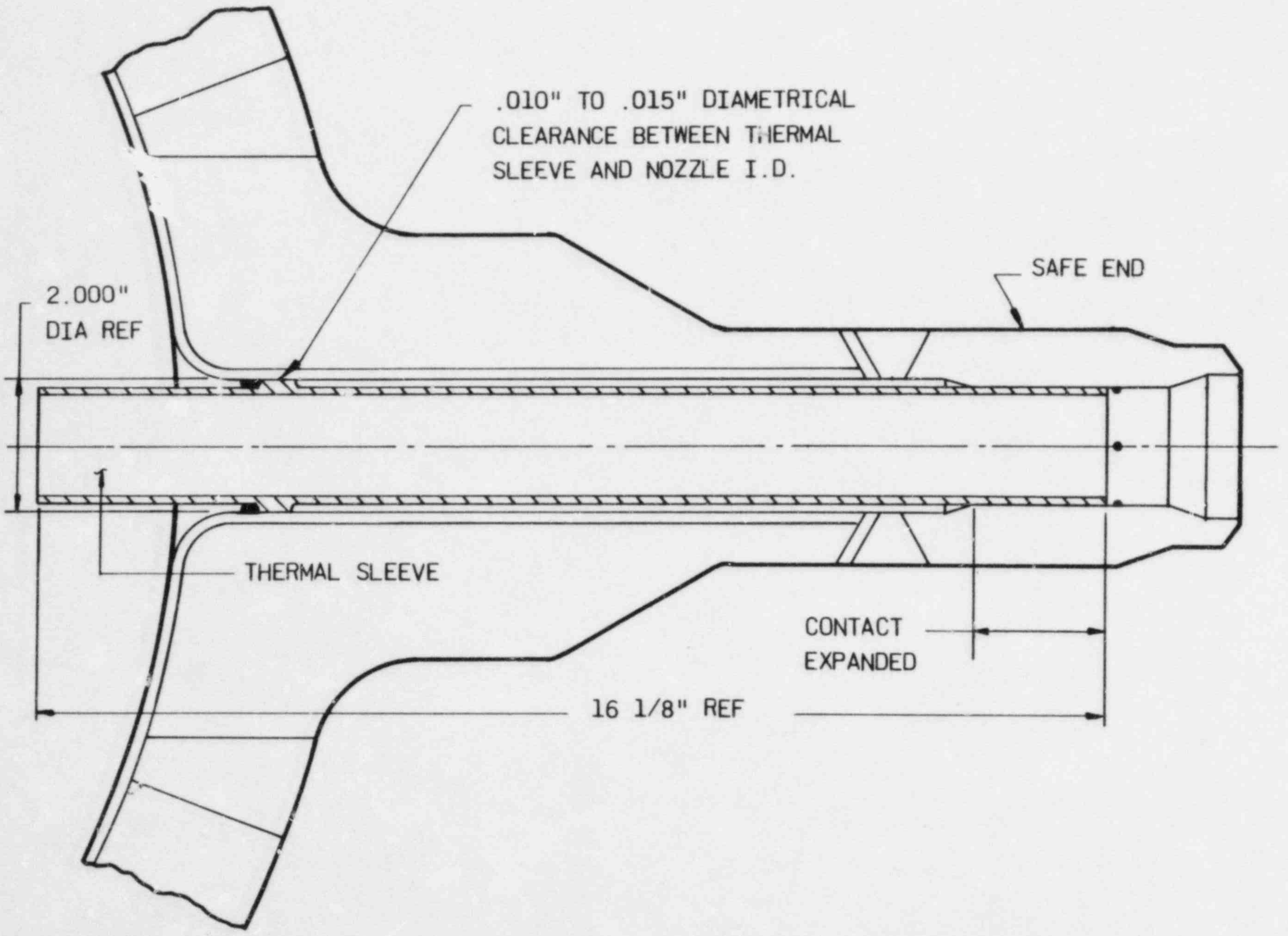


Figure 4

TYPICAL LAYOUT OF HPI OR HPI/MU LINE

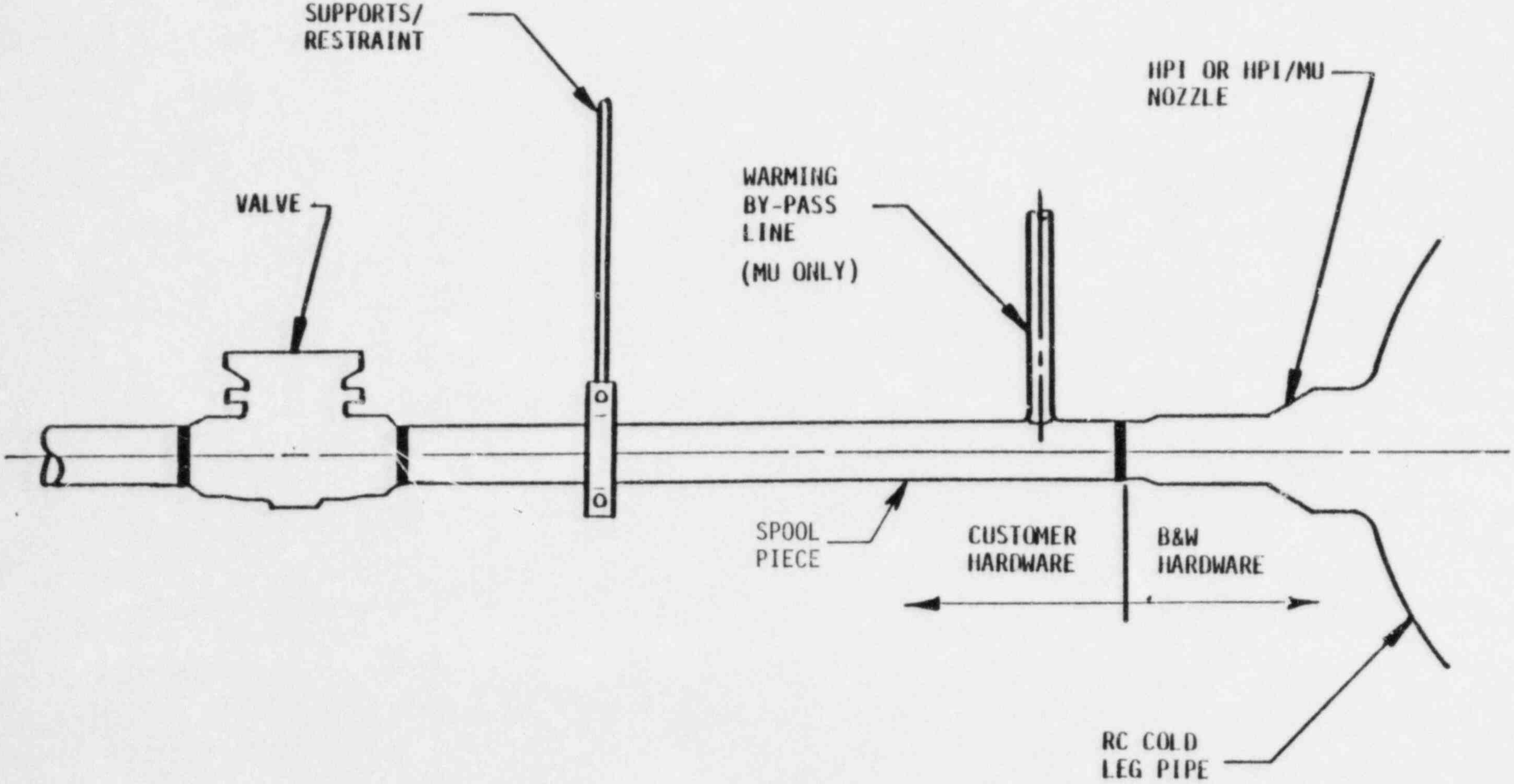


Figure 5

SAFE END TASK FORCE ACTION PLAN - REV 02

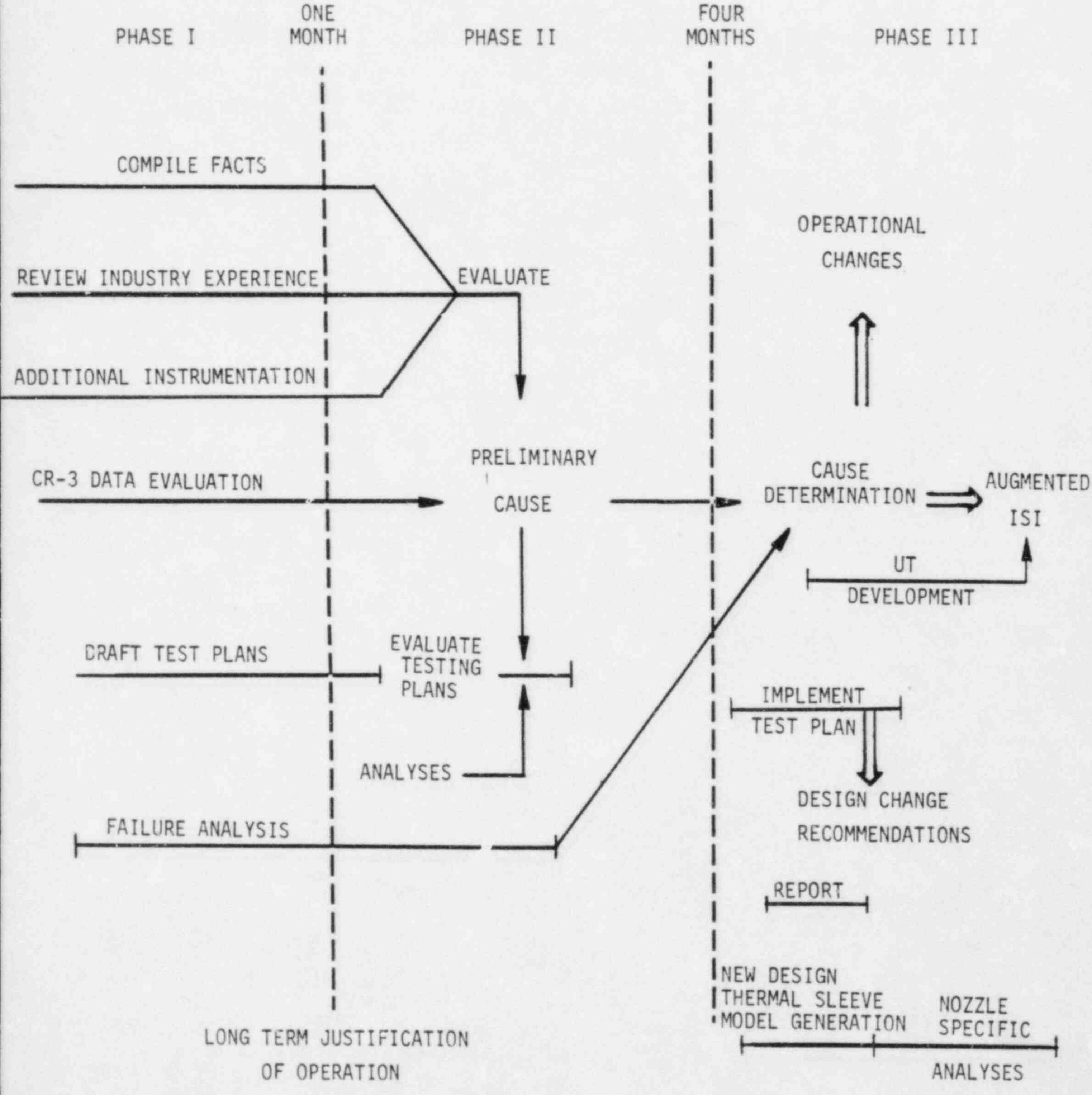


Figure 6

INSTRUMENTATION ARRANGEMENT AT CRYSTAL RIVER-3

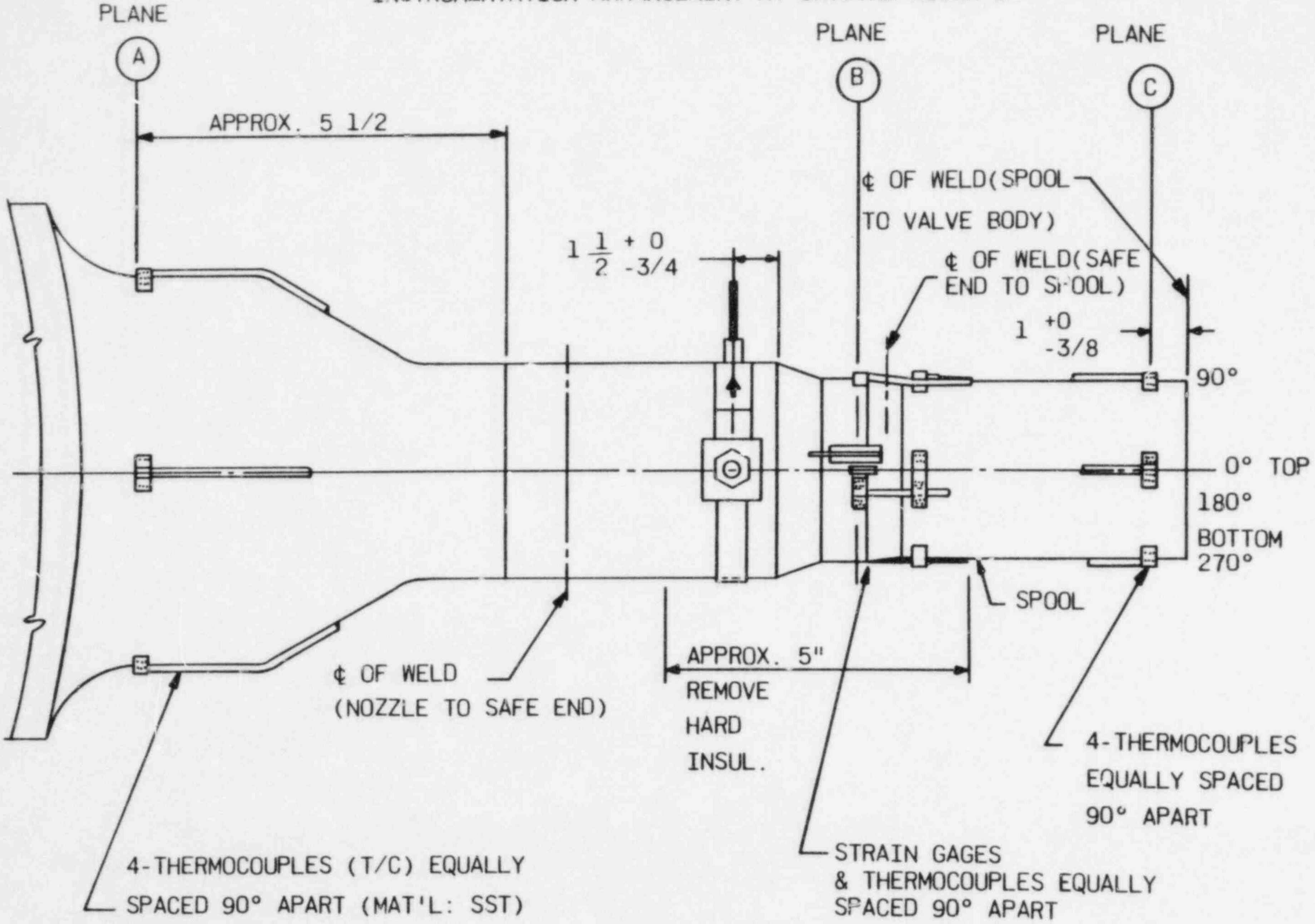


Figure 7 "GOODNESS OF ROLL" RESULTS

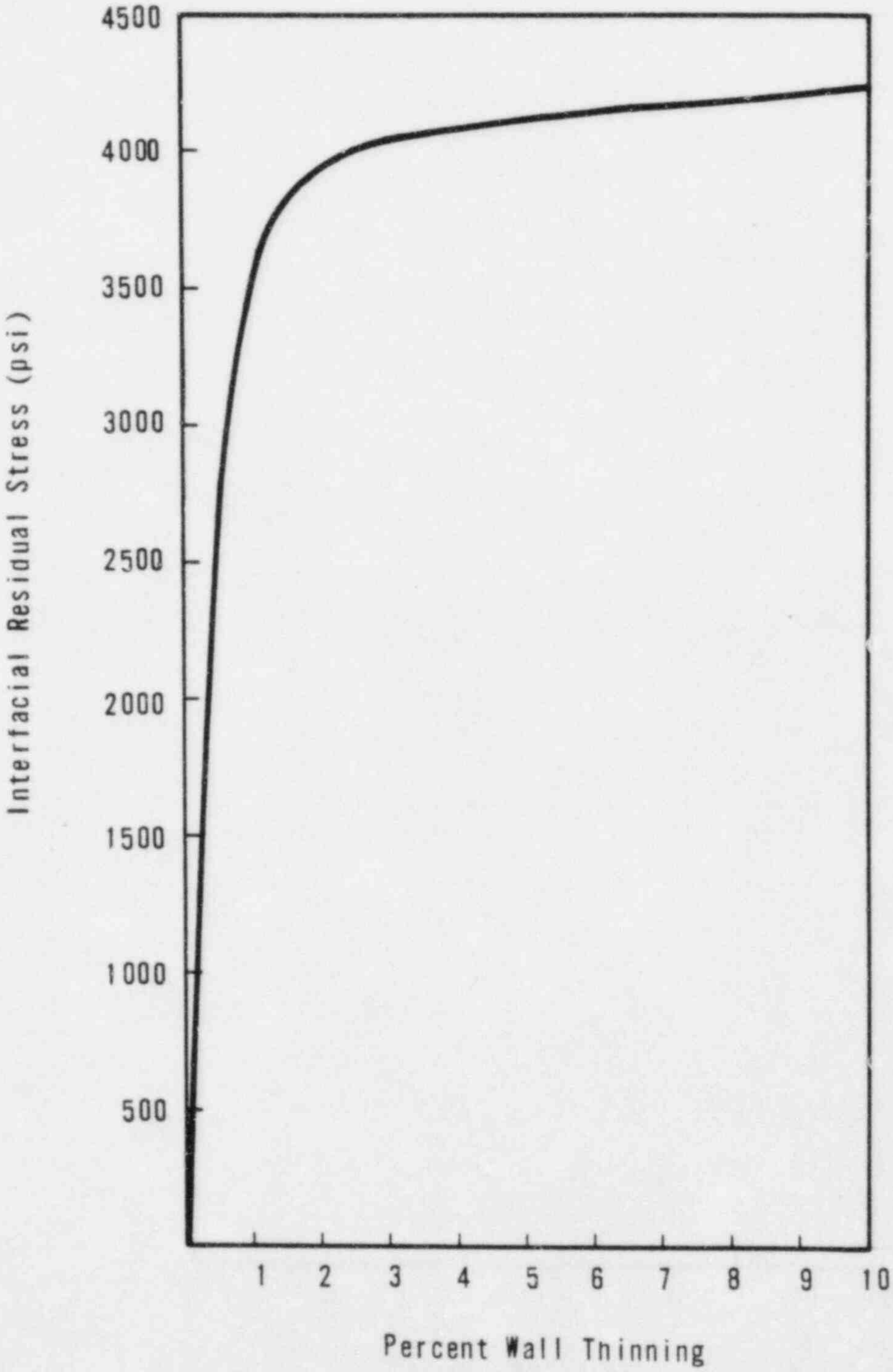


Figure 8

HARD ROLLED HPI/MU NOZZLE

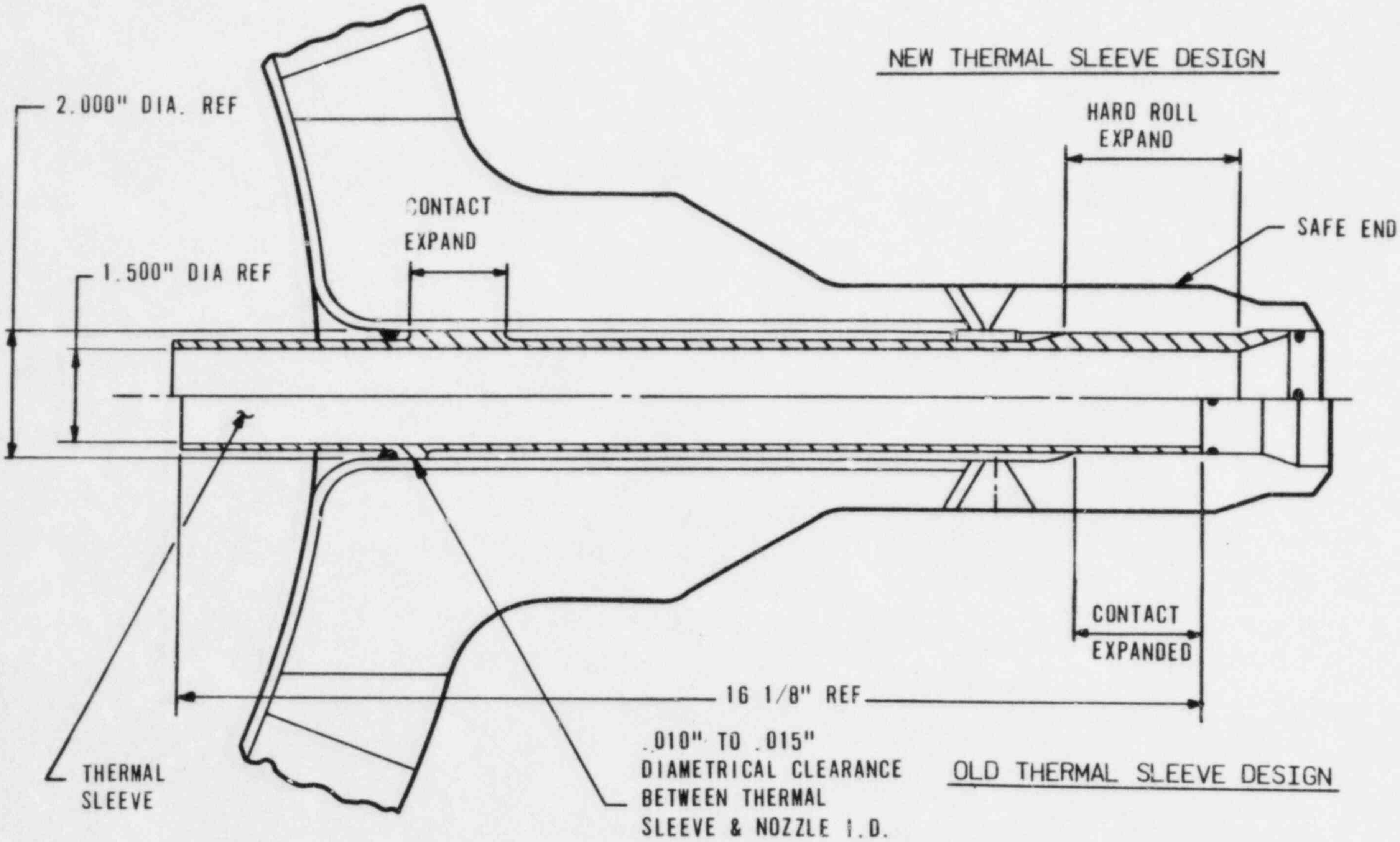


Figure 9 INTEGRAL HPI/MU NOZZLE MODIFICATION

HPI/MU NOZZLE
CONCEPTUAL DESIGN
FOR INTEGRAL SAFE-END/
THERMAL SLEEVE

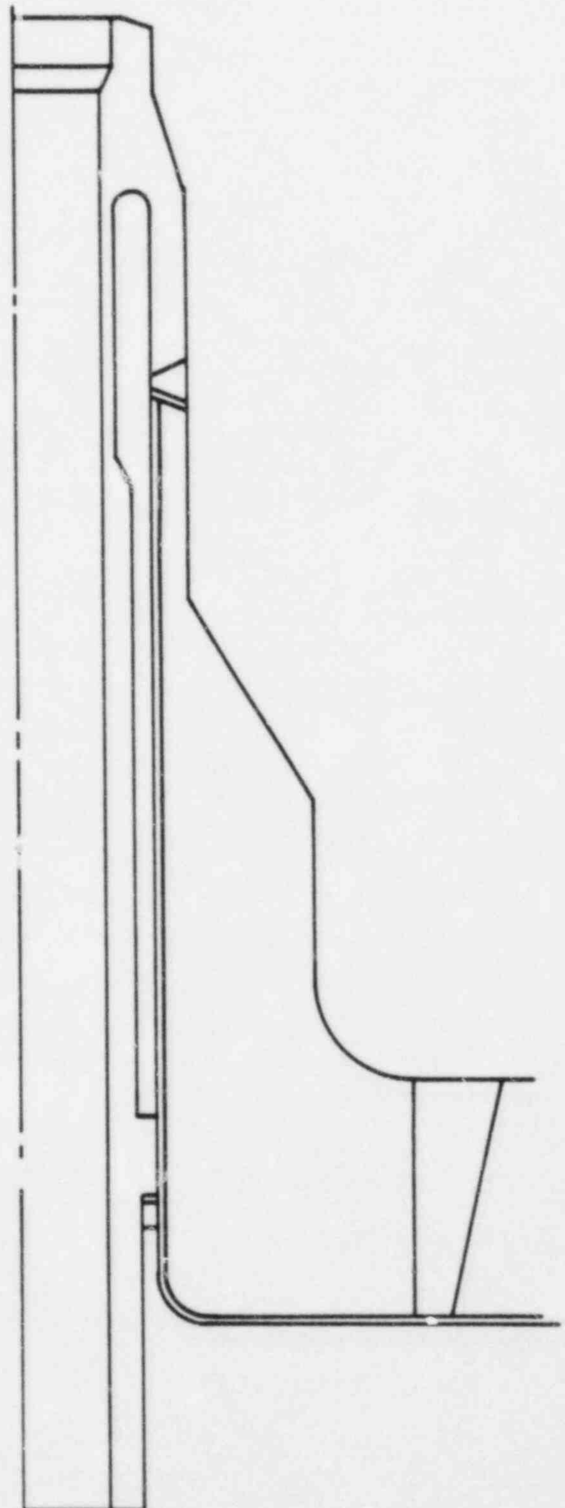
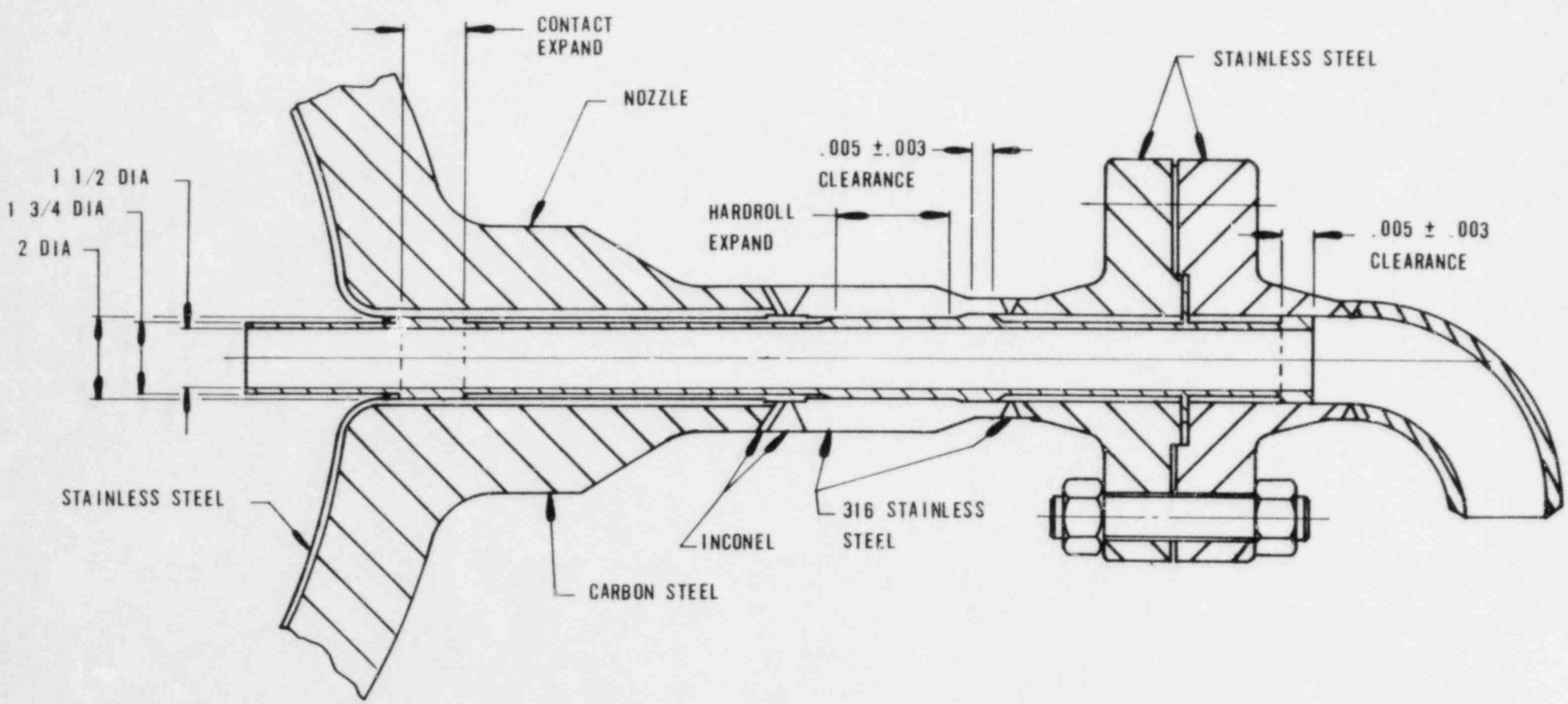


Figure 10 FLANGED MAKE-UP/HPI NOZZLE



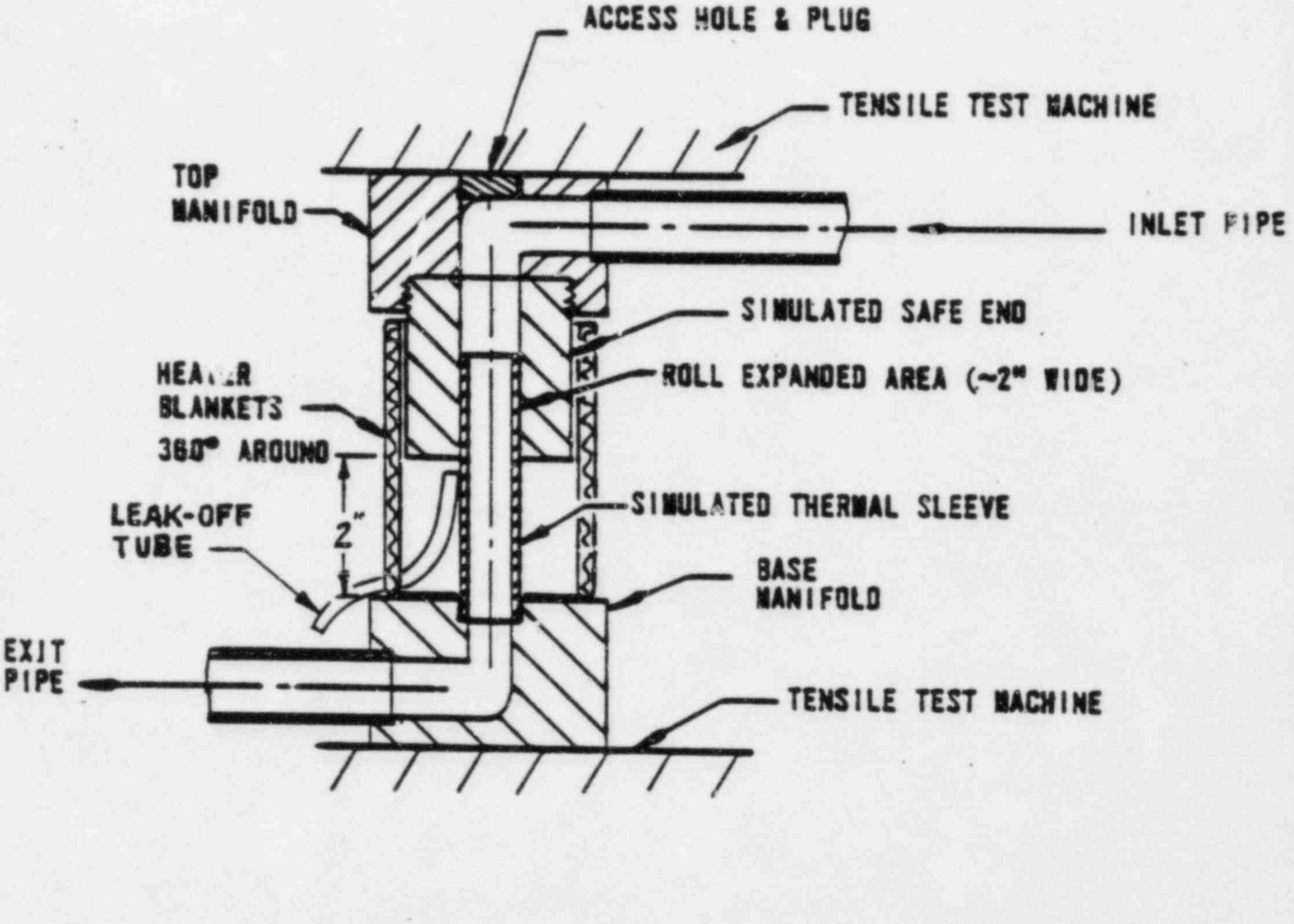


FIGURE 11. - ROLL EXPANSION TEST SCHEMATIC
DIAGRAM OF TEST FIXTURE

Figure 12 HPI/MU STATIC TEST RESULTS

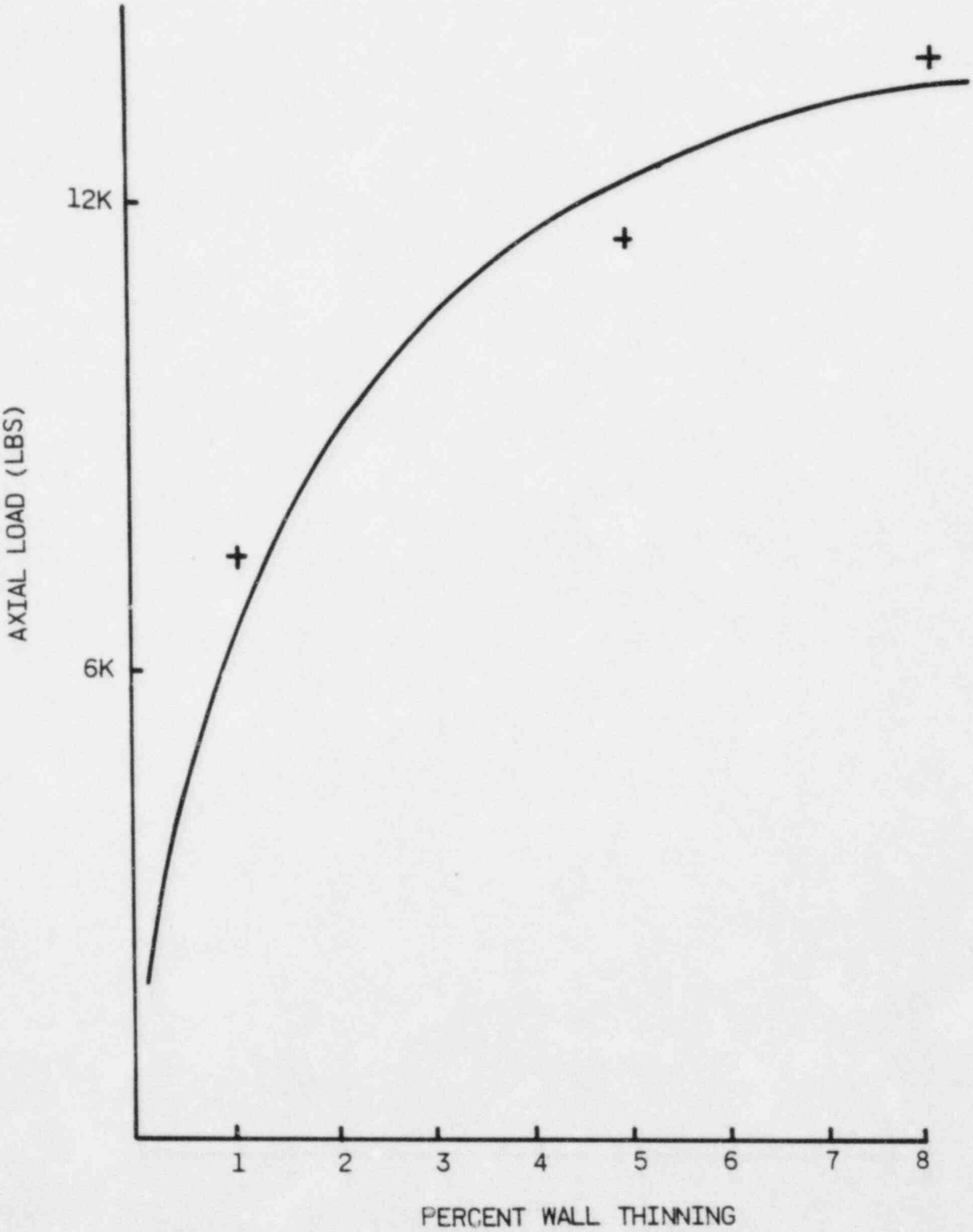


FIGURE 13

HPI/MU NOZZLE TEST RESULTS

TRANSIENT LOAD TESTS (PHASE II A)

	THERMAL SLEEVE WALL REDUCTION			
	0%	2%	4%	5%
DISPLACEMENT AFTER QUENCH (IN.)	1.053*	1.251	0.841	0
LEAKAGE (FL. OZ.)	~8	~4	0	0

POSITIVE DOWNWARD EQUIVALENT LOAD: 86 LBS.

TEMPERATURE: MAX: 550^{o}F, MIN: 200^{o}F

QUENCH FLOW: 275 GPM AT 65^{o}F

*THE MOTION OF THE SLEEVE WAS STOPPED PREMATURELY BY JAMMING THE LEAK-OFF TUBE IN THE GAP.

FIGURE 14

HPI/MU NOZZLE TEST RESULTS

VIBRATION TEST (NO FREE END RESTRAINT)

	THERMAL SLEEVE WALL REDUCTION			
	1%	1%	5%	8%
CONTACT LENGTH (IN.)	1 1/2	2	2	2
NATURAL FREQUENCY (H_Z)	221.8	236.0	237.5	237.5
NATURAL FREQUENCY AT (H_Z) 90° FROM ABOVE	239.0	250.1	251.6	253.1
DAMPING(%)	1.86	1.79	1.59	1.39

Figure 15 NATURAL VIBRATION FREQUENCY TEST SCHEMATIC DIAGRAM

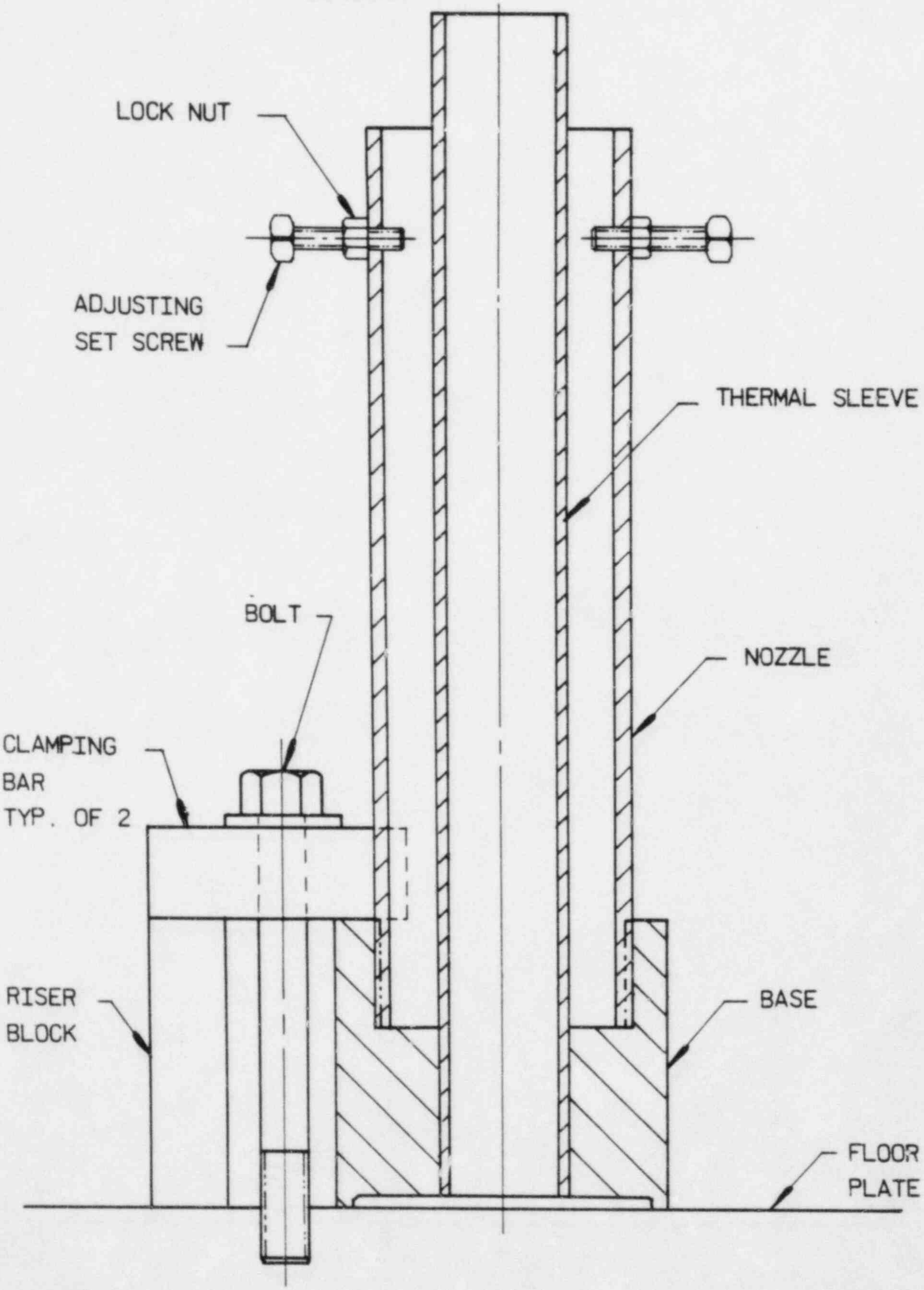


TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	INSPECTION RESULTS (See Note 2)	TH.SLEEVE COLLAR OD	NOZZLE ID IN COLLAR AREA	DIAMETRICAL GAP BETWEEN TH.SL.COL.& NOZ. (MIL)	THERMAL SLEEVE ID/OD	SAFE END ID
OCONEE 1	WX		A1	MU/HPI	OK					
	XY		A2	MU/HPI	"					
	YZ		B2	HPI	"					
	ZW		B1	HPI	"					
OCONEE 2	WX	B44	B1	HPI	B					1.762
	XY	B41	B2	HPI	C		2.031			1.763
	YZ	B40	A2	MU/HPI	A					1.763
	ZW	B46	A1	MU/HPI	OK					1.763
OCONEE 3	WX	B44	B1	HPI	B	2.003	2.015	12	1.500/1.754	1.762
	XY	(See Note 4)	B2	HPI	OK					
	YZ	B40	A2	MU/HPI	A	1.992	2.003	11	1.500/1.752	1.762
	ZW	(See Note 4)	A1	MU/HPI	OK					
TMI 1	WX	B44		HPI	OK					
	XY	B41		MU/HPI	"					
	YZ	B40		HPI	"					
	ZW	B46		HPI	"					
TMI 2	WX									
	XY									
	YZ									
	ZW									
CR 3	WX	B44	A2	HPI	OK	1.993	2.004	11	1.498/1.754	1.763
	XY	B41	A1	MU/HPI	A	1.994	2.004	10	1.498/1.752	1.764
	YZ	B40	B1	HPI	OK	1.992	2.003	11	1.497/1.753	1.762
	ZW	B46	B2	HPI	OK	2.003	2.013	10	1.502/1.754	1.763
ANO 1	WX	B44	C	HPI	OK	1.991	2.002	11	1.500/1.754	1.762
	XY	B41	D	MU/HPI	C	1.989	2.002	13	1.499/1.754	1.762
	YZ	B40	B	HPI	B	1.982	1.994	12	1.500/1.754	1.762
	ZW	B41	A	HPI	B	1.993	2.003	10	1.499/1/754	1.764
RANCHO SECO	WX	B44	D	HPI	OK	1.989	2.000	11	?/?	1.762
	XY	B46	C	HPI	OK	1.992	2.003	11	1.500/1.754	1.762
	YZ	B40	A	MU/HPI	A	1.981	1.992	11	1.500/1.753	1.761
	ZW	B41	B	HPI	B	1.990	2.003	13	1.498/1.754	1.764
MIDLAND 1	WX	B44	A	HPI		1.993	2.005	12		1.762
	XY	B41	B	MU/HPI		1.993	2.006	13		1.762
	YZ	B40	C	HPI		1.990	2.002	12		1.762
	ZW	B41	D	HPI		2.008	2.020	12		1.762
MIDLAND 2	WX	B44	C	HPI		1.998	2.010	12		
	XY	B41	D	HPI		1.993	2.006	13		
	YZ	B40	A	MU/HPI		1.997	2.010	13		
	ZW	B41	B	HPI		1.994	2.006	12		
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	OK	2.004	2.016	12	1.500/1.753	1.762
	XY	B61	A1	HPI	"	2.003	2.015	12	1.498/1.754	"
	YZ	B59	B1	MU/HPI	"	1.985	1.997	12		"
	ZW	B44	B2	HPI	"	2.003	2.018	15	1.500/1.750	"

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	THERMAL SLEEVE HT. NO. AND MAT'L. SPEC.	SAFE END HT. NO. AND MAT'L. SPEC.	EXPANSION INFO. LOC.	EXPANSION INFO. DATE	EXPANSION INFO. TOOL NO.	SOURCE REFERENCE DOC. REFERENCE DRAWINGS	SOURCE REFERENCE DOC. SHOP RECORDS IDENTIFIED BY PIPE SER.NO.
CONEE 1	WX		A1	MU/HPI							
	XY		A2	MU/HPI							
	YZ		B2	HPI							
	ZW		B1	HPI							
CONEE 2	WX	B44	B1	HPI	-A336F8M	43116-A336F8M	SITE	(See Note 3)	(See Note 3)	146614E-5	B44-204-50-1
	XY	B41	B2	HPI	"	" "	"			146629E-7	B41-204-50-1
	YZ	B40	A2	MU/HPI	"	" "	"				B40-204-50-1
	ZW	B46	A1	MU/HPI	"	" "	"				B46-204-50-1
CONEE 3	WX	B44	B1	HPI	05477-A336F8M	65047-A336F8M	MTV			150141E-7	B44-209-50-1
	XY	(See Note 4)	B2	HPI	" "	" "	"			150156E-7	
	YZ	B40	A2	MU/HPI	" "	" "	"	11-18-71	7573-1		B40-209-50-1
	ZW	(See Note 4)	A1	MU/HPI	" "	" "	"				
MI 1	WX	B44		HPI		-SB 166	SITE	(See Note 3)	(See Note 3)	131956E-7	
	XY	B41		MU/HPI		"	"			160493E-0	
	YZ	B40		HPI		"	"			131960E-9	
	ZW	B46		HPI		"	"				
MI 2	WX									141578E-9	
	XY									141576E-13	
	YZ										
	ZW										
R 3	WX	B44	A2	HPI	05477-A336F8M	810906-A336F8M	MTV	9-7-71	7573-1	141599E-5	B44-207-50-1
	XY	B41	A1	MU/HPI	" "	" "	"			141597E-5	B41-207-50-1
	YZ	B40	B1	HPI	" "	" "	"	9-8-71	7573-1		B40-207-50-1
	ZW	B46	B2	HPI	" "	" "	"	9-11-71	7573-1		B46-207-50-1
ANO 1	WX	B44	C	HPI	05477-A336F8M	811236-A336F8M	MTV	3-7-72	7573-1	131998E-4	B44-208-50-1
	XY	B41	D	MU/HPI	" "	" "	"	3-15-72	"	131996E-6	B41-208-50-2
	YZ	B40	B	HPI	" "	81564- "	"	11-12-71	"		B40-208-50-1
	ZW	B41	A	HPI	" "	811236- "	"	12-1-71	"		B41-208-50-1
RANCHO SECO	WX	B44	D	HPI	05477-A336F8M	129186-A336F8M	MTV	1-8-72	7573-1	143491E-7	B44-2011-50-1
	XY	B46	C	HPI	" "	" "	"	12-30-71	"	143509E-8	B46-2011-50-1
	YZ	B40	A	MU/HPI	" "	" "	"	12-30-71	"		B40-2011-50-1
	ZW	B41	B	HPI	" "	" "	"	1-6-72	"		B41-2011-50-1
MIDLAND 1	WX	B44	A	HPI	818442-A336F8M	43116-A336F8M	MTV	9-20-74	7573-1	150176E-6	B44-2012-50-1
	XY	B41	B	MU/HPI	" "	" "	"	12-9-74	"	150191E-1	B41-2012-50-1
	YZ	B40	C	HPI	" "	" "	"	10-16-74	"		B40-2012-50-1
	ZW	B41	D	HPI	" "	" "	"	9-27-74	"		B41-2012-50-2
MIDLAND 2	WX	B44	C	HPI	121294-A336F8M	817962-A336F8M	MTV	10-15-75	7573-1	150206E-4	B44-2013-50-1
	XY	B41	D	HPI	" "	29006- "	"	9-28-75	"	150221E-2	B41-2013-50-1
	YZ	B40	A	MU/HPI	" "	817962- "	"	10-16-75	"		B40-2013-50-1
	ZW	B41	B	HPI	" "	43116- "	"	9-23-75	"		B41-2013-50-2
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	05477-A336F8M	811584-A336F8M	MTV & SITE (See Note 5)	6-27-72	7673-1	152027E-4	B56-2014-50-1
	XY	B61	A1	HPI	" "	" "		7-6-72	"	152042E-4	B61-2014-50-1
	YZ	B59	B1	MU/HPI	" "	" "		6-16-72	"		B59-2014-50-1
	ZW	B44	B2	HPI	" "	48417- "		7-3-72	"		B44-2014-50-1

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	PUMP ROTATION	FLOW LENGTH FROM RC PUMP	(a) COLD LEG GEOM. & NOZZLE DATE ORIENTATION	2/2 RC FLOW (% of 131.3 x 10 lbm/hr)	NO. OF RC PUMP IMPELLER VANES	NO. OF RC PUMP DIFFUSER VANES
ONEE 1	WX		A1	MU/HPI	2 CCW/LOOP	5.2 ft.	Type A	109%	7	12
	XY		A2	MU/HPI	"	"	"	"	"	"
	YZ		B2	HPI	"	"	"	"	"	"
	ZW		B1	HPI	"	"	"	"	"	"
ONEE 2	WX	B44	B1	HPI	2 CCW/LOOP	5.2 ft.	Type A	112%	5	4
	XY	B41	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	B46	A1	MU/HPI	"	"	"	"	"	"
ONEE 3	WX	B44	B1	HPI	2 CCW/LOOP	5.2 ft.	Type A	112%	5	4
	XY	(See Note 4)	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	(See Note 4)	A1	MU/HPI	"	"	"	"	"	"
I 1	WX	B44		HPI	2 CCW/LOOP	5.2 ft.	Type A	109%	7	12
	XY	B41		MU/HPI	"	"	"	"	"	"
	YZ	B40		HP	"	"	"	"	"	"
	ZW	B46		HPI	"	"	"	"	"	"
I 2	WX									
	XY									
	YZ									
	ZW									
3	WX	B44	A2	HP	2 CCW/LOOP	5.2 ft.	Type B	112%	5	9
	XY	B41	A1	MU/HP	"	"	"	"	"	"
	YZ	B40	B1	HP	"	"	"	"	"	"
	ZW	B46	B2	HPI	"	"	"	"	"	"
O 1	WX	B44	C	HP	2 CCW/LOOP	5.2 ft.	Type B	112%	5	9
	XY	B41	D	MU/HP	"	"	"	"	"	"
	YZ	B40	B	HP	"	"	"	"	"	"
	ZW	B41	A	HP	"	"	"	"	"	"
NCHO ECO	WX	B44	D	HPI	2 CCW/LOOP	5.2 ft.	Type A	116%	5	4
	XY	B46	C	HPI	"	"	"	"	"	"
	YZ	B40	A	MU/HPI	"	"	"	"	"	"
	ZW	B41	B	HPI	"	"	"	"	"	"
DLAND 1	WX		A	HPI	*2 CCW/LOOP	5.2 ft.	Type B	*100%	*5	*9
	XY		B	MU/HPI		"	"			
	YZ		C	HPI		"	"			
	ZW		D	HPI		"	"			
DLAND 2	WX		C	HPI	*2 CCW/LOOP	5.2 ft.	Type B	*100%	*5	*9
	XY		D	HPI		"	"			
	YZ		A	MU/HPI		"	"			
	ZW		B	HPI		"	"			
VIS SSE 1 ee ote 5)	WX	B56	A2	HPI	1 CW & 1 CCW per LOOP	9.1 ft	Type C	114%	5	9
	XY	B61	A1	HPI	"	"	"	"	"	"
	YZ	B59	B1	MU/HPI	"	"	"	"	"	"
	ZW	B44	B2	HP	"	"	"	"	"	"

) See Attachments

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	MINIMUM ALLOWABLE RC PRESSURE TO PROVIDE NPSH FOR RC PUMPS AT 160° F (2/2)	TOTAL MAKEUP FLOW WITH 1 MU PUMP OPERATION AT 2150 PSIG	TOTAL MAKEUP FLOW WITH 2 MU PUMP OPERATION AT 2150 PSIG	TOTAL HPI FLOW WITH 1 PUMP OPERATION AT 1500 PSIG
OCONEE 1	WX		A1	MU/HPI	300 PSIG	157 GPM	186 GPM	360 GPM
	XY		A2	MU/HPI	"	"	"	"
	YZ		B2	HPI	"	"	"	"
	ZW		B1	HPI	"	"	"	"
OCONEE 2	WX	B44	B1	HPI	170 PSIG	157 GPM	186 GPM	360 GPM
	XY	B41	B2	HPI	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"
	ZW	B46	A1	MU/HPI	"	"	"	"
OCONEE 3	WX	B44	B1	HPI	215 PSIG	157 GPM	186 GPM	360 GPM
	XY	(See Note 4)	B2	HPI	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"
	ZW	(See Note 4)	A1	MU/HPI	"	"	"	"
TMI 1	WX	B44		HPI	290 PSIG	145 GPM	165 GPM	405 GPM
	XY	B41		MU/HPI	"	"	"	"
	YZ	B40		HPI	"	"	"	"
	ZW	B46		HPI	"	"	"	"
TMI 2	WX							
	XY							
	YZ							
	ZW							
CR 3	WX	B44	A2	HPI	230 PSIG (c)	147 GPM	185 GPM	410 GPM
	XY	B41	A1	MU/HPI	"	"	"	"
	YZ	B40	B1	HPI	"		"	"
	ZW	B46	B2	HPI	"	"	"	"
ANO 1	WX	B44	C	HPI		142 GPM	180 GPM	405 GPM
	XY	B41	D	MU/HPI		"	"	"
	YZ	B40	B	HPI		"	"	"
	ZW	B4[illegible]	A	HPI		"	"	"
RANCHO SECO	WX	B44	D	HPI	102 PSIG	192 GPM	288 GPM	405 GPM
	XY	B46	C	HPI	"	"	"	"
	YZ	B40	A	MU/HPI	"	"	"	"
	ZW	B41	B	HPI	"	"	"	"
MIDLAND 1	WX		A	HPI	*265 PSIG for minimum seal staging	140 GPM	NOT AVAILABLE	*420 GPM TOTAL
	XY		B	MU/HPI				
	YZ		C	HPI				
	ZW		D	HPI				
MIDLAND 2	WX		C	HPI	*265 PSIG for minimum seal staging	140 GPM	NOT AVAILABLE	*420 GPM TOTAL
	XY		D	HPI				
	YZ		A	MU/HPI				
	ZW		B	HPI				
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	190 PSIG (c)	164 GPM	264 GPM	300 GPM
	XY	B61	A1	HPI	"	"	"	"
	YZ	B59	B1	MU/HPI	"	"	"	"
	ZW	B44	B2	HPI	"	"	"	"

(c) at 260°F

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	TOTAL HPI FLOW WITH 2 PUMP OPERATION AT 1500 PSIG	TOTAL HPI FLOW WITH 3 PUMP OPERATION AT 1500 PSIG	RECIRCULATION CONTROL MEANS	BWST TEMPERATURE (NORMAL OPERATION)	FULL POWER YEARS	REACTOR TRIPS
OCONEE 1	WX		A1	MU/HPI	(b) 720/540 GPM	900 GPM	BLOCK ORIFICE (NO ESFAS ISOL.)	80° F	5.1	87
	XY		A2	MU/HPI	"	"	"	"	"	"
	YZ		B2	HPI	"	"	"	"	"	"
	ZW		B1	HPI	"	"	"	"	"	"
OCONEE 2	WX	B44	B1	HPI	(b) 720/540 GPM	900 GPM	BLOCK ORIFICE (NO ESFAS ISOL.)	80° F	4.82	53
	XY	B41	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	B46	A1	MU/HPI	"	"	"	"	"	"
OCONEE 3	WX	B44	B1	HPI	(b) 720/540 GPM	900 GPM	BLOCK ORIFICE (NO ESFAS ISOL.)	80° F	4.99	47
	XY	(See Note 4)	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	(See Note 4)	A1	MU/HPI	"	"	"	"	"	"
TMI 1	WX	B44		HPI	810 GPM		FLOW ORIFICE	70° F	3.51	18
	XY	B41		MU/HPI	"		"	"	"	"
	YZ	B40		HPI	"		"	"	"	"
	ZW	B46		HPI	"		"	"	"	"
TMI 2	WX									
	XY									
	YZ									
	ZW									
CR 3	WX	B44	A2	HPI	790 GPM	1130 GPM	FLOW ORIFICE		2.66	56
	XY	B41	A1	MU/HPI	"	"	"		"	"
	YZ	B40	B1	HPI	"	"	"		"	"
	ZW	B46	B2	HPI	"	"	"		"	"
ANO 1	WX	B44	C	HPI	780 GPM		FLOW ORIFICE		4.63	56
	XY	B41	D	MU/HPI	"		"		"	"
	YZ	B40	B	HPI	"		"		"	"
	ZW	B41	A	HPI	"		"		"	"
RANCHO SECO	WX	B14	D	HPI	585 GPM	650 GPM	FLOW ORIFICE		3.87	52
	XY	B46	C	HPI	"	"	"		"	"
	YZ	B40	A	MU/HPI	"	"	"		"	"
	ZW	B41	B	HPI	"	"	"		"	"
MIDLAND 1	WX		A	HPI	*675 GPM TOTAL	NOT AVAILABLE	*FLOW ORIFICE	40^oF-110^oF (DEPENDING ON THE WEATHER)	0	0
	XY		B	MU/HPI					"	"
	YZ		C	HPI					"	"
	ZW		D	HPI					"	"
MIDLAND 2	WX		C	HPI	*675 GPM TOTAL	NOT AVAILABLE	*FLOW ORIFICE	40^oF-110^oF (DEPENDING ON THE WEATHER)	0	0
	XY		D	HPI					"	"
	YZ		A	MU/HPI					"	"
	ZW		B	HPI					"	"
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	600 GPM		FLOW ORIFICE		2.01	46
	XY	B61	A1	HPI	"		"		"	"
	YZ	B59	B1	MU/HPI	"		"		"	"
	ZW	B44	B2	HPI	"		"		"	"

(b) 2 pump operation for ONS-III can either be:

1 HPI Train with 2 pumps
or 1 HPI Train with 1 pump and 1 HPI Train with 1 pump

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	EST. MAX. HPI NOZZLE ACT.	EST. HPI TO NOZZLE	MU/HPI CONNECTION
OCONEE 1	WX		A1	MU/HPI	(20)	87	PIPE/PIPE
	XY		A2	MU/HPI		87	"
	YZ		B2	HPI			"
	ZW		B1	HPI			"
OCONEE 2	WX	B44	B1	HPI	(13)		PIPE/PIPE
	XY	B41	B2	HPI			"
	YZ	B40	A2	MU/HPI		53	"
	ZW	B46	A1	MU/HPI		53	"
OCONEE 3	WX	B44	B1	HPI	(17)		PIPE/PIPE
	XY	(See Note 4)	B2	HPI			"
	YZ	B40	A2	MU/HPI		47	"
	ZW	(See Note 4)	A1	MU/HPI		47	"
TMI 1	WX	B44		HPI	-	-	CHECK VALVE
	XY	B41		MU/HPI			"
	YZ	B40		HPI			"
	ZW	B46		HPI			"
TMI 2	WX						
	XY						
	YZ						
	ZW						
CR 3	WX	B44	A2	HPI	39		CHECK VALVE
	XY	B41	A1	MU/HPI		49	"
	YZ	B40	B1	HPI	36		"
	ZW	B46	B2	HPI	37		"
ANO 1	WX	B44	C	HPI	(17)		ELBOW
	XY	B41	D	MU/HPI		56	"
	YZ	B40	B	HPI			"
	ZW	B41	A	HPI			"
RANCHO SECO	WX	B44	D	HPI	(31)		ELBOW
	XY	B46	C	HPI			"
	YZ	B40	A	MU/HPI		52	"
	ZW	B41	B	HPI			"
MIDLAND 1	WX		A	HPI	*0	*0	SEVERAL FEET
	XY		B	MU/HPI			" "
	YZ		C	HPI			" "
	ZW		D	HPI			" "
MIDLAND 2	WX		C	HPI	*0	*0	SEVERAL FEET
	XY		D	HPI			" "
	YZ		A	MU/HPI			" "
	ZW		B	HPI			" "
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	(3)		ELBOW
	XY	B61	A1	HPI			"
	YZ	B59	B1	MU/HPI		46	"
	ZW	B44	B2	HPI			"

NOTES: 1. SHOP ASSEMBLIES WERE CLEANED TO CLASS C PER SPECIFICATION S-107 E.

2. INSPECTION RESULTS NOMENCLATURE

A. SAFE END CRACKED, SLEEVE LOOSE/WORN/MISSING
B. SLEEVE INDICATED SOME LOOSENESS/WEAR - NO SAFE END CRACKING
C. CIRCUMFERENTIAL CRACK OR MARK

OK - NO ABNORMAL INDICATIONS

3. INFORMATION MUST BE OBTAINED FROM SITE RECORDS

4. INFORMATION FOR THIS MATRIX CONCERNING COLD LEG PIPE ASSEMBLY SERIAL NO'S. B41-209-50-1 AND B41-209-50-2 IS AVAILABLE BUT WHICH ASSEMBLY IS LOCATED IN THE B2 LEG AND A1 LEG MUST BE OBTAINED FROM SITE RECORDS.

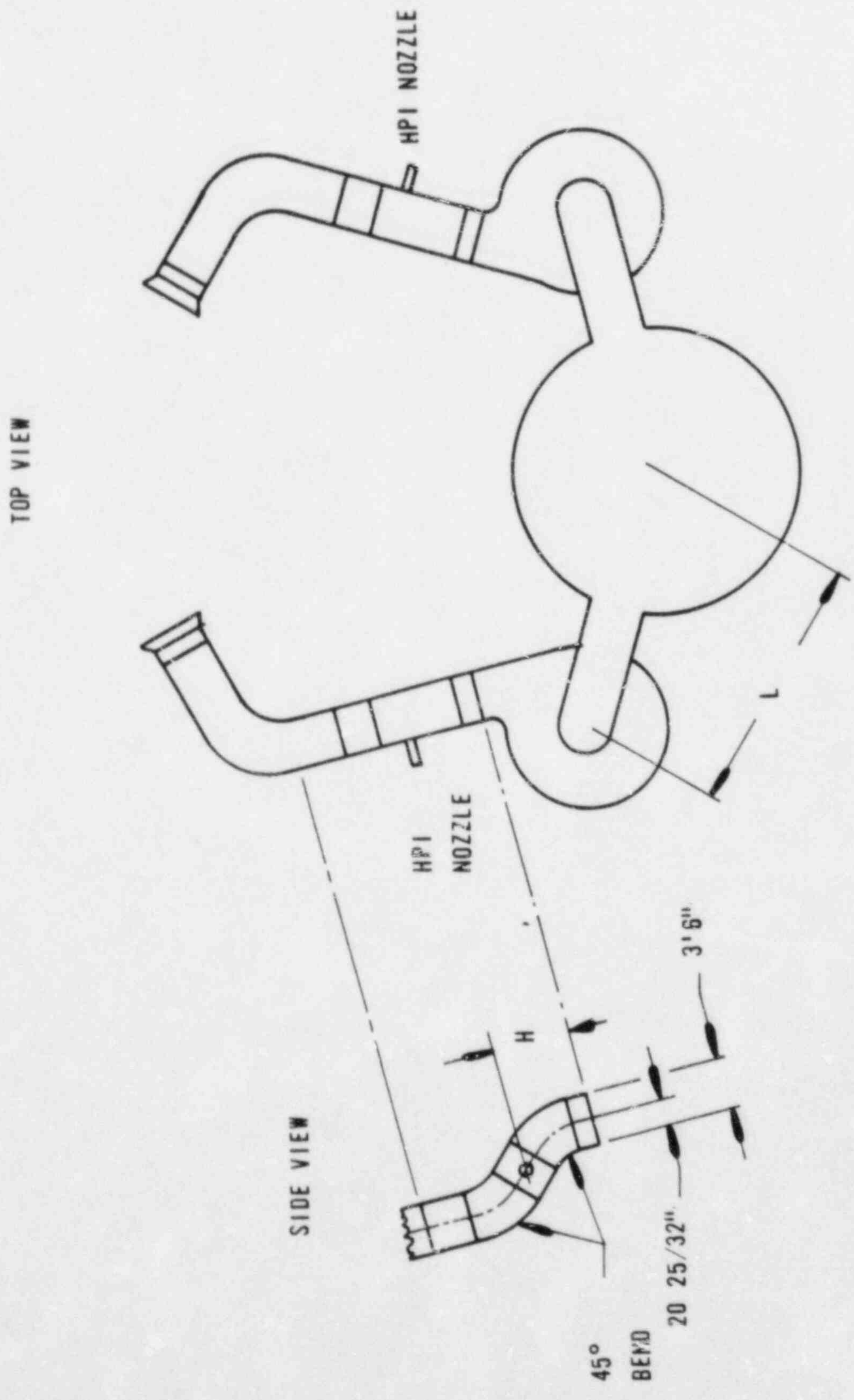
5. WHILE TAKING MEASUREMENTS OF THE A-1 RC PUMP FIXED VANES, IT WAS DISCOVERED THAT THE THERMAL SLEEVE IN THE HPI LINE NOZZLES WAS LOOSE. ALL THERMAL SLEEVES WERE REROLLED. THE FOLLOWING INFORMATION WAS RECORDED AT THE SITE.

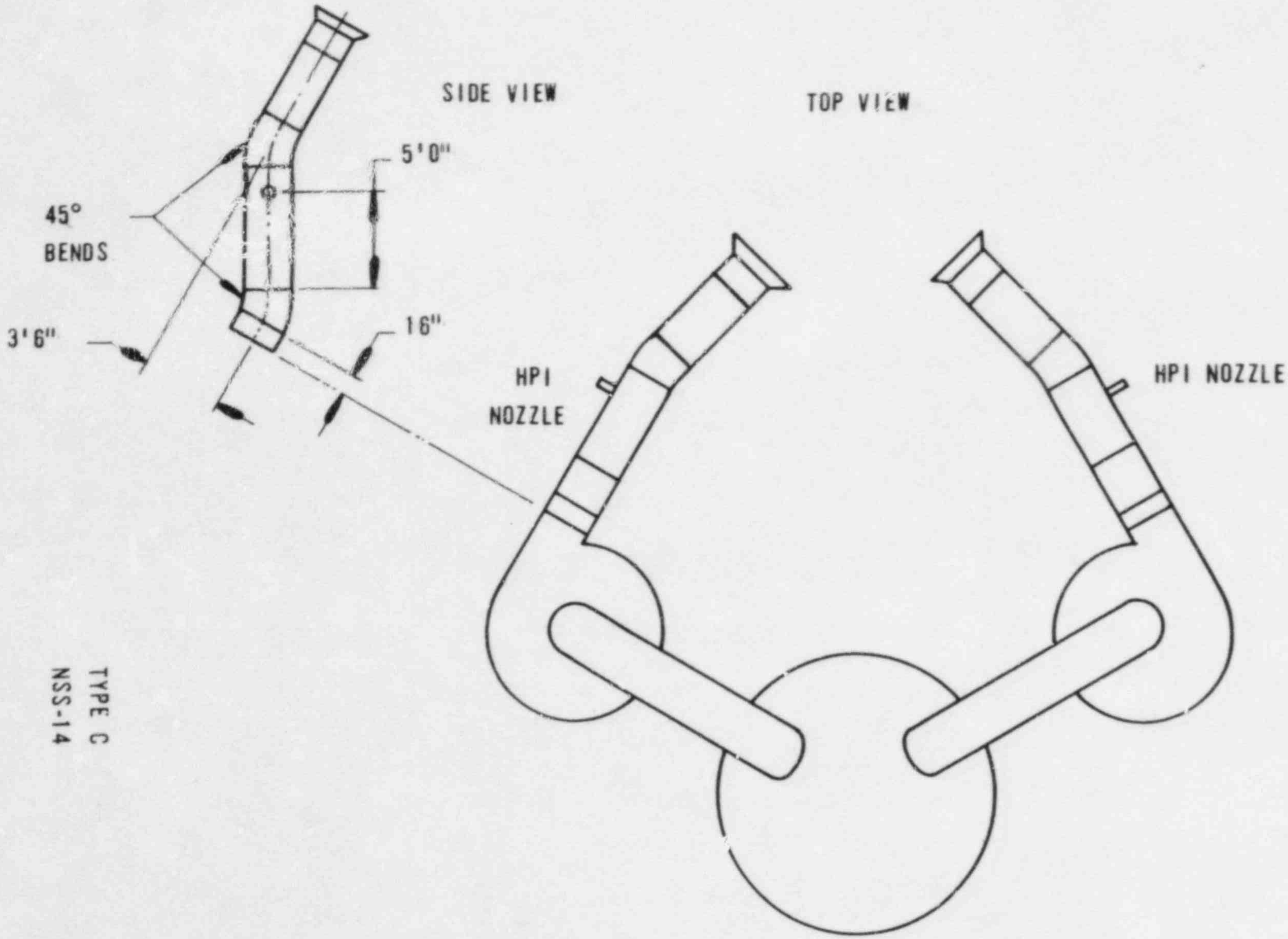
CUST. IDENTIFICATION		THERMAL SLEEVE ID IN EXPANDED AREA
A2	TH. SLEEVE TIGHT	1.5086
A1	TH. SLEEVE LOOSE	1.5060
B1	TH. SLEEVE TIGHT	1.5178
B2	TH. SLEEVE TIGHT	1.5162

	AFTER REROLLING	THERMAL SLEEVE ID IN EXPANDED AREA
A2	TH. SLEEVE TIGHT	1.5162
A1	TH. SLEEVE TIGHT	1.5190
B1	TH. SLEEVE TIGHT	1.5178
B2	TH. SLEEVE TIGHT	1.5183

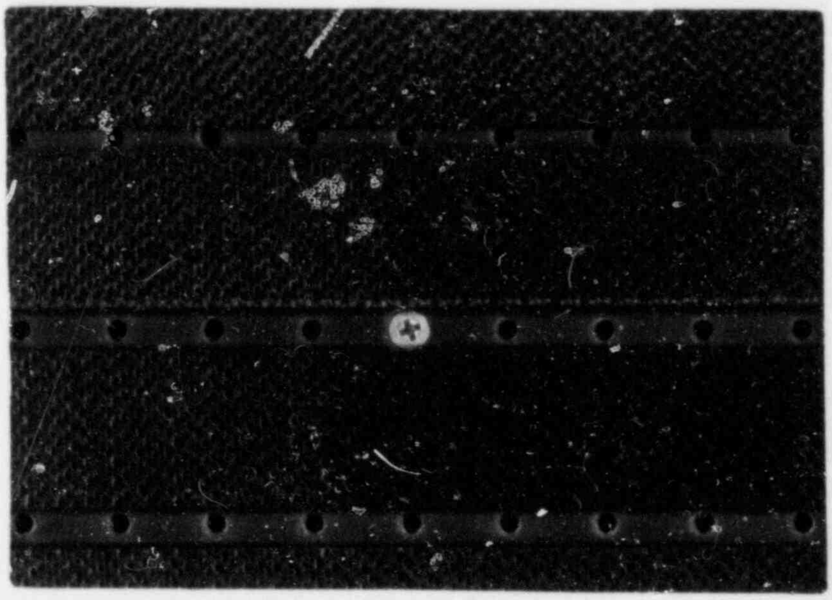
TYPE A H = 4'5 3/16" L = 12'6"
FOR NSS 3,4,5,9 11

TYPE B H = 4'9 3/16" L = 13'
FOR NSS 7,8





TYPE C
NSS-14



Engineering Services

Babcock & Wilcox
a McDermott company

BABCOCK & WILCOX
177 FUEL ASSEMBLY OWNER'S GROUP
SAFE END TASK FORCE REPORT
ON
GENERIC INVESTIGATION OF
HPI/MU NOZZLE COMPONENT CRACKING

B&W Document Number: 77-1140611-00

Prepared for

Arkansas Power & Light Company
Consumers Power Company
Duke Power Company
Florida Power Corporation
Sacramento Municipal Utilities District
Toledo Edison Company

by

The Babcock & Wilcox Company
Utility Power Generation Division
Lynchburg, Virginia

TABLE OF CONTENTS

	PAGE
1.0 EXECUTIVE SUMMARY	1
2.0 INTRODUCTION	2
2.1 Background	2
2.2 Scope	5
2.3 Results	6
2.4 Organization	7
3.0 COMPILATON OF FACTS	8
3.1 Failure Analyses	8
3.2 Matrix of Facts	11
4.0 REVIEW OF INDUSTRY EXPERIENCE	14
5.0 CRYSTAL RIVER-3 INSTRUMENTED NOZZLE DATA EVALUATION	17
6.0 ANALYTICAL INVESTIGATION OF EXISTING DESIGN	19
7.0 POSSIBLE ROOT AND CONTRIBUTORY CAUSES	21
8.0 PROBABLE FAILURE SCENARIO	25
9.0 TESTS TO SUBSTANTIATE THE ROOT CAUSE	27
10.0 MODIFIED THERMAL SLEEVE DESIGN	30
10.1 Conceptual Designs	30
10.2 Design Improvements	31

TABLE OF CONTENTS (cont'd)

	PAGE
11.0 MAKEUP SYSTEM OPERATING CONDITIONS	33
12.0 AUGMENTED INSERVICE INSPECTION PLAN	34
13.0 JUSTIFICATION OF LONG TERM OPERATION	36
13.1 Analytical Justification	36
13.2 Experimental Justification	38
14.0 CONCLUSIONS	39
15.0 RECOMMENDATIONS	40
16.0 REFERENCES	42

LIST OF FIGURES

Title

1. Typical Elevation View of Reactor Coolant System Arrangement Showing Location of HPI Nozzle

2. Typical Plan View of Reactor Coolant System Arrangement Showing Location of HPI Nozzle

3. Typical HPI and HPI/MU Nozzle

4. Typical Layout of HPI and HPI/MU Line

5. Safe-End Task Force Action Plan

6. Instrumentation Arrangement at Crystal River-3

7. "Goodness of Roll" Results

8. Hard Rolled HPI/MU Nozzle Concept

9. Integral HPI/MU Nozzle Concept

10. Flanged HPI/MU Nozzle Concept

11. Roll Expansion Test Schematic Diagram of Test Fixture

12. HPI/MU Static Test Results

13. HPI/MU Nozzle Test Results - Transient Load Tests (Phase IIA)

14. HPI/MU Nozzle Test Results - Vibration Test (No Free End Restraint)

15. Natural Vibration Frequency Test Schematic Diagram

1.0 EXECUTIVE SUMMARY

The purpose of this report is to summarize the Safe-End Task Force's involvement in the high pressure injection/makeup (HPI/MU) nozzle cracking problems which affected Crystal River-3, Oconee-3, Oconee-2, Arkansas Nuclear One-1, and Rancho Seco. Formed by the Babcock & Wilcox (B&W) 177 Fuel Assembly Owner's Group, the Task Force has identified the root cause of the failures, recommended modifications to eliminate future failures, and identified studies to support these modifications on a long term basis.

Site inspections conducted in February-April 1982 indicated that both the HPI only nozzles and the double-duty HPI/MU nozzles were affected. Loose, out-of-place, and cracked thermal sleeves were observed in 6 of the HPI only nozzles, while 4 of the double-duty nozzles also contained cracked safe-ends. Failure analyses indicated that the cracks were initiated on the inside diameter and were propagated by thermal fatigue. The cracked safe-end at Crystal River also contained mechanically initiated outside diameter cracking which appeared to be unrelated. Previous inspections at two plants (Davis Besse-1 and Three Mile Island-2) under construction revealed that one of the Davis Besse sleeves was loose. All four sleeves were subsequently re-rolled at Davis Besse (hard rolled, instead of contact expanded as originally specified). Recent inspections at Midland have also shown that gaps may be present between the thermal sleeve and safe-end in the contact expanded joint. These findings along with stress analysis and testing have implicated insufficient contact expansion of the thermal sleeves as the most probable root cause of the failures.

With this in mind, B&W has recommended modifications to the design, operation and inspection of the HPI/MU nozzles. A hard rolled thermal sleeve design has been developed which helps prevent thermal shock to the nozzle assembly and helps reduce flow induced vibrations more effectively. An increase in minimum continuous makeup flow has been suggested to help prevent thermal stratification in the MU line and more effectively cool the safe-end. An inservice inspection (ISI) plan has also been developed to provide a means of early problem detection.

2.0 INTRODUCTION

On January 24, 1982, normal monitoring of the Crystal River-3 reactor coolant system (RCS) indicated an unexplained loss of coolant. After an orderly plant shutdown, the double duty high pressure injection makeup (HPI/MU) nozzle check valve-43 was identified as the source. The valve, the valve to the safe-end weld, the safe-end, and the thermal sleeve were cracked as a result of thermal and/or mechanical fatigue. Inspections at other Babcock & Wilcox (B&W) operating plants indicated similar types of cracking, but to a lesser extent. As a result, the Safe-End Task Force (SETF) was formed to compile the pertinent facts and to determine a most probable root cause for the failures. Since the failures were apparently generic in nature, the following report was compiled describing the Task Force's investigation. Specifically, the relevant facts and most probable failure scenario are presented, as well as recommended modifications to the thermal sleeve design, makeup system operating conditons and inservice inspection (ISI) plan.

2.1 Background

On the 145, 177 and 205 fuel assembly (FA) plants, four HPI/MU nozzles (one per cold leg) are used to: (1) provide a coolant source for emergency core cooling, and (2) supply normal makeup (purification flow) to the primary system (see Figures 1 and 2). In general, one or two of the nozzles are used for both HPI and MU, while the remaining nozzles are used for HPI alone.

The incorporation of a thermal sleeve into a nozzle assembly is a common practice in the nuclear industry (See Figure 3). The function of the thermal sleeve is to provide a thermal barrier between the cold HPI/MU fluid and the hot high pressure injection nozzle. This helps prevent thermal shock and fatigue of the nozzle. The purpose of the safe-end is to make the field weld easier (pipe to safe-end) by allowing similar metals to be welded. The dissimilar metal weld between the safe-end and the nozzle can then be made under controlled conditions in the vendor's shop. The use of the safe-end also eliminates the need to do any post-weld heat treating in the field.

While monitoring the Crystal River-3 RCS for unidentified leakage, a notable increase was observed on January 24, 1982. On January 25, a further increase in leakage was observed and the unit was subsequently placed in Hot Standby on January 28. The check valve (MUV-43) to safe-end weld on the double duty HPI/MU nozzle contained a thru-wall circumferential crack which caused the leak. Following removal of the valve, visual inspection of the safe-end and thermal sleeve revealed that both components were cracked and worn (see Figure 3). Inspection of the other three HPI nozzles indicated that no cracking or wear was present, and no sleeve movement had occured.

Following the incident at Crystal River-3, letters were issued to each of the B&W 177 FA utilities informing them of the discoveries at Crystal River-3. Inspections were performed at all 177 FA plants to determine whether the problem was site-specific, or generic in nature.

Oconee-1 was shutdown for refueling when Duke Power received B&W's correspondence. Consequently, Oconee-1 was the first unit to be inspected in detail. Radiographic tests (RT) and ultrasonic tests (UT) of the four suspect nozzles indicated that no abnormal conditions were present in any of the nozzles. These findings suggested that the problem may be site-specific to Crystal River-3.

Oconee-3 was also shutdown at that time for a Once-Through Steam Generator (OTSG) tube leak. Radiography of one of the makeup nozzles (A2) showed that the thermal sleeve was displaced about 5/8 inch upstream from its normal location. The radiographic test also revealed that a gap was present between the outside diameter (OD) of the thermal sleeve and the inside diameter (ID) of the safe-end in the contact expanded region. The weld buttons in the safe-end, which prevent upstream motion of the thermal sleeve, had been worn away (see Figure 3). Weld buttons in the nozzle throat, which prevent downstream motion of the thermal sleeve, were still present, but were worn. A UT of the nozzle also revealed that cracking was present. Given these indications, the HPI/MU piping and warming line were cut

from the safe-end and a dye penetrant test (PT) of the safe-end and associated hardware was conducted (see Figure 4). The safe-end, thermal sleeve, spool piece and warming line were cracked. Subsequent RT's of the remaining nozzles revealed that the other makeup nozzle (A1) and one of the HPI nozzles (B2) were not damaged and the thermal sleeves were in position. However, the other HPI nozzle (B1) had a .030 inch gap between the thermal sleeve OD and the safe-end ID as indicated by the RT.

With the cracking problem substantiated at Oconee-3, Duke quickly inspected their Oconee-2 unit. Three of the Oconee-2 nozzles contained anomalies: (1) the makeup nozzle (A2) had a cracked safe-end and a loose thermal sleeve, (2) the HPI nozzle (B1) had a 1/32 inch gap between the thermal sleeve and safe-end as indicated by the RT, and (3) the HPI nozzle (B2) had a tight thermal sleeve which contained a circumferential crack in the roll expanded region.

Inspections at four other operating plants were also conducted. The thermal sleeves at Davis Besse-1 and Three Mile Island-1 (TMI-1) were in position and tight. No cracking was observed and the weld buttons were not worn. However, inspections at Arkansas Nuclear One-1 (ANO-1) and Rancho Seco indicated that abnormal conditions were present at these sites. At ANO-1, three problems were discovered: (1) one HPI nozzle (A1) had a loose sleeve, (2) one HPI nozzle (A2) had a tight sleeve with a partial gap indicated by radiography between the sleeve and safe-end, and (3) the HPI/MU nozzle (B2) had a tight sleeve which contained a circumferential crack in the roll expanded region (similar to the Oconee-2(B2) failure). At Rancho Seco, two problems were discovered: (1) the HPI nozzle (A1) had a loose sleeve, and (2) the HPI/MU nozzle (A2) had a cracked safe-end and a missing thermal sleeve.

Inspections at two plants under construction, Midland and North Anna, were also conducted to determine the conditions present prior to initial plant startup. Radiographs of the two Midland units indicated that a number of the nozzles may have gaps between the thermal sleeve

and safe-end. Supplemental visual inspectic s revealed that all 8 sleeves w e tight and in place. However, one of the HPI thermal sleeves cn Unit 2 was conspicuously skewed relative to the safe-end center line. Visual inspections at North Anna revealed that one sleeve had a partial gap in the rolled region, but the sleeve was tight and in place. The length of the rolled region was also observed to vary between 1 1/2 and 2 inches at North Anna. In addition, the TMI-2 and Davis Besse-1 nozzles were inspected in 1971 while the plants were under construction. At TMI-2, all 4 HPI/MU nozzles were inspected and no defects were observed. However, at Davis Besse-1, one of the sleeves was found to be loose and all 4 sleeves were subsequently re-rolled (hard rolled, instead of contact expanded).

These findings indicate that loose sleeves, or sleeves with gaps between the thermal sleeve and safe-end, may have been present in other plants prior to initial plant startup.

2.2 Scope

Given this background information, the Task Force chose to approach the problem from a generic standpoint (see Figure 5 for the Task Force Action Plan). To do this, a root cause(s) must be first identified, and then a generic solution could be recommended. To determine the root cause(s), the following tasks were performed:

1. reviewed manufacturing data
2. compiled and compared site specific facts and inspection results
3. evaluated metallurgical examinations
4. reviewed industry experience
5. evaluated data from the instrumented Crystal River-3 HPI/MU nozzle
6. evaluated the existing design analytically
7. postulated possible failure scenarios
8. determined a most probable root cause(s)

Having determined a most probable root cause(s), a solution was developed which addressed:

1. modified thermal sleeve design for the damaged nozzles
2. makeup system operating conditions
3. augmented inservice inspection plan

Finally, B&W also proposed studies to demonstrate the adequacy of the recommended fix on a long term basis.

2.3 Results

Results of the investigation indicate the following facts:

1. The thermal sleeve manufacturing installation procedure called for a contact roll of the thermal sleeve, not a hard roll.

2. Varying degrees of contact expansion rolls could be performed even for the same plant.

3. Gaps between the thermal sleeve and safe-end have been found in plants under construction.

4. All cracked safe-ends were associated with loose thermal sleeves. However, not all loose thermal sleeves had safe-ends that were cracked.

5. All cracked safe-ends were associated with the makeup nozzle.

6. A makeup nozzle may be subject to random and continuous makeup flow oscillations.

7. The cracks found were ID initiated (Crystal River-3 OD crack initiation appeared to be unrelated).

8. The cracks were propagated by thermal fatigue.

9. Where controlled hard rolling of the thermal sleeve was accomplished, no failures have occurred.

10. Oconee-1, which has the most operating experience, contained no abnormal conditions when recently inspected. Oconee-1 is the only plant which uses a double thermal sleeve design.

2.4 Organization

This report has been organized to address three primary questions:

1. How did the Task Force determine the root cause of the problem?

2. What modifications (design, operation, inspection) were made to correct the problem?

3. What was done to justify these modifications?

Specifically, sections 3 through 9 describe what was done to determine a most probable root cause, sections 10 through 12 describe what modifications were suggested, and section 13 supplies the justification for these modifications. In addition, sections 14 and 15 summarize the conclusions and recommendations of this investigation.

3.0 COMPILATION OF FACTS

Following the incidents at Crystal River-3 and Oconee, the Safe-End Task Force requested that B&W compile a list of facts concerning the HPI/MU nozzle cracking problem, such that possible correlations between plants could be identified. To accomplish this task, B&W reviewed the manufacturing records and the site specific failure analysis reports, and then developed a matrix of facts.

3.1 Failure Analyses

Failure analyses were performed on four of the units (Crystal River-3, Oconee-3, Oconee-2, and Arkansas Nuclear One-1). These studies were conducted to determine the most probable method of crack initiation and propagation. The results are as follows:

Crystal River-3/Florida Power Corporation

While the repair efforts were being completed on the Crystal River-3 unit, the cracked safe-end and thermal sleeve of the HPI/MU nozzle (A1) were sent to B&W's Lynchburg Research Center (LRC), and the cracked valve and section of pipe near MUV-43 were sent to Battelle Columbus Laboratories for failure analysis.

The results of the LRC study indicated that both the sleeve and the safe-end most likely failed by thermal fatigue. Cracking initiated on the ID of both components and was transgranular. The thermal sleeve cracking was confined to the roll expansion area only. The safe-end was cracked in the valve end down to the seating area of the thermal sleeve. Extensive wear was found on the safe-end ID and the thermal sleeve OD in the region of roll expansion of the sleeve into the safe-end. From this and other surface damage, it was concluded that the sleeve had become unseated and was probably rotating due to flow forces. Evidence to confirm or refute whether the sleeve had been roll expanded on installation was not conclusive.[1]

Battelle's inspection of the pipe section revealed that separate circumferential cracks from the inside diameter (ID) and the outside diameter (OD) on half of the pipe section were present, as well as multiple longitudinal cracks. The circumferential crack on the ID was associated with a machine tool mark, while the crack on the OD was associated with the valve to weld bead discontinuity. Fractographic evidence suggested that fatigue was responsible for both the ID and OD circumferential cracks. Metallography showed that the cracks were transgranular. The ID cracks were believed to have initiated by thermal fatigue caused by (1) turbulent mixing of hot and cold water during makeup system additions, and/or by (2) periodic chilling of hot metal during makeup system additions. Crack propagation probably occurred by combined thermal and mechanical loading of the system. The OD crack is believed to have initiated and propagated by mechanical loading of the system.[2]

Oconee-3/Duke Power

The LRC examined the safe-end, thermal sleeve, spool piece, and warming line of the damaged Oconee-3 makeup nozzle (A2) (See Figures 3 and 4). Component failures were due to thermal fatigue as with Crystal River; however, the cracking was not as deep or as widespread. The cracking was transgranular and confined to three regions:

1. the roll expanded end of the thermal sleeve

2. the safe-end ID from the upstream edge of the thermal sleeve seat to the spool piece weld

3. the spool piece from the safe-end to about 2 inches upstream of the warming line tee

In addition, evidence of wear was found on the thermal sleeve OD and the safe-end ID in the area of the contact expansion seat. As with the Crystal River components, this suggests that the thermal sleeve had become unseated and was rotating/vibrating due to flow forces.[3]

Oconee-2/Duke Power

B&W's LRC also peformed the metallurgical examination of the Oconee-2 HPI nozzle (B2) thermal sleeve. This sleeve contained a visually observable crack extending approximately 270° around the circumference located about 1 1/2 inches from the roll expanded end of the sleeve. This large crack was transgranular and at one location was shown to be propagating from ID to OD. A small axial branch of this crack contained some fatigue striations, but the bulk of the fracture surface could not be interpreted due to heavy oxidation and damage incurred during removal. Metallographic examination also revealed shallow (<3 mils) transgranular cracking on the OD near the large crack. This sleeve did not contain a large amount of wear compared to the Oconee-3 and Crystal River sleeves; however, the downstream collar contained a peened surface along a 180° arc (See Figure 3). In general, the basic failure mode appeared to be transgranular fatigue as occurred in the Crystal River and Oconee-3 thermal sleeves, but the arrangement of the cracking pattern and differences in surface damage suggested that the stress state required to create this failure was either different, or more dominant than in the previous failures.[4]

Arkansas Nuclear One-1/Arkansas Power & Light

The Lynchburg Research Center also performed a metallurgical examination of the ANO-1 HPI/MU nozzle (B2) thermal sleeve. The sleeve contained a visible crack extending approximately 270° around the circumference located about 1 1/2 inches from the roll expanded end of the sleeve. The crack was transgranular, had propagated by fatigue, and followed a machining mark. No axial cracking was present. The collar end of the sleeve showed damage to the collar itself approximately 180° around the circumference. Below this damaged area, approximately 90° apart, two gouged out areas were also present. The failure mode of this sleeve appeared to be similar in nature to that suggested for the Oconee-2 thermal sleeve.[5]

3.2 Matrix of Facts

While the failure analysis studies were being conducted, a site specific matrix of facts was compiled. Five major areas were addressed: (1) system characterization, (2) component characterization, (3) operating conditions, (4) unit operation, and (5) inspection results. Within each specific area, the following items were included:

1. System Characterization
   - loop designation
   - nozzle type (HPI/MU)
   - pipe layout
   - pump characterization
     - rotation (CW/CCW)
     - distance from pump discharge
     - number of impeller vanes
     - number of diffuser vanes
   - makeup recirculation control

2. <u>Component Characterization</u>

- thermal sleeve geometry
- safe-end geometry
- thermal sleeve/safe-end interface
- material
- sleeve expansion procedure

3. <u>Operating Conditions</u>

- minimum bypass flow
- total makeup flow
- total HPI flow
- minimum RC pressure to provide net positive suction head (NPSH)
- borated water storage tank (BWST) temperature

4. <u>Unit Operation</u>

- full power years
- reactor trips
- estimated HPI actuations

5. <u>Inspection Results</u>

- gaps between thermal sleeve OD and safe-end ID
- thermal sleeve axial location
- weld button integrity/geometry
- thermal sleeve cracking
- safe-end cracking

Table 1 contains the matrix of facts compiled by B&W. Examination of this table suggests that two possible correlations may exist between HPI/MU nozzle failures and sites.

First, neither of the units operating with RC pumps which contain 7 impeller vanes (Oconee-1 and TMI-1) have ever shown any indications of loosening or cracking of the thermal sleeves. On the other hand, 5 out of 6 units operating with RC pumps which contain 5 impeller vanes have shown indications of loosening or cracking of the thermal sleeves. This implies that the dynamics of the pressure field generated by the RC pumps may lead to flow induced vibration damage. However, these observations may simply reflect design differences among the plants (Oconee-1 uses a double thermal sleeve and TMI-1 uses an Inconel safe-end).

Second, either operating unit which has undergone post-installation inspection or modification (Oconee-1 and Davis Besse-1) has not shown any indications of loosening or cracking when recently inspected. At Oconee-1, a single thermal sleeve was originally installed which extended into the cold leg flowstream approximately 2 1/8 inches less than the sleeves used at the other plants. A number of boiling water reactors (BWR) employing a similar design experienced cracking problems. Consequently, a second longer sleeve was re-rolled inside of the original sleeve. Aside from increasing the overall length of the sleeve assembly, the rolling of the second sleeve may have also resulted in the re-rolling of the original sleeve. The second sleeve also had an interlocking flange which contained 4 axial notches in the flanged region. Weld buttons were placed within these notches to provide additional anti-rotation protection. At Davis Besse-1, an inspection of the HPI/MU nozzles was performed in 1977 prior to operation. One sleeve was found to be loose and all four sleeves were subsequently re-rolled. Consequently, the post-installation modifications and inspections have at least mitigated the problem, and may have completely eliminated the problem.

4.0 REVIEW OF INDUSTRY EXPERIENCE

A literature review of recent nuclear industry experience in cracking problems was performed by B&W. Five events of interest were identified:

Babcock & Wilcox PWR, Indian Point Thermal Sleeve Failure, 1970 [6]

While plugging tubes at the Indian Point-1 facility, fragments of the makeup line thermal sleeve were discovered in the primary side of the steam generator water box. Apparently, the sleeve had failed as a result of thermal fatigue in the sleeve to makeup line welded area. The thermal stresses resulted from the flow and temperature gradients associated with normal plant makeup system operations. The problem was eliminated by (1) using a thermal sleeve assembly made from a solid forging, (2) projecting the thermal sleeve into the RC cold leg an additional 1/2 inch to induce better mixing, and (3) increasing the minimum makeup flow to 5000 lb/hr.

GE - BWR, Feedwater Nozzle/Sparger Cracking, 1974-1980 [7]

From 1974 through 1980, 22 of 23 BWR's inspected had experienced some degree of cracking in their primary system feedwater nozzles. The failures occurred due to thermal fatigue with crack initiation caused by turbulent mixing (high-cycle) and crack propagation caused by intermittent feedwater flow (low-cycle) during startup, shutdown, and hot standby. The "loose sleeve design" was identified as the root cause which allowed bypass flow within the annulus between the sleeve and the nozzle. A tight fitting thermal sleeve to restrict bypass flow was used as an interim fix and a triple thermal sleeve design was recommended as a permanent fix.

GE - BWR, Control Rod Drive Return Line Nozzle Cracking, 1975 [8]

In 1975, 12 BWR's were inspected and found to have cracking in the control rod drive return lines (CRDRL) and the reactor vessel beneath the nozzles. As with the BWR feedwater problem, the failures were attributed to thermal fatigue cracking due to turbulent mixing and intermittent cold water flow. The problem was eliminated by plugging the nozzle and rerouting the CRDRL.

Westinghouse - PWR, Steam Generator Feedwater Line Cracking, 1979 [8-10]

In 1979 cracking was discovered in the steam generator feedwater lines of 5 operating PWR systems. The cracking was attributed to thermal fatigue due to flow stratification in the feedwater lines. Corrosion fatigue was subsequently declared to be the root cause.

Westinghouse - PWR, Loss of Thermal Sleeves in Reactor Coolant System Piping at Certain Westinghouse PWR Power Plants, 1982 [14]

In 1982, 2 Westinghouse PWR's were inspected and found to have missing thermal sleeves in their safety injection (SI) nozzles.

Radiography and ultrasonic examinations confirmed that the 10-inch thermal sleeves were missing from all four SI nozzles at the Trojan nuclear plant. Supplemental inspections of the sleeves in the pressurizer surge line, and normal and alternate charging lines revealed that cracking was present in some of the retaining welds.

At Duke Power's McGuire-1 reactor, radiography and underwater camera inspection revealed that the thermal sleeve in one of the four SI accumulator piping nozzles to RCS cold leg piping was missing. Radiography confirmed that the other three SI sleeves and the pressurizer surge line sleeve were in place. Westinghouse recommended that (1) the loose parts monitoring system be fully operational, and (2) a non-destructive examination be performed to assess the thermal sleeve conditions of the affected systems at the next extended plant outage.

In summary, the following observations can be made:

1. Crack initiation was due to high-cycle thermal fatigue caused by turbulent mixing.

2. Crack propagation was due to low-cycle thermal fatigue caused by intermittent flow of cold water.

3. Tests conducted by Hu et.al. [9] have shown that for loose fitting thermal sleeves, leakage flow (up or down stream) may occur within the annulus between the sleeve and nozzle.

4. Cracking occurs in high stress areas, i.e., counter bore transition, weld discontinuities, nozzles blend radius, etc.

5. All failed components were subjected to a stratified flow caused by low flow rates.

5.0 CRYSTAL RIVER-3 INSTRUMENTED HPI/MU NOZZLE DATA EVALUATION

Following the cracking incident at Crystal River-3, metallurgical examinations of the thermal sleeve, safe-end and spool piece were conducted by the LRC and Battelle as previously discussed. Results of these studies indicated that the cracking was attributable to thermal fatigue. Given this information, qualitative modifications were made to minimize the thermal stresses within the nozzle assembly. Subsequent to this effort, the thermal sleeve was replaced with a modified design, the safe-end was replaced, and the HPI/MU check valve was replaced and relocated approximately 5 inches upstream from its original location.

To verify the structural integrity of the modified HPI/MU nozzle design (see Figure 8) and gain insight into the failures, B&W recommended that the makeup nozzle assembly (A1) be instrumented. Information was required regarding the thermal stresses and vibrational environment associated with normal plant heatup, hot standby, and power operation. To provide this information, 12 thermocouples, 4 welded strain gauges, 4 bonded strain gauges and 2 accelerometers were installed at three axial planes (A, B, and C), as shown in Figure 6.

Evaluation of the data obtained from the instrumented nozzle indicated that:

1. The external temperature of the safe-end (plane B) remains at or near the makeup water temperature, while the thick portion of the nozzle (plane A) tends to follow the RC cold leg temperature.

2. Circumferental temperature gradients were small indicating that no significant "hot spots" or flow stratification was occurring.

3. Several continuous makeup flow rates were tested (1.6, 5.0, 15.0, and 130.0 gallons per minute). In all cases, the safe-end metal temperature did not change, while the nozzle metal temperature changed by a maximum of 20°F.

4. During heatup, the makeup flow cycled approximately every three minutes. The resultant stresses were small.

5. Makeup flow induced vibrations could be detected with the supplemental instrumentation and tended to increase as makeup flow increased. The resultant stresses were small.

6. Nozzle/safe-end stresses due to thermal expansion are smaller than design values.

7. High stresses were recorded while a pipe hanger was being set. This was an isolated occurrence and had no significant influence on the other test results.

For further details, the reader is referred to B&W document 77-1134571-00, "Evaluation of Crystal River-3 HPI/MU Nozzle Testing". [11]

6.0 ANALYTICAL INVESTIGATION OF EXISTING DESIGN

The previous discussion revealed that the thermal stresses in the modified HPI/MU nozzle at Crystal River-3 were within design values. However, no data was obtained for the old nozzle design. Consequently, B&W developed a program to evaluate the original (existing) design. The program consisted of two phases: (1) analytical, and (2) experimental. A discussion of the analytical phase follows, while details of the experimental phase are included in Section 9.

The purpose of the analytical study was two-fold: (1) to determine the relationship between wall thinning of the HPI thermal sleeve during roll expansion and residual stresses at the thermal sleeve to safe-end interface, and (2) to determine if the rolled joint becomes loose during steady-state plant operation, or during the most severe transient (HPI event).

To determine the thermal sleeve thinning to thermal sleeve/safe-end interfacial residual stress relationship, a finite element model was constructed for a radial sector of the assembly in the contact expanded region (See Figure 3). Assuming that a generalized plane strain condition exists within this region and that end effects are negligible, a simple axisymmetric, non-linear, inelastic analysis was performed using the ANSYS Code. [12] Results of this finite element analysis follow; however, these results have not been verified and should be used for information only.

The relationship between thermal sleeve wall thinning and sleeve/safe-end interfacial stress is shown in Figure 7. For wall reductions in the 2-10% range, the resulting interfacial residual stress lies in the 4000-4200 psi range. The residual stress varies in a non-linear fashion which suggests that above a certain degree of wall thinning, probably greater than 5%, the beneficial effects of increased wall thinning are negligible. This non-linear behavior is also characteristic of the axial load carrying capability of the joint (see Figure 12 and Section 9); however, the results cannot be simply correlated due to the number of uncertainties, i.e., coefficient of friction, effective contact area, material properties, etc.

The loosening of the rolled joint during steady-state and most severe transient operation was investigated analytically by imposing appropriate thru-wall temperature variations on the model used to determine interfacial residual stress. The temperature distributions were determined assuming one-dimensional heat transfer. The results show that no gap forms between the sleeve and safe-end during stready-state operation. However, the results indicate that during an HPI event (most severe transient), the thermal sleeve contraction relative to the safe-end causes a small gap to form between the sleeve and safe-end for a short period of time. This characteristic behavior is in agreement with the test results described in Section 9.

7.0 POSSIBLE ROOT AND CONTRIBUTORY CAUSES

Following the discovery of cracking at Crystal River-3, an effort was made to identify possible root and contributory causes. The following causes were hypothesized:

1. Makeup flow conditions maintained outside of design limits - this includes either a low MU temperature, or an incorrect bypass flow rate. In particular, the bypass flow rate may have been set at ambient conditions instead of at operating conditions, or may not have been properly maintained.

2. Excessive cycling of the check valve due to improper valve performance

3. Flow stratification in the MU line due to minimal MU flow

4. Thermal stratification and recirculation in the MU line due to minimal flow

5. Cold working of the thermal sleeve due to roll expansion

6. Stress corrosion cracking of the thermal sleeve due to excessive roll expansion

7. Convective heating of the safe-end due to an air gap in the insulation

8. External loading of the attached piping due to thermal transients

9. Sympathetic vibration of the thermal sleeve due to dynamic pressure field generated by the RC pumps

10. Flow induced vibrations due to cross-flow in the RC cold leg pipe

11. Annular flow between the thermal sleeve OD and the safe-end ID due to insufficient rolling of the thermal sleeves

As additional information was obtained from the failure analysis studies and the site inspections, the validity of these causes could be suitably evaluated. It must also be pointed out that this list was compiled after Crystal River-3; therefore, some of the causes identified are site specific to Crystal River-3 and, thus, do not apply to all of the sites.

Of the 11 postulated causes, the first 4 pertain to the makeup system exclusively. A quick inspection of the matrix of facts, Table 1, reveals that both HPI and MU nozzles were affected. Consequently, any cause(s) which pertain to the MU nozzles alone can only be contributory at best. With this in mind, the validity of each cause was evaluated as follows:

1. Makeup flow control problems due to improper maintenance of minimum bypass flow may have occured at all of the sites. Plant data obtained during heatup and cooldown revealed that makeup flow rates were often unknown to the operators. As such, minimum continuous flow rates may not have been properly maintained which could lead to thermal fatigue of the nozzle components. However, since all of the plants experienced similar flow control problems and only 5 of the operating plants contained anomalies, makeup flow control was probably not the root cause.

2. Excessive cycling of the MU check valve may have contributed to the failure at Crystal River-3, but this was probably an isolated occurrence.

3. Flow stratification in the MU line due to minimal MU flow may have occurred at all of the plants since the same design value (1-3 gpm) was used inclusively. However, the results from the instrumented Crystal River-3 nozzle indicated that no significant circumferential temperature gradients were present, even at the lowest flow rate tested (1.6 gpm). From these findings, it can be inferred that the makeup flow was probably not stratified.

4. Low flow velocities in the MU line could also lead to thermal stratification and recirculation zones in the thermal sleeve. However, since the MU line is predominantly filled with MU flow, the thermal shock to the sleeve should not be too extensive (compared to the flow stratification described in 3). As a result, this can be disregarded as a probable cause.

5. Cold working of the thermal sleeve was not responsible for crack initiation or growth according to the failure analysis reports discussed in section 3.2. Consequently, this cannot be considered a probable cause.

6. Also, stress corrosion cracking due to roll expansion was not observed in the failure analysis studies. Consequently, this too cannot be considered a probable cause.

7. Convective heating of the safe-end via an air gap in the insulation may have contributed to the failure at Crystal River-3; however, since some of the plants are uninsulated, this can be disregarded as a probable cause.

8. Excessive loading of the attached piping due to thermal transients may occur at all of the plants. To ascertain the extent of the thermal transient loading, a structural analysis was performed for the Crystal River-3 piping arrangement. The results indicated that all stresses were well within the allowable design constraints. Therefore, this cause can be disregarded.

9. Sympathetic vibration of the thermal sleeve induced by the motion of the impeller vanes past the discharge port of the RC pumps may have occurred at all of the plants. The matrix of facts, Table 1, indicates that 5 of 6 plants using RC pumps with 5 impeller vanes have shown loosening or damage of the thermal sleeves. In contrast, both plants which use RC pumps with 7 impeller vanes have not shown any signs of failure.

   The results from the instrumented nozzle at Crystal River-3 indicated that the flow induced vibrations (FIV), as measured by strain gauges and accelerometers, were minimal. From these findings, it can be inferred that (1) the modifications made at Crystal River-3 have either substantially reduced or eliminated the FIV problem, and/or (2) the FIV problem is a typical high-cycle fatigue problem which takes a finite amount of time to loosen the rolled joint. Loosening of the joint would allow mixing of hot RC cold leg water and cold MU water in the annular region between the thermal sleeve and safe-end. This, in turn, would lead to thermal fatigue of the thermal sleeve and safe-end as described in the failure analysis reports. Consequently, FIV due to the RC pumps may have contributed to the failures.

10. Similarily, FIV due to cross-flow in the RC cold leg may have loosened the rolled joints. However, all of the plants experienced this form of FIV and were not affected. Therefore, this is probably not a root cause.

11. The thermal sleeves could have been rolled to varying degrees (loose and/or with gaps between the thermal sleeve and safe-end) when originally installed. This would allow mixing of the hot RC cold leg flow and the cold HPI/MU flow in the annular region between the thermal sleeve OD and the safe-end ID. This phenomenon, in turn, would thermally shock the nozzle components and eventually lead to crack initiation and propagation.

8.0 PROBABLE FAILURE SCENARIO

With the foregoing discussion in mind, the Safe End Task Force developed a probable failure scenario based on hypothesis 11 of Section 7.0.

"The most likely scenario for failure is that the thermal sleeve is loose after construction or a minimum contact expansion roll becomes loose during operation due to mechanical vibration and/or thermal cycling of the contact expansion joint. This looseness causes wear of the OD of the thermal sleeve and the ID of the safe-end. This wear in the rolled area allows a larger gap to form between the thermal sleeve and safe-end. Hot reactor coolant flows around the sleeve through this gap. The hot coolant randomly impacts the safe-end and thermal sleeve area because of random motions of the sleeve. The cooler makeup flow cools these heated areas when random motion shuts off the annular flow or makeup flow is increased. This random alternating heating and cooling eventually causes thermal fatigue cracking of the safe-end. This cracking may be aggravated by heating and cooling caused by significant cycling of makeup flow."[13]

Facts to support this hypothesis are as follows:

- Inspections conducted at Davis Besse, Midland and North Anna have shown that loose sleeves, or sleeves with gaps between the thermal sleeve and safe-end were present in plants under construction. In addition, the North Anna inspection indicated that the length of the rolled area varied from nozzle to nozzle between 1-1/2 and 2 inches.

- The thermal sleeve contact expansion process, as defined in the original installation procedure, is ambiguous.

- Since the sleeves were rerolled (hard rolled to 3% wall thinning) at Davis Besse-1 in 1977, no additional problems have been observed.

- When the modified thermal sleeve was meticulously rolled into the HPI/MU nozzle at Crystal River-3, no abnormal conditions were observed.

- When the failure analyses were performed (see section 3.2), thermal fatigue was identified as the mechanism of crack propagation.

9.0 TESTS TO SUBSTANTIATE THE ROOT CAUSE

To substantiate the probable root cause, B&W executed a test program with the following objectives:

1. Quantify the axial force required to loosen a thermal sleeve at ambient conditions as a function of degree of wall thinning achieved during contact expansion.

2. Determine if a gap of sufficient size to loosen a thermal sleeve forms when the thermal sleeve is subjected to a thermal quench transient for various degrees of wall thinning.

3. Determine the natural vibration frequency of a thermal sleeve as a function of roll expansion length and degree of wall thinning.

4. Determine the natural vibration frequency of a thermal sleeve with the collar area in contact with a simulated nozzle.

Given these objectives, the program was conducted in four phases. The test apparatus used for the first and second phases is shown in Figure 11, while the test apparatus used for the third and fourth phases is shown in Figure 15.

The first phase compared, under ambient conditions, the axial force required to move the sleeve versus the degree of thermal sleeve wall thinning. The results of these tests were used as a basis for subsequent tests and analytical evaluations. These results are plotted in Figure 12.

The second phase of testing involved thermal quenching of the simulated nozzle at operating temperature by injecting ambient water through the simulated nozzle and thermal sleeve. A predetermined axial force was applied to the unrestrained sleeve (no weld buttons) as water was injected through the nozzle. This axial force was based on the results of phase one and analytical evaluations of the steady-state hydraulic forces acting on the thermal sleeve. These results are tabulated in Figure 13.

The third phase of testing determined the natural vibration frequency of the thermal sleeve. The natural frequency was established as a function of contact expansion length and degree of wall thinning. The tests used a full-scale thermal sleeve mounted in a simulated safe-end. These results are tabulated in Figure 14.

The fourth phase of testing examined the natural frequency of the thermal sleeve with the collar area in contact with a simulated nozzle. The third phase test apparatus was used along with a simulated nozzle consisting of a retaining collar with adjustable set screws. Adjustment of the set screws was used to simulate the gap between the "downstream" collar of the thermal sleeve and the HPI/MU nozzle.

The tests conducted for the simulated safe-end indicated that:

1. Under static (ambient) conditions, the axial load carrying capability of the rolled joint varies in a non-linear fashion. Load carrying capacities in the 6000-13000 lb. range can be anticipated for wall reductions in the 1-8% range. Analytical predictions of the steady drag load exerted on the sleeve suggest that nominal loads applied perpendicular to the sleeve of about 100 lb. should be experienced in service. Worst case loads of 1300 lb. could occur if the vortex shedding frequency coincides with the natural frequency of the sleeve. Therefore, even the worst case analytical predictions, applied perpendicular to the sleeve, fall far below the limiting axial load carrying capability determined by the test.

2. Under transient (thermally quenched) conditions, the rolled joint loses load carrying capability for roll expansions less than 5% wall thinning as evidenced by the sleeve movement and leakage flow. However, should the joint loosen in actual service conditions, sleeve movement would be precluded by the upstream and downstream weld buttons. Above 5% wall thinning, the integrity of the rolled joint is not compromised (i.e., no sleeve movement or leakage flow) during the thermal quench transient.

3. The natural frequency of the sleeve varies as a function of roll expansion length and degree of wall thinning. Natural frequencies in the 220-250 Hz range can be anticipated for wall reductions in the 1-8% range.

4. When the restrained vibration test was conducted, the displacement of the sleeve was less than the sleeve/restraining collar gap. Therefore, the sleeve did not impact the simulated nozzle and no conclusive data was obtained.

10.0 MODIFIED THERMAL SLEEVE DESIGN

The previous sections of this report have been dedicated to determining the root cause of the HPI/MU nozzle cracking problem. The next three sections address the modifications made to alleviate the problem. Specifically, these modifications affect the design, operation, and inspection of the HPI/MU nozzles.

10.1 Conceptual Designs

In the aftermath of the Crystal River incident, the effectiveness of the contact rolled thermal sleeve design was re-evaluated. Three alternative concepts for shielding the HPI nozzle from cold injection water were developed. Each concept uses a stainless steel thermal sleeve which is secured into the nozzle and projects into the RC cold leg piping. The approaches are as follows:

Hard Rolled Thermal Sleeve Concept

A hard rolled thermal sleeve design was developed (see Figure 8), which requires a hard roll of the upstream end of the thermal sleeve, instead of a contact roll. Since the same concept was used in the original design, the hard rolled concept should be easy to implement. However, the problem of loosening of the rolled joints may still exist.

Integral Thermal Sleeve Concept

An integral thermal sleeve concept was developed which incorporates the thermal sleeve and the safe-end into a single component (see Figure 9). This design eliminates the possibility of the sleeve loosening and also eliminates the concern about annular flow

between the thermal sleeve and the safe-end. However, disadvantages of this concept include: (1) increased pressure drop due to reduced thermal sleeve ID, (2) fabrication problems, (3) welding problems, (4) excessive cost, and (5) an inability to meet fatigue design requirements as specified in code B31.7, 1968 draft.

Flanged Thermal Sleeve Concept

B&W's flanged thermal sleeve concept is shown in Figure 10. The flanged connections allow easy access to the thermal sleeves for inspection and replacement. The concept also provides a positive seal against water flow in the annular region. The disadvantages of this concept, on the other hand, include: (1) re-routing of piping, (2) thermal shock to the gasket, and (3) reliability of the gasket.

B&W engineers concluded that the hard rolled thermal sleeve concept represented the optimum choice from a cost, licensing, and leakage standpoint.

10.2 Design Improvements

The redesigned hard rolled thermal sleeve (See Figure 8) was developed with some notable improvements:

1. Bell shaped upstream end on the thermal sleeve - This should prevent movement of the sleeve towards the RC cold leg piping.

2. Increased length and width of the upstream end of the thermal sleeve - This feature provides more roll surface contact area and more metal to be cold worked during the rolling process.

3. Hard roll of the thermal sleeve shoulder - The original thermal sleeve was only contact rolled. The increased compression and subsequent deformation of the thermal sleeve material should provide a more secure bond with the safe-end. Also, the additional wall thinning should mitigate sleeve to safe-end separation during HPI events.

4. Contact roll at the thermal sleeve collar - The effects of possible flow induced vibration will be reduced with the sleeve surface in contact with the nozzle ID.

5. Axially notched upstream end of the thermal sleeve - The 4 notches allow the placement of weld beads to provide additional anti-rotation protection.

In summary, the thermal sleeve has been redesigned to eliminate the causes which contributed to the failures at Crystal River, Oconee, ANO, and Rancho Seco.

11.0 MAKEUP SYSTEM OPERATING CONDITIONS

Aside from the redesign of the thermal sleeve, modifications to the makeup system operating conditions were also suggested following the Crystal River incident. The original design specification called for a minimum continuous makeup flow of 1-3 gpm. It was believed that at this limited flow rate, flow and thermal stratification could occur in the makeup line which may lead to thermal fatigue of the nozzle assembly. Similar flow conditions at 5 Westinghouse PWR's [8-10] in 1979 lead to cracking of the steam generator feedwater lines. Consequently, a minimum bypass flow of 15 gpm was suggested to eliminate, or at least mitigate this potential problem.

As additional information was obtained, the recommended 15 gpm minimum makeup flow rate was re-evaluated. The results from the instrumented Crystal River-3 nozzle indicated that the new design achieved all design requirements even at the lowest flow rate tested (1.6 gpm). The safe-end remained cool, while the outer surface of the nozzle varied by at most 20°F. The circumferential temperature gradients were small indicating that no significant "hot spots" or flow stratification was occurring. Also, as the makeup flow rate was increased to a maximum of 130 gpm, the nozzle thermal stresses tended to decrease.

In light of these findings, a minimum continuous makeup flow of 1-3 gpm (as originally specified) should adequately maintain all design parameters within analyzed limits and prevent thermal stratification. However, it must also be pointed out that increasing continuous makeup flow may decrease the nozzle thermal stresses.

12.0 AUGMENTED INSERVICE INSPECTION PLAN

Along with the thermal sleeve redesign and the MU system operating changes, an augmented inservice inspection (ISI) plan was also developed. An ISI provides a means of early problem detection, such that repairs can be effected before extensive damage occurs. Prior to Crystal River, no HPI/MU nozzle assembly inspection was required.

B&W and the Safe-End Task Force developed an augmented ISI for the 177 FA Owner's Group. Specifically, the plan calls for:

Makeup Nozzles

1. Unrepaired Nozzles

   - RT during the next five refueling outages to ensure that the thermal sleeve is in the proper location and no gap exists between the thermal sleeve and safe end. Ensure RT is comparable with "baseline" first RT taken. Perform RT every fifth refueling outage thereafter.

   - UT the safe end and some length of adjacent pipe/valve during the next five refueling outages to ensure no cracking. Perform UT every fifth refueling outage thereafter.

2. Repaired Nozzles (New Sleeve Design)

   - RT during the first refueling outage to ensure that the thermal sleeve is in the proper location and no gap has formed.

   - UT safe end, cold leg ID nozzle knuckle transition, and adjacent piping/valve during the first refueling outage to ensure no cracking exists.

   - RT and UT again at third and fifth refueling outages after repair and every fifth refueling outage thereafter.

3. Repaired Nozzles (with re-rolling)

- RT during the next five refueling outages to ensure that the thermal sleeve is in the proper location and no gap exists between the thermal sleeve and safe end. Ensure RT is comparable with "baseline" first RT taken. Perform RT every fifth refueling outage thereafter.

High Pressure Injection Nozzles

1. Unrepaired

- RT during the next five refueling outages to ensure that the thermal sleeve is in the proper location and no gap exists. Ensure RT is comparable with "baseline" first RT taken. Perform RT every fifth refueling outage thereafter.

2. Repaired (New Sleeve Design)

- RT during first refueling outage to ensure that the thermal sleeve is in the proper location and no gap has formed. RT during third and fifth refueling outages and every fifth refueling outage thereafter.

- UT the ID nozzle/cold leg transition knuckle area during the first refueling outage to assure that no cracking is present. UT during third and fifth refueling outages thereafter.

3. Repaired (with re-rolling)

- RT during the next five refueling outages and every fifth refueling outage thereafter to ensure a gap does not form.

13.0 JUSTIFICATION OF LONG TERM OPERATION

Finally, having described the modifications (design, operation inspection) made to correct the problem, we must now consider the steps taken to support these changes. Specifically, continued operation on a long term basis will be justified analytically, experimentally, and by inspections of nozzles in service.

13.1 Analytical Justification

After the repair efforts were completed at the damaged sites, the NRC staff required that the new design be proven safe for operation in the near term. In response to this request, B&W provided certified field change authorizations (FCA) to the utilities. These FCA's were predicated on simple, yet conservative stress analysis, worst case operational histories, and the consideration of continued nozzle usage through the next fuel cycle only. As such, these studies were only valid in the short term.

In order to justify long term use, B&W recommended a more extensive stress analysis. The stress information required for more detailed evaluation of makeup and HPI nozzle design changes can be obtained most accurately through the use of the finite element method of structural analysis. This analysis technique will determine, in detail, the stresses in the critical areas and will provide the means to assess the impact of unanticipated operating transients on the makeup and HPI nozzles. Such an analytical capability will be invaluable at some later date if, for example, an HPI nozzle that had a loose thermal sleeve was subjected to more HPI flow cycles than can presently be shown to be acceptable using conservative techniques. In addition, evaluation of thermal sleeve/safe-end interface stresses may be required, at a later date, for unanticipated makeup nozzle flow transients. Inservice inspection (ISI) detected flaws could also be less conservatively evaluated if the new detailed stress profiles were available for use in determining the number of cycles for thru-wall crack propagation.

B&W's modified nozzle design is currently being used for both the double-duty HPI/MU nozzles and the HPI only nozzles. However, design differences in service conditions between the two nozzle functions lead to radically different stress distributions.

For the HPI/MU nozzle with continuous 95°F makeup flow, injection of HPI water at 40°F (design temperature) is normally not considered to be a severe transient. The highest stresses for this nozzle are at the point where the HPI/MU pipe penetrates the RC pipe (nozzle "knuckle" region) and are due to the steady axial temperature gradient between the relatively cool safe-end and the hot RC pipe.

On the other hand, the insulated HPI only nozzle is kept hot through heat conduction from the RC pipe under conditions of no HPI flow. When HPI is actuated, the sudden flow of 40°F water (design conditions) causes severe thermal stresses at the thin walled portion of the upstream end of the safe-end. Contributing to the stresses in this region are a severe radial temperature gradient and a local axial temperature gradient.

Although the HPI/MU and HPI only nozzles see different service conditions and experience different stress distributions, a single finite element model will suffice for both nozzle functions. The only exception will be substructured regions where a refined mesh is required to investigate highly stressed locations (e.g., near the wide collar for the makeup nozzle and in the safe-end for the HPI nozzle).

Ultimately, the stress analysis using this model will quantify the usable lifetime of the modified design.

13.2 Experimental Justification

To substantiate the results of the analytical study, an experimental study was conducted (see Section 9.0 for details). The thermal sleeve/safe-end geometry was simulated using the test apparatus shown in Figure 11. The results indicated that under static conditions, the axial load carrying capability of the rolled joint varies in a non-linear manner with nominal values in the 6000-13000 lb. range (1-8% range). Thermal transient characteristics were obtained by injecting cold water through a heated simulated nozzle. During these thermal quench tests, the rolled joint lost load carrying capability (i.e., sleeve movement and leakage flow) for roll expansions less than 5% wall thinning. The natural vibration frequency of the thermal sleeves was also quantified in another segment of the test program. These tests showed that the natural frequency of the sleeve varies as a function of roll expansion length and degree of wall thinning with nominal values in the 220-250 Hz range.

14.0 CONCLUSIONS

Based upon the information presented, the following conclusions can be drawn:

1. Variations in contact expansion of the thermal sleeves is the most probable root cause of the failures.

2. Continued operation in the short term is acceptable with the modified design.

3. If continued inspections show that the sleeves are properly in place, it is not expected that the sleeves will loosen during plant operation prior to subsequent inspections.

15.0 RECOMMENDATIONS

As a result of the Safe End Task Force's investigation into the HPI/MU nozzle component failures, the following recommendations are made:

1. In terms of future repairs, it is recommended that:

   ### Nozzles with Original Design Thermal Sleeves

   Reroll the upstream end of the thermal sleeve when inspections indicate that a gap exists. A 5.0% wall reduction is suggested to achieve an adequate interfacial residual stress and avoid stress corrosion cracking of the thermal sleeve.

   ### Nozzles with Modified Design Thermal Sleeve

   Repair and/or replace the damaged components if inspections reveal that abnormal conditions are present.

   In either case, the affected utility should also verify that the components attached to the safe-end meet the design constraints used in the stress analysis.

2. In order to ensure proper HPI/MU system operation, it is recommended that:
   - A continuous makeup flow via bypass of the Pressurizer Level Control Valve should be maintained.

   - A known amount of bypass flow which is greater than 1.5 gpm should be maintained and checked frequently (increased flows of up to about 10-15 gpm may be preferable depending upon plant configuration and operating practices).

- There should be a consistent set of procedures to initiate continuous bypass flow
  - RCS temperature
  - RCS pressure
  - Bypass flow rate
  - Frequency of adjustment and calibration

- The makeup tank temperature should be maintained within the proper control band as determined by other plant parameters.

- In the event that future anomalies are discovered, proper logging of HPI initiations will be invaluable. This procedure should include:
  - Nozzles used
  - Temperature of BWST
  - Temperature of cold leg before and after HPI initiation
  - Pressure
  - Flow rate
  - Duration of HPI flow

3. An augmented inservice inspection plan as stated in Section 12.0 should be implemented.

4. A detailed stress analysis of a nozzle with a modified thermal sleeve design should be performed to justify long term operation.

REFERENCES

1. Lynchburg Research Center, "Examination of Normal Makeup Nozzle Thermal Sleeve and Safe-End", No. 77-1131543-00.

2. Sykes, J. F., Hoch, G. H., Beavers, J. A. and Berry, W. E. of Battelle Columbus Laboratories, "Failure Analysis of Safe-End to Check Valve Pipe Weld in the Crystal River-3 Makeup Water System", March 1, 1982.

3. D. L. Baty of Lynchburg Research Center, "Examination of Oconee-3 HPI Thermal Sleeve, Safe-End", LR:82:5463-08:01, March 26, 1982.

4. D. L. Baty of Lynchburg Research Center, "Examination of HPI Thermal Sleeve from Oconee-2", RDD:83:5492-08:01, June 2, 1982.

5. M. R. Dietrich of Lynchburg Research Center, "Examination of Thermal Sleeve from ANO", RDD:83:5032-08:01, June 28, 1982.

6. A. Flynn, et al., "Thermal Sleeve Failure and Repairs - Indian Point #1 Nuclear Unit (285 MW)", Nuclear Technology, Vol. 25, January 1975.

7. R. Snaider, "BWR Feedwater Nozzle and Control Rod Drive Return Line Nozzle Cracking", NUREG-0619, November 1980.

8. R. W. Klecker, "Thermal Fatigue Cracking in Pressurized Water Reactor Feedwater Lines", Pipe Crack Study Group Supporting Document, June 18, 1980.

9. M. H. Hu, J. L. Houtman and D. H. White, "Flow Model Test for the Investigation of Feedwater Line Cracking for PWR Steam Generators", ASME Conference, Denver, Colorado, June 21-25, 1981.

10. W. H. Bamford, A. Thurman and M. Mahlab, "Fatigue Crack Growth in Pressurized Water Reactor Feedwater Lines", ASME Conference, Denver, Colorado, June 21-25, 1981.

11. "Evaluation of Crystal River-3 HPI/MU Nozzle Testing", B&W Document ID 77-1134571-00, May 1982.

12. "ANSYS Engineering Analysis System - User's Manual", Swanson Analysis Systems, Inc., 1978 Edition, Revision 3, (Update 67L).

13. "Evaluation of Preliminary Cause of HPI/MU Nozzle Thermal Sleeve and Safe-End Failures", Minutes from the Safe End Task Force Meeting, Bethesda, Maryland, May 7, 1982.

14. <u>Loss of Thermal Sleeves in Reactor Coolant System Piping at Certain Westinghouse PWR Power Plants</u>, Nuclear Regulatory Commission Office of Inspection and Enforcement, IN 82-30, Washington, D.C. (1982), pp 1-2.

Figure 1. TYPICAL ELEVATION VIEW OF REACTOR COOLANT SYSTEM ARRANGEMENT SHOWING LOCATION OF HPI NOZZLE

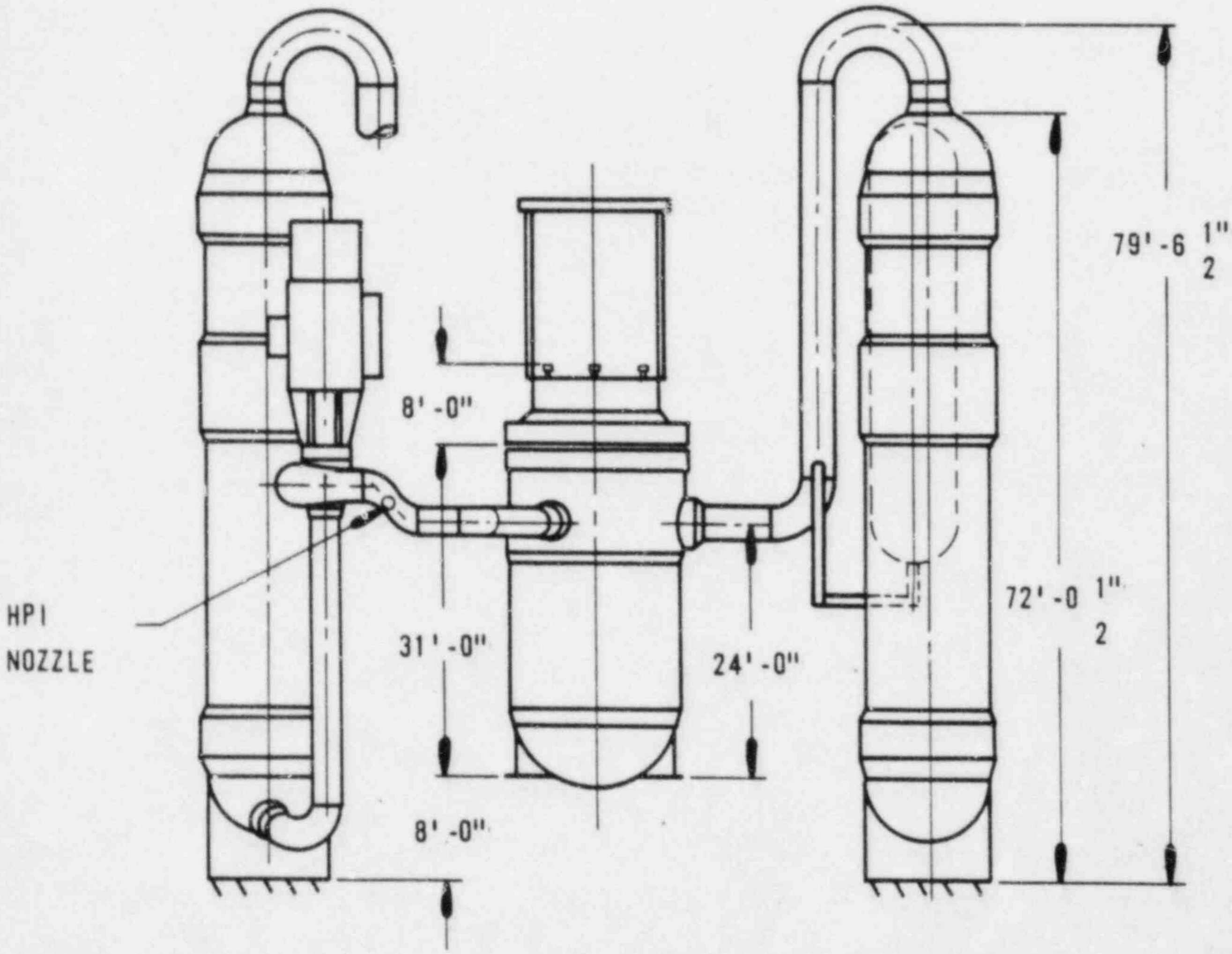


Figure 2 TYPICAL PLAN VIEW OF REACTOR COOLANT SYSTEM ARRANGEMENT SHOWING LOCATION OF HPI NOZZLE

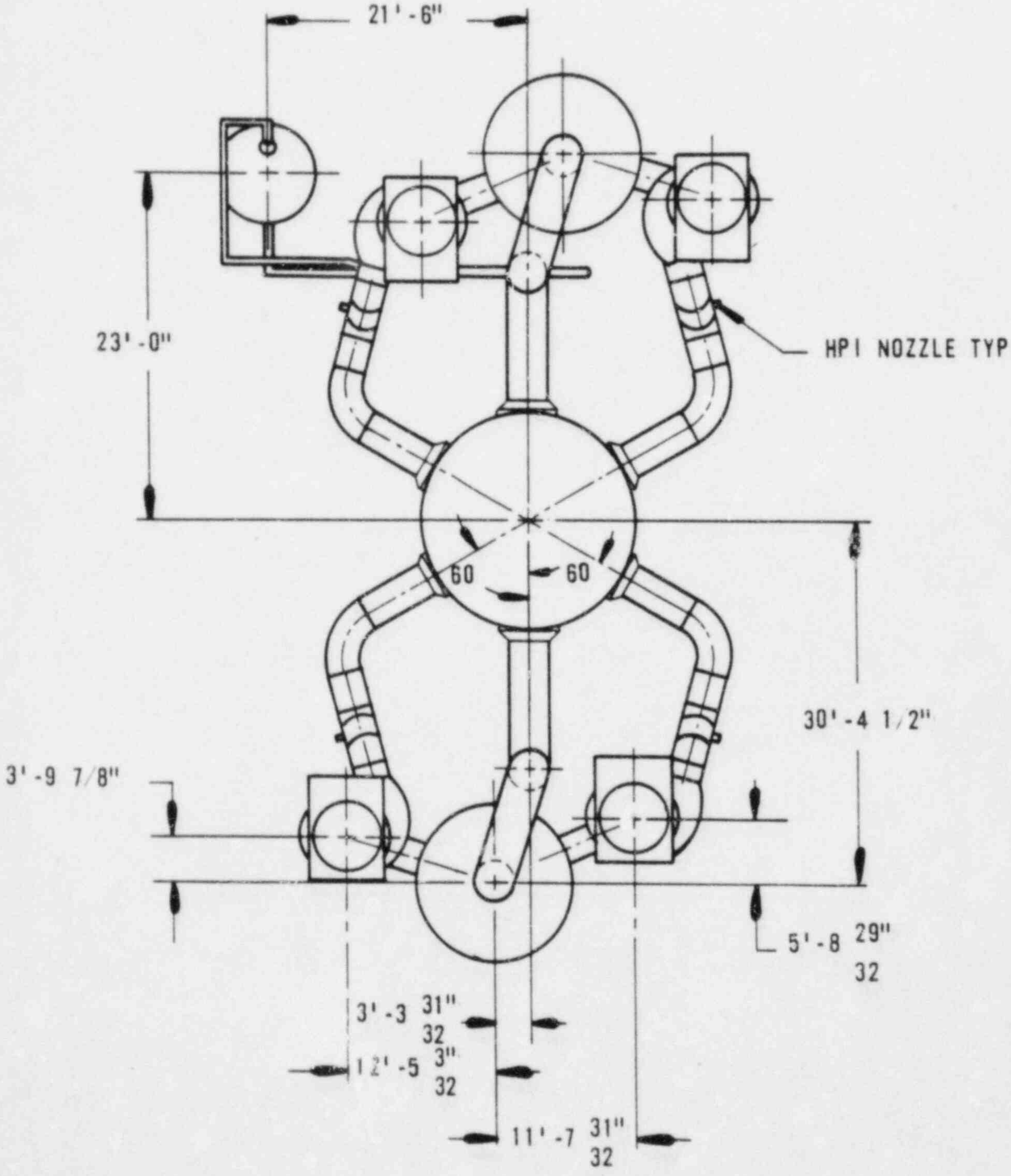


Figure 3

TYPICAL HPI AND HPI/MU NOZZLE

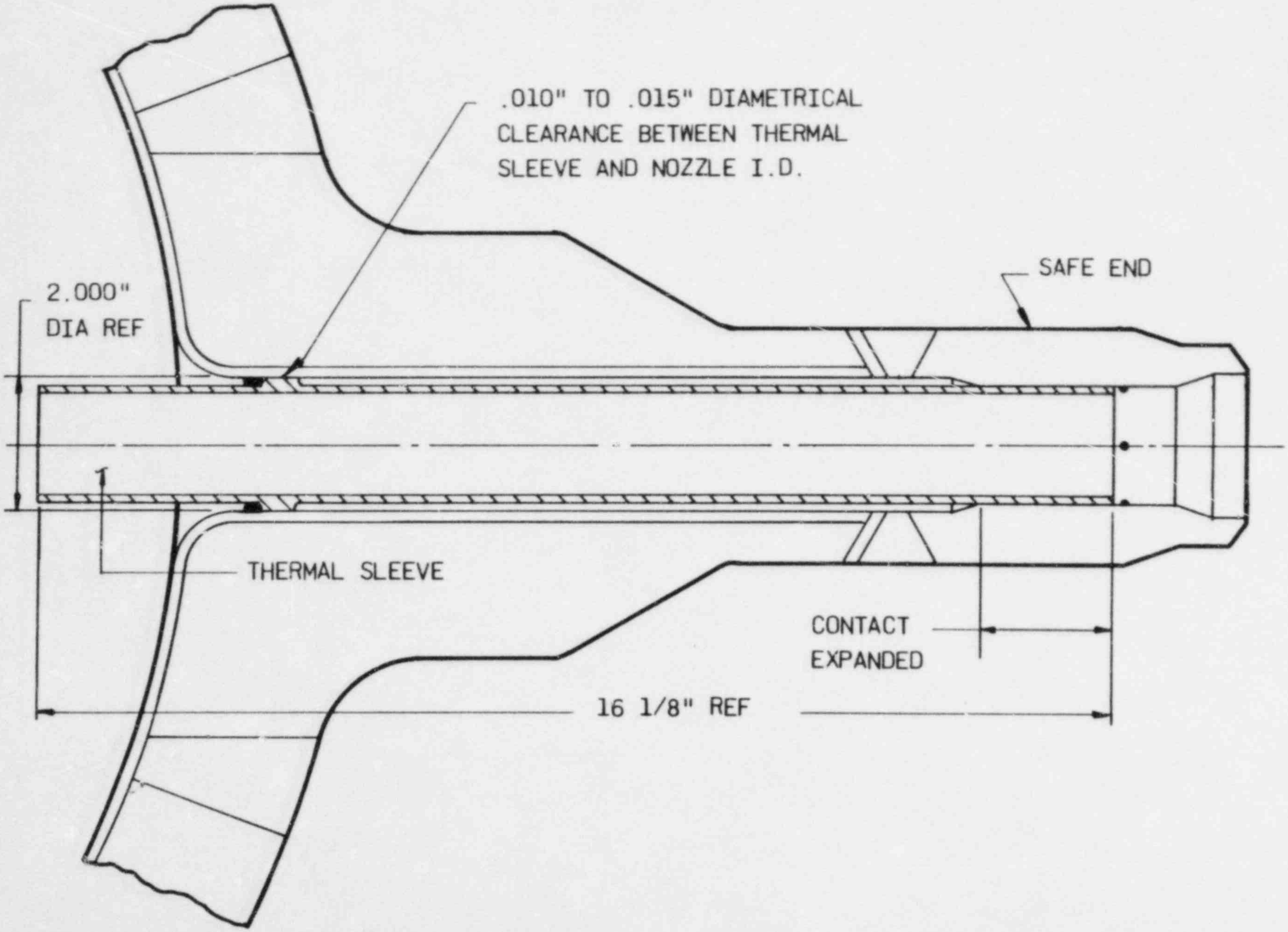


Figure 4

TYPICAL LAYOUT OF HPI OR HPI/MU LINE

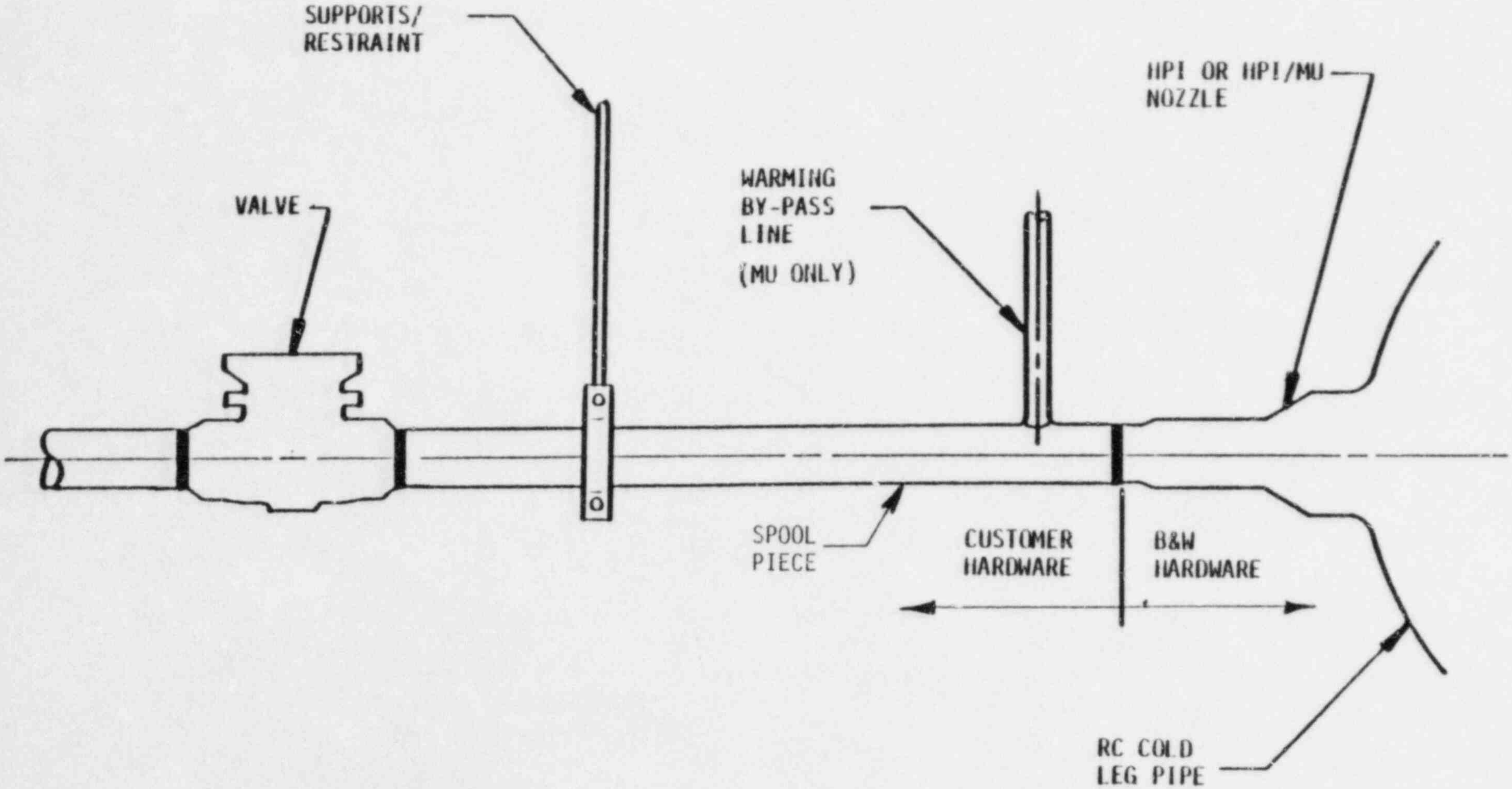


Figure 5

SAFE END TASK FORCE ACTION PLAN - REV 02

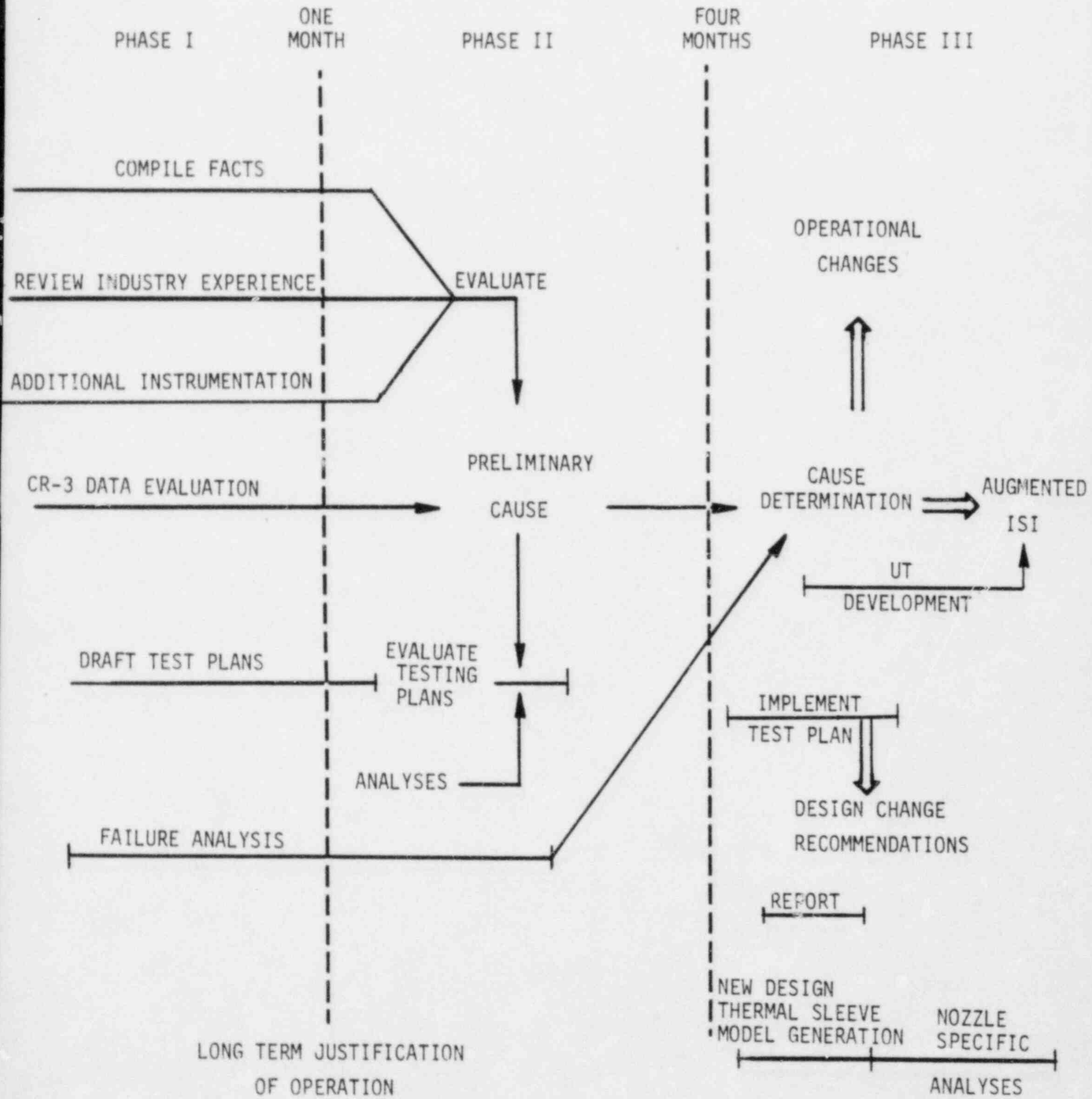


Figure 6

INSTRUMENTATION ARRANGEMENT AT CRYSTAL RIVER-3

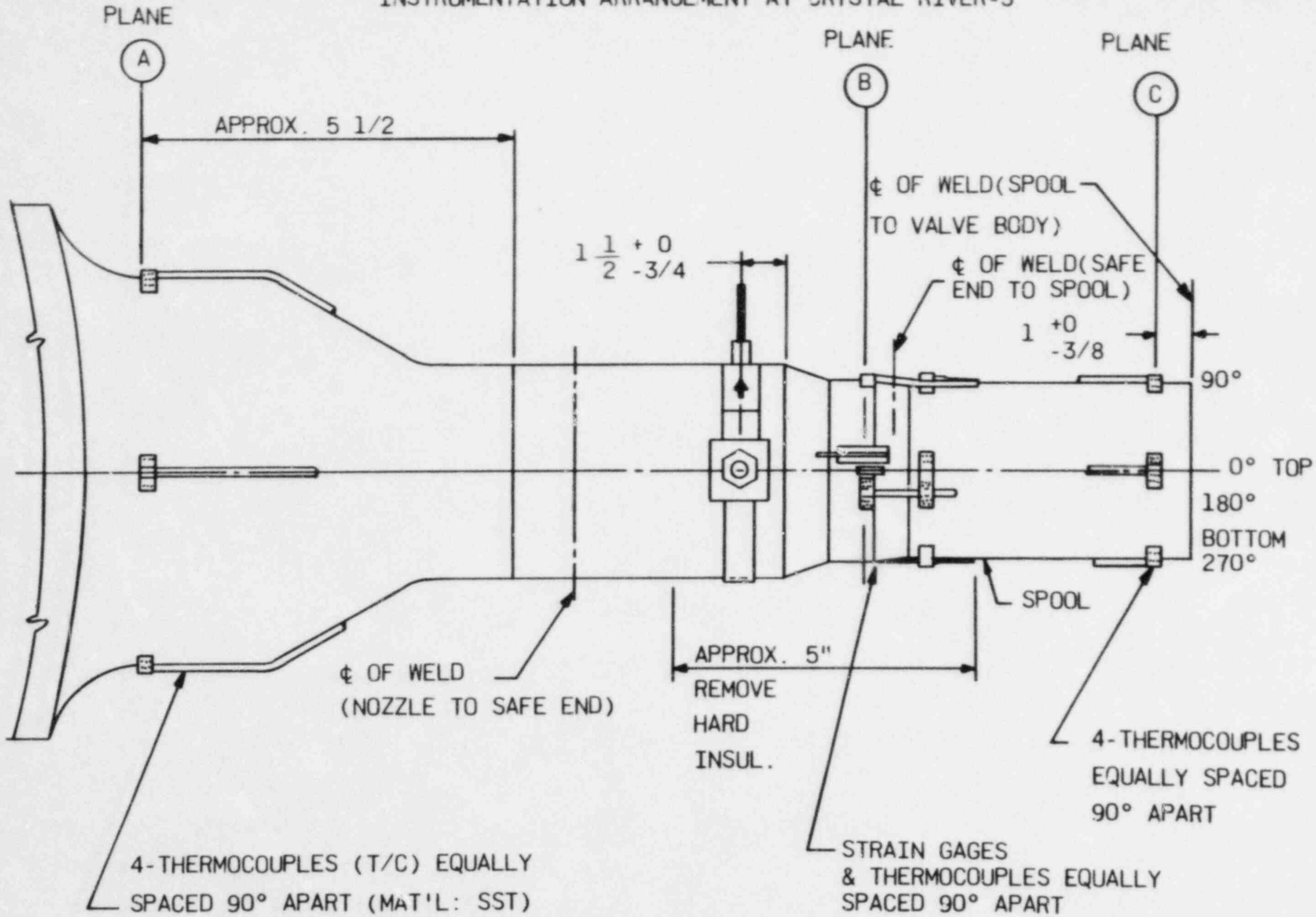


Figure 7 "GOODNESS OF ROLL" RESULTS

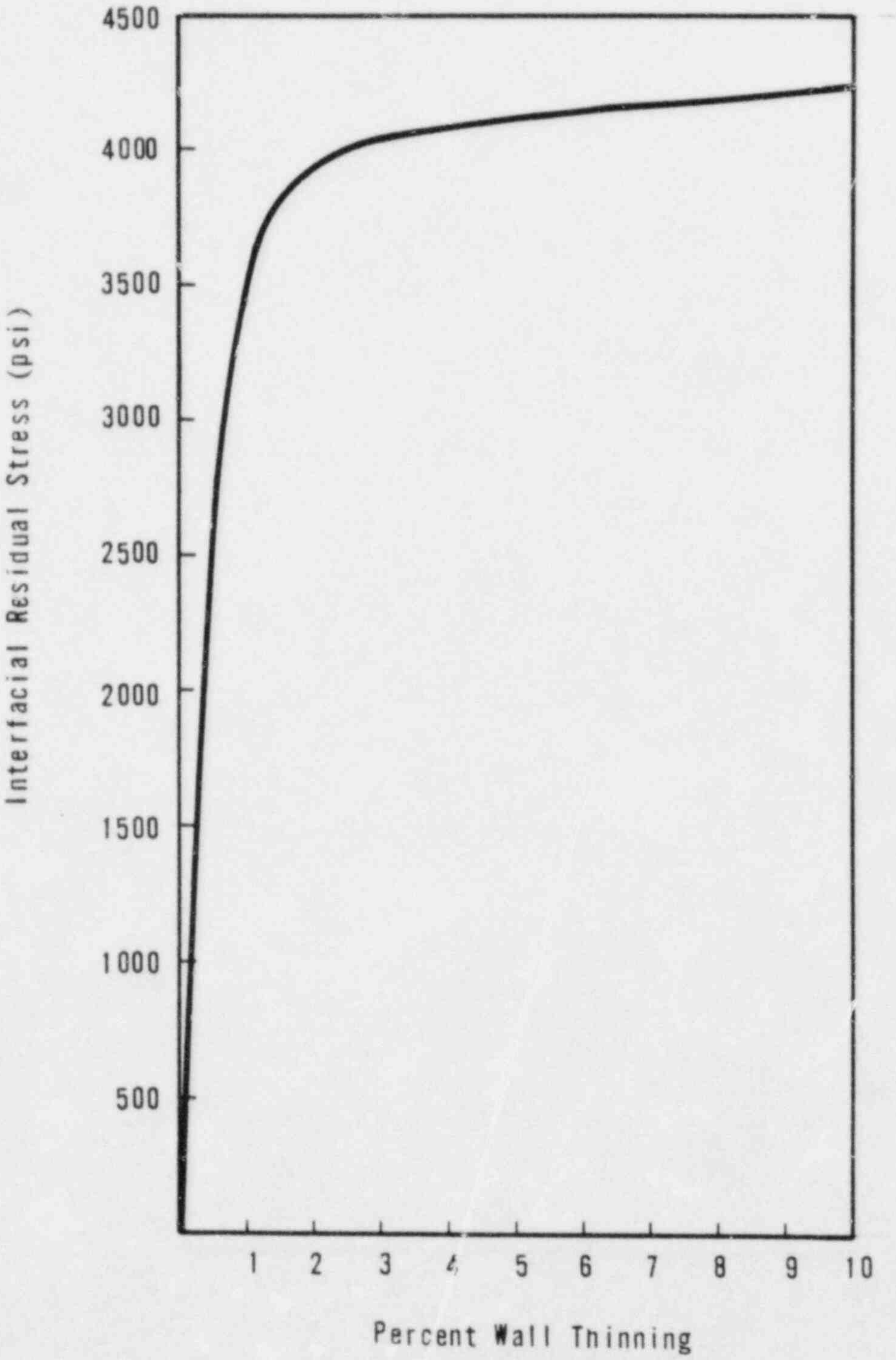


Figure 8

HARD ROLLED HPI/MU NOZZLE

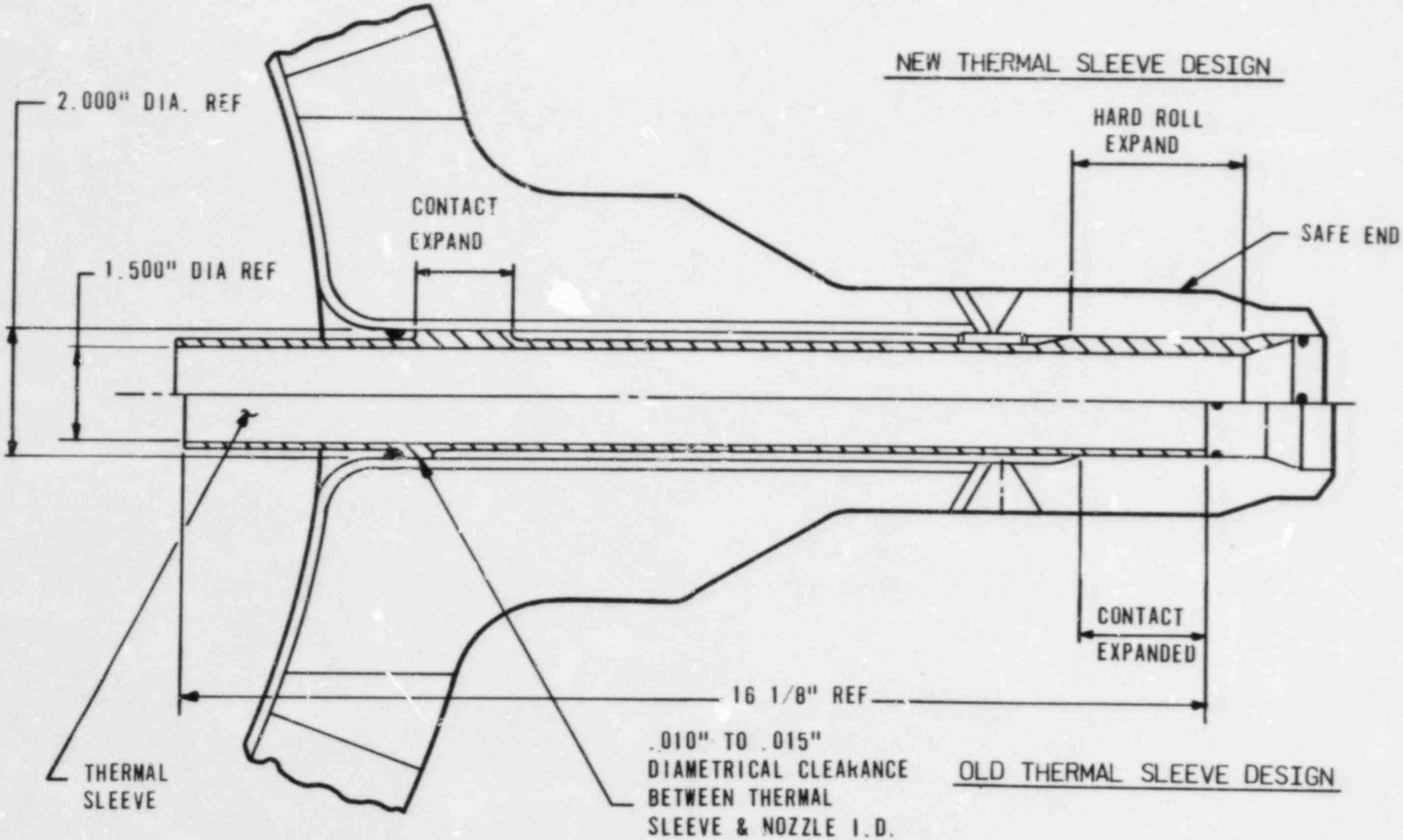


Figure 9 INTEGRAL HPI/MU NOZZLE MODIFICATION

HPI/MU NOZZLE
CONCEPTUAL DESIGN
FOR INTEGRAL SAFE-END/
THERMAL SLEEVE

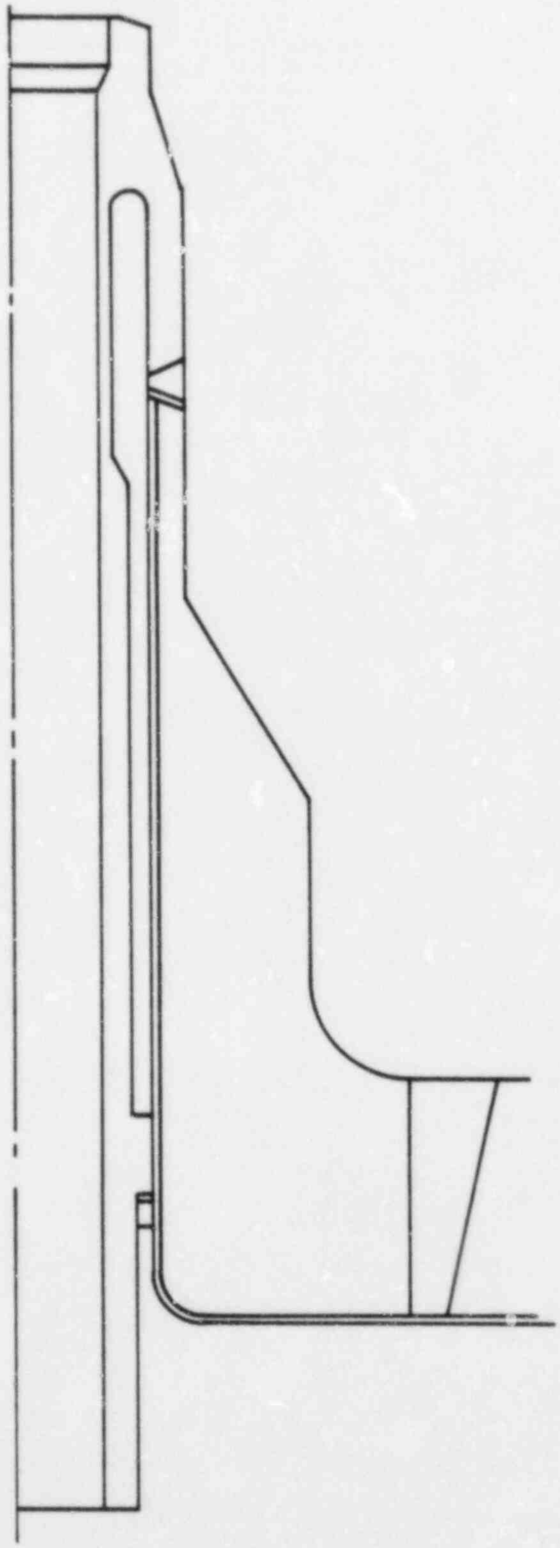
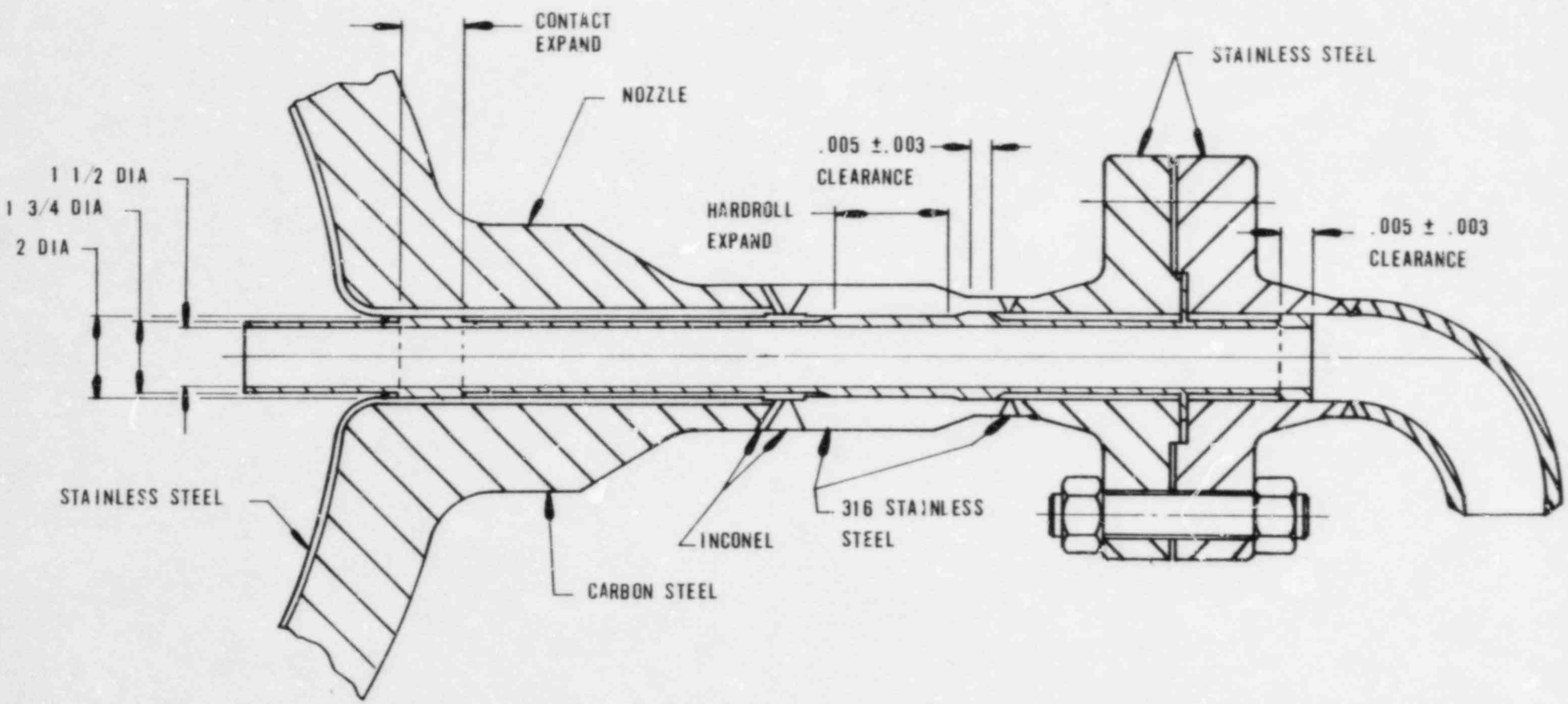


Figure 10 FLANGED MAKE-UP/HPI NOZZLE



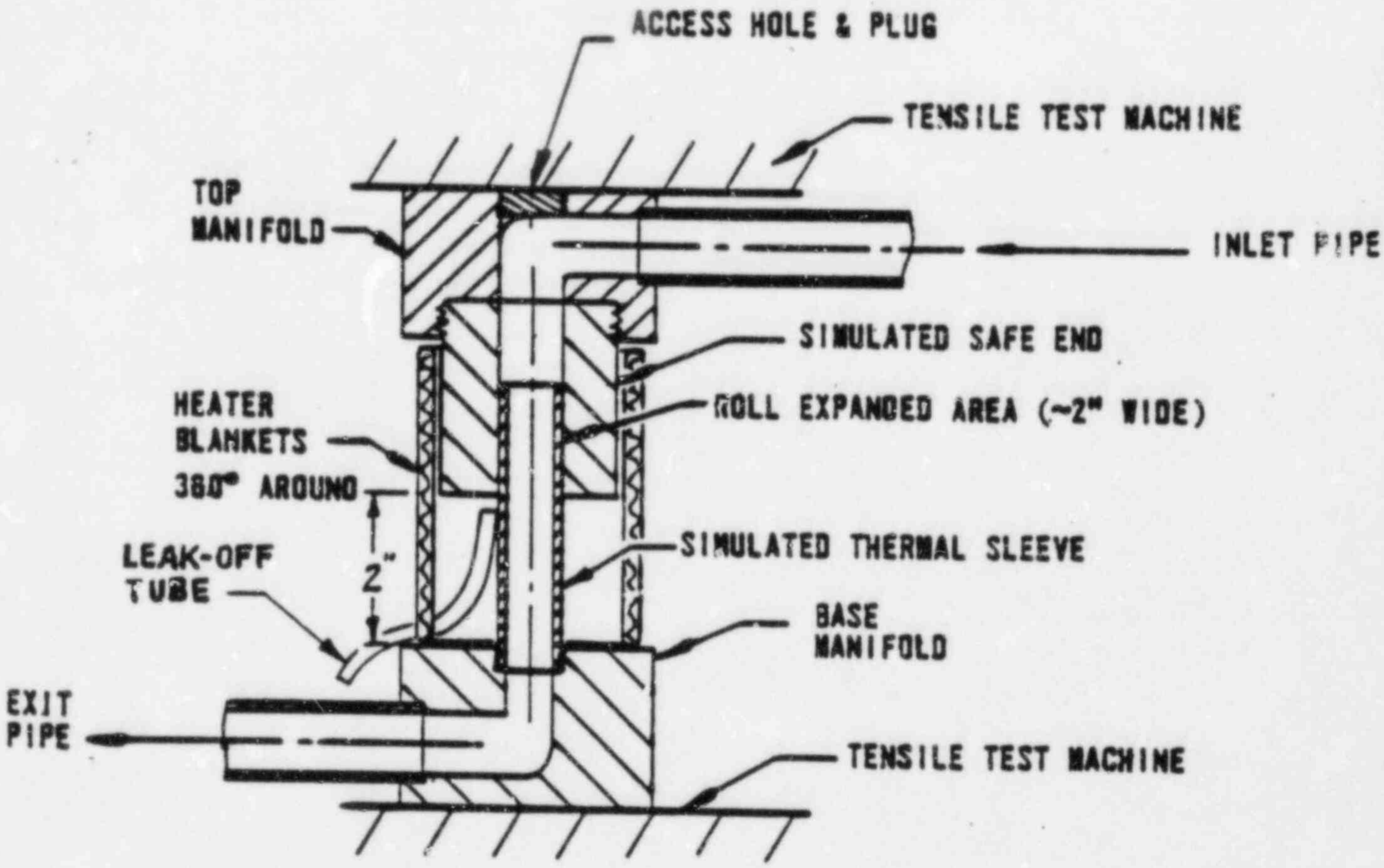


FIGURE 11. - ROLL EXPANSION TEST SCHEMATIC DIAGRAM OF TEST FIXTURE

Figure 12 HPI/MU STATIC TEST RESULTS

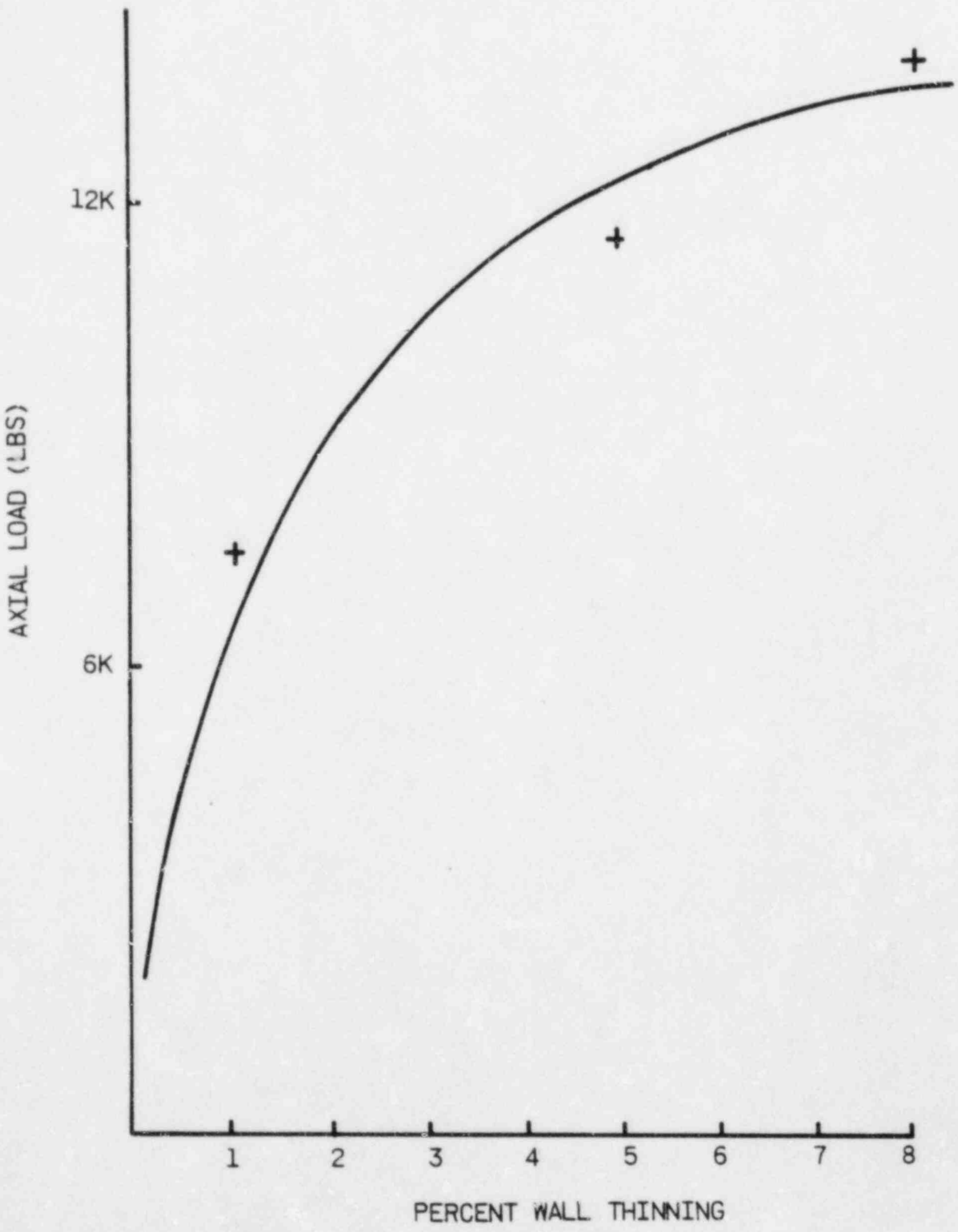


FIGURE 13

HPI/MU NOZZLE TEST RESULTS

TRANSIENT LOAD TESTS (PHASE II A)

	THERMAL SLEEVE WALL REDUCTION			
	0%	2%	4%	5%
DISPLACEMENT AFTER QUENCH (IN.)	1.053*	1.251	0.841	0
LEAKAGE (FL. OZ.)	~8	~4	0	0

POSITIVE DOWNWARD EQUIVALENT LOAD: 86 LBS.

TEMPERATURE: MAX: 550^{o}F, MIN: 200^{o}F

QUENCH FLOW: 275 GPM AT 65^{o}F

*THE MOTION OF THE SLEEVE WAS STOPPED PREMATURELY BY JAMMING THE LEAK-OFF TUBE IN THE GAP.

FIGURE 14

HPI/MU NOZZLE TEST RESULTS

VIBRATION TEST (NO FREE END RESTRAINT)

	THERMAL SLEEVE WALL REDUCTION			
	1%	1%	5%	8%
CONTACT LENGTH (IN.)	1 1/2	2	2	2
NATURAL FREQUENCY (H_Z)	221.8	236.0	237.5	237.5
NATURAL FREQUENCY AT (H_Z) 90° FROM ABOVE	239.0	250.1	251.6	253.1
DAMPING(%)	1.86	1.79	1.59	1.39

Figure 15 NATURAL VIBRATION FREQUENCY TEST SCHEMATIC DIAGRAM

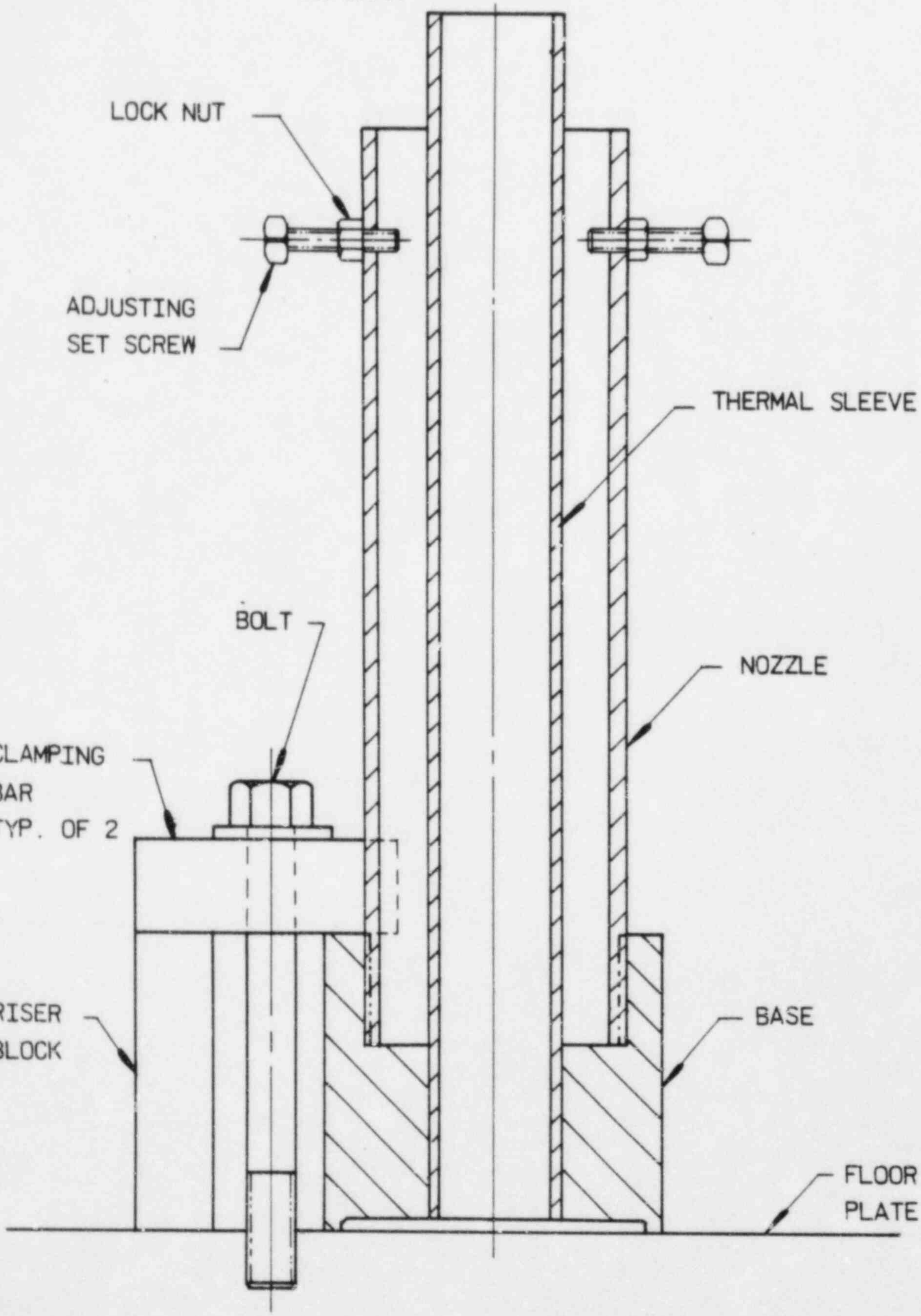


TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	INSPECTION RESULTS (See Note 2)	TH.SLEEVE COLLAR OD	NOZZLE ID IN COLLAR AREA	DIAMETRICAL GAP BETWEEN TH.SL.COL.& NOZ. (MIL)	THERMAL SLEEVE ID/OD	SAFE END ID
CONEE 1	WX		A1	MU/HPI	OK					
	XY		A2	MU/HPI	"					
	YZ		B2	HPI	"					
	ZW		B1	HPI	"					
CONEE 2	WX	B44	B1	HPI	B					1.762
	XY	B41	B2	HPI	C		2.031			1.763
	YZ	B40	A2	MU/HPI	A					1.763
	ZW	B46	A1	MU/HPI	OK					1.763
CONEE 3	WX	B44	B1	HPI	B	2.003	2.015	12	1.500/1.754	1.762
	XY	(See Note 4)	B2	HPI	OK					
	YZ	B40	A2	MU/HPI	A	1.992	2.003	11	1.500/1.752	1.762
	ZW	(See Note 4)	A1	MU/HPI	OK					
TMI 1	WX	B44		HPI	OK					
	XY	B41		MU/HPI	"					
	YZ	B40		HPI	"					
	ZW	B46		HPI	"					
TMI 2	WX									
	XY									
	YZ									
	ZW									
CR 3	WX	B44	A2	HPI	OK	1.993	2.004	11	1.498/1.754	1.763
	XY	B41	A1	MU/HPI	A	1.994	2.004	10	1.498/1.752	1.764
	YZ	B40	B1	HPI	OK	1.992	2.003	11	1.497/1.753	1.762
	ZW	B46	B2	HPI	OK	2.003	2.013	10	1.502/1.754	1.763
ANO 1	WX	B44	C	HPI	OK	1.991	2.002	11	1.500/1.754	1.762
	XY	B41	D	MU/HPI	C	1.989	2.002	13	1.499/1.754	1.762
	YZ	B40	B	HPI	B	1.982	1.994	12	1.500/1.754	1.762
	ZW	B41	A	HPI	B	1.993	2.003	10	1.499/1/754	1.764
RANCHO SECO	WX	B44	D	HPI	OK	1.989	2.000	11	?/?	1.762
	XY	B46	C	HPI	OK	1.992	2.003	11	1.500/1.754	1.762
	YZ	B40	A	MU/HPI	A	1.981	1.992	11	1.500/1.753	1.761
	ZW	B41	B	HPI	B	1.990	2.003	13	1.498/1.754	1.764
MIDLAND 1	WX	B44	A	HPI		1.993	2.005	12		1.762
	XY	B41	B	MU/HPI		1.993	2.006	13		1.762
	YZ	B40	C	HPI		1.990	2.002	12		1.762
	ZW	B41	D	HPI		2.008	2.020	12		1.762
MIDLAND 2	WX	B44	C	HPI		1.998	2.010	12		
	XY	B41	D	HPI		1.993	2.006	13		
	YZ	B40	A	MU/HPI		1.997	2.010	13		
	ZW	B41	B	HPI		1.994	2.006	12		
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	OK	2.004	2.016	12	1.500/1.753	1.762
	XY	B61	A1	HPI	"	2.003	2.015	12	1.498/1.754	"
	YZ	B59	B1	MU/HPI	"	1.985	1.997	12		"
	ZW	B44	B2	HPI	"	2.003	2.018	15	1.500/1.750	"

TABLE 1 MATRIX OF FACTS

LANT ITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	THERMAL SLEEVE HT. NO. AND MAT'L. SPEC.	SAFE END HT. NO. AND MAT'L. SPEC.	EXPANSION INFO. LOC.	EXPANSION INFO. DATE	EXPANSION INFO. TOOL NO.	SOURCE REFERENCE DOC. REFERENCE DRAWINGS	SOURCE REFERENCE DOC. SHOP RECORDS IDENTIFIED BY PIPE SER.NO.
NEE 1	WX		A1	MU/HPI							
	XY		A2	MU/HPI							
	YZ		B2	HPI							
	ZW		B1	HPI							
NEE 2	WX	B44	B1	HPI	-A336F8M	43116-A336F8M	SITE	(See Note 3)	(See Note 3)	146614[illegible]-5	B44-204-50-1
	XY	B41	B2	HPI	"	" "	"			146629E-7	B41-204-50-1
	YZ	B40	A2	MU/HPI	"	" "	"				B40-204-50-1
	ZW	B46	A1	MU/HPI	"	" "	"				B46-204-50-1
NEE 3	WX	B44	B1	HPI	05477-A336F8M	65047-A336F8M	MTV			150141E-7	B44-209-50-1
	XY	(See Note 4)	B2	HPI	" "	" "	"			150156E-7	
	YZ	B40	A2	MU/HPI	" "	" "	"	11-18-71	7573-1		B40-209-50-1
	ZW	(See Note 4)	A1	MU/HPI	" "	" "	"				
1	WX	B44		HPI		-SB 166	SITE	(See Note 3)	(See Note 3)	131956E-7	
	XY	B41		MU/HPI		"	"			160493E-0	
	YZ	B40		HPI		"	"			131960E-9	
	ZW	B46		HPI		"	"				
2	WX									141578E-9	
	XY									141576E-13	
	YZ										
	ZW										
3	WX	B44	A2	HPI	05477-A336F8M	810906-A336F8M	MTV	9-7-71	7573-1	141599E-5	B44-207-50-1
	XY	B41	A1	MU/HPI	" "	" "	"			141597E-5	B41-207-50-1
	YZ	B40	B1	HPI	" "	" "	"	9-8-71	7573-1		B40-207-50-1
	ZW	B46	B2	HPI	" "	" "	"	9-11-71	7573-1		B46-207-50-1
O 1	WX	B44	C	HPI	05477-A336F8M	811236-A336F8M	MTV	3-7-72	7573-1	131998E-4	B44-208-50-1
	XY	B41	D	MU/HPI	" "	" "	"	3-15-72	"	131996E-6	B41-208-50-2
	YZ	B40	B	HPI	" "	81564- "	"	11-12-71	"		B40-208-50-1
	ZW	B41	A	HPI	" "	811236- "	"	12-1-71	"		B41-208-50-1
NCHO ECO	WX	B44	D	HPI	05477-A336F8M	129186-A336F8M	MTV	1-8-72	7573-1	143491E-7	B44-2011-50-1
	XY	B46	C	HPI	" "	" "	"	12-30-71	"	143509E-8	B46-2011-50-1
	YZ	B40	A	MU/HPI	" "	" "	"	12-30-71	"		B40-2011-50-1
	ZW	B41	B	HPI	" "	" "	"	1-6-72	"		B41-2011-50-1
DLAND 1	WX	B44	A	HPI	818442-A336F8M	43116-A336F8M	MTV	9-20-74	7573-1	150176E-6	B44-2012-50-1
	XY	B41	B	MU/HPI	" "	" "	"	12-9-74	"	150191E-1	B41-2012-50-1
	YZ	B40	C	HPI	" "	" "	"	10-16-74	"		B40-2012-50-1
	ZW	B41	D	HPI	" "	" "	"	9-27-74	"		B41-2012-50-2
DLAND 2	WX	B44	C	HPI	121294-A336F8M	817962-A336F8M	MTV	10-15-75	7573-1	150206E-4	B44-2013-50-1
	XY	B41	D	HPI	" "	29006- "	"	9-28-75	"	150221E-2	B41-2013-50-1
	YZ	B40	A	MU/HPI	" "	817962- "	"	10-16-75	"		B40-2013-50-1
	ZW	B41	B	HPI	" "	43116- "	"	9-23-75	"		B41-2013-50-2
AVIS ESSE 1 (See Note 5)	WX	B56	A2	HPI	05477-A336F8M	811584-A336F8M	MTV & SITE (See Note 5)	6-27-72	7673-1	152027E-4	B56-2014-50-1
	XY	B61	A1	HPI	" "	" "		7-6-72	"	152042E-4	B61-2014-50-1
	YZ	B59	B1	MU/HPI	" "	" "		6-16-72	"		B59-2014-50-1
	ZW	B44	B2	HPI	" "	48417- "		7-3-72	"		B44-2014-50-1

TABLE 1 MATRIX OF FACTS

ANT TE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	PUMP ROTATION	FLOW LENGTH FROM RC PUMP	COLD LEG GEOM. & NOZZLE DATE ORIENTATION [a]	2/2 RC FLOW (% of 131.3 x 10 lbm/hr)	NO. OF RC PUMP IMPELLER VANES	NO. OF RC PUMP DIFFUSER VANES
EE 1	WX		A1	MU/HPI	2 CCW/LOOP	5.2 ft.	Type A	109%	7	12
	XY		A2	MU/HPI	"	"	"	"	"	"
	YZ		B2	HPI	"	"	"	"	"	"
	ZW		B1	HPI	"	"	"	"	"	"
EE 2	WX	B44	B1	HPI	2 CCW/LOOP	5.2 ft.	Type A	112%	5	4
	XY	B41	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	B46	A1	MU/HPI	"	"	"	"	"	"
EE 3	WX	B44	B1	HPI	2 CCW/LOOP	5.2 ft.	Type A	112%	5	4
	XY	(See Note 4)	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	(See Note 4)	A1	MU/HPI	"	"	"	"	"	"
	WX	B44		HPI	2 CCW/LOOP	5.2 ft.	Type A	109%	7	12
	XY	B41		MU/HPI	"	"	"	"	"	"
	YZ	B40		HPI	"	"	"	"	"	"
	ZW	B46		HPI	"	"	"	"	"	"
	WX									
	XY									
	YZ									
	ZW									
	WX	B44	A2	HPI	2 CCW/LOOP	5.2 ft.	Type B	112%	5	9
	XY	B41	A1	MU/HPI	"	"	"	"	"	"
	YZ	B40	B1	HPI	"	"	"	"	"	"
	ZW	B46	B2	HPI	"	"	"	"	"	"
	WX	B44	C	HPI	2 CCW/LOOP	5.2 ft.	Type B	112%	5	9
	XY	B41	D	MU/HPI	"	"	"	"	"	"
	YZ	B40	B	HPI	"	"	"	"	"	"
	ZW	B41	A	HPI	"	"	"	"	"	"
)	WX	B44	D	HPI	2 CCW/LOOP	5.2 ft.	Type A	116%	5	4
	XY	B46	C	HPI	"	"	"	"	"	"
	YZ	B40	A	MU/HPI	"	"	"	"	"	"
	ZW	B41	B	HPI	"	"	"	"	"	"
D 1	WX		A	HPI	*2 CCW/LOOP	5.2 ft.	Type B	*100%	*5	*9
	XY		B	MU/HPI		"	"			
	YZ		C	HPI		"	"			
	ZW		D	HPI		"	"			
D 2	WX		C	HPI	*2 CCW/LOOP	5.2 ft.	Type B	*100%	*5	*9
	XY		D	HPI		"	"			
	YZ		A	MU/HPI		"	"			
	ZW		B	HPI		"	"			
1	WX	B56	A2	HPI	1 CW & 1 CCW per LOOP	9.1 ft	Type C	114%	5	9
	XY	B61	A1	HPI	"	"	"	"	"	"
	YZ	B59	B1	MU/HPI	"	"	"	"	"	"
5)	ZW	B44	B2	HPI	"	"	"	"	"	"

Attachments

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	MINIMUM ALLOWABLE RC PRESSURE TO PROVIDE NPSH FOR RC PUMPS AT 160° F (2/2)	TOTAL MAKEUP [illegible]OW WITH 1 MU PUMP OPERATION AT 2150 PSIG	TOTAL MAKEUP FLOW WITH 2 MU PUMP OPERATION AT 2150 PSIG	TOTAL HPI FLOW WITH 1 PUMP OPERATION AT 1500 PSIG
OCONEE 1	WX XY YZ ZW		A1 A2 B2 B1	MU/HPI MU/HPI HPI HPI	300 PSIG " " "	157 GPM " " "	186 GPM " " "	360 GPM " " "
OCONEE 2	WX XY YZ ZW	B44 B41 B40 B46	B1 B2 A2 A1	HPI HPI MU/HPI MU/HPI	170 PSIG " " "	157 GPM " " "	186 GPM " " "	360 GPM " " "
OCONEE 3	WX XY YZ ZW	B44 (See Note 4) B40 (See Note 4)	B1 B2 A2 A1	HPI HPI MU/HP. MU/HPI	215 PSIG " " "	157 GPM " " "	186 GPM " " "	360 GPM " " "
TMI 1	WX XY YZ ZW	B44 B41 B40 B46		HPI MU/HPI HPI HPI	290 PSIG " " "	145 GPM " " "	165 GPM " " "	405 GPM " " "
TMI 2	WX XY YZ ZW							
CR 3	WX XY YZ ZW	B44 B41 B40 B46	A2 A1 B1 B2	HPI MU/HPI HPI HPI	(c) 230 PSIG " " "	147 GPM " " "	185 GPM " " "	410 GPM " " "
ANO 1	WX XY YZ ZW	B44 B41 B40 B4[illegible]	C D B A	HPI MU/HPI HPI HPI		142 GPM " " "	180 GPM " " "	405 GPM " " "
RANCHO SECO	WX XY YZ ZW	B44 B46 B40 B41	D C A B	HPI HPI MU/HPI HPI	102 PSIG " " "	192 GPM " " "	288 GPM " " "	405 GPM " " "
MIDLAND 1	WX XY YZ ZW		A B C D	HPI MU/HPI HPI HPI	*265 PSIG for minimum seal staging	140 GPM	NOT AVAILABLE	*420 GPM TOTAL
MIDLAND 2	WX XY YZ ZW		C D A B	HPI HPI MU/HPI HPI	*265 PSIG for minimum seal staging	140 GPM	NOT AVAILABLE	*420 GPM TOTAL
DAVIS BESSE 1 (See Note 5)	WX XY YZ ZW	B56 B61 B59 B44	A2 A1 B1 B2	HPI HPI MU/HPI HPI	(c) 190 PSIG " " "	164 GPM " " "	264 GPM " " "	300 GPM " " "

(c) at 260°F

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	TOTAL HPI FLOW WITH 2 PUMP OPERATION AT 1500 PSIG	TOTAL HPI FLOW WITH 3 PUMP OPERATION AT 1500 PSIG	RECIRCULATION CONTROL MEANS	BWST TEMPERATURE (NORMAL OPERATION)	FULL POWER YEARS	REACTOR TRIPS
OCONEE 1	WX		A1	MU/HPI	(b) 720/540 GPM	900 GPM	BLOCK ORIFICE (NO ESFAS ISOL.)	80° F	5.1	87
	XY		A2	MU/HPI	"	"	"	"	"	"
	YZ		B2	HPI	"	"	"	"	"	"
	ZW		B1	HPI	"	"	"	"	"	"
OCONEE 2	WX	B44	B1	HPI	(b) 720/540 GPM	900 GPM	BLOCK ORIFICE (NO ESFAS ISOL.)	80° F	4.82	53
	XY	B41	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	B46	A1	MU/HPI	"	"	"	"	"	"
OCONEE 3	WX	B44	B1	HPI	(b) 720/540 GPM	900 GPM	BLOCK ORIFICE (NO ESFAS ISOL.)	80° F	4.99	47
	XY	(See Note 4)	B2	HPI	"	"	"	"	"	"
	YZ	B40	A2	MU/HPI	"	"	"	"	"	"
	ZW	(See Note 4)	A1	MU/HPI	"	"	"	"	"	"
TMI 1	WX	B44		HPI	810 GPM		FLOW ORIFICE	70°F	3.51	18
	XY	B41		MU/HPI	"		"	"	"	"
	YZ	B40		HPI	"		"	"	"	"
	ZW	B46		HPI	"		"	"	"	"
TMI 2	WX									
	XY									
	YZ									
	ZW									
CR 3	WX	B44	A2	HPI	790 GPM	1130 GPM	FLOW ORIFICE		2.66	56
	XY	B41	A1	MU/HPI	"	"	"		"	"
	YZ	B40	B1	HPI	"	"	"		"	"
	ZW	B46	B2	HPI	"	"	"		"	"
ANO 1	WX	B44	C	HPI	780 GPM		FLOW ORIFICE		4.63	56
	XY	B41	D	MU/HPI	"		"		"	"
	YZ	B40	B	HPI	"		"		"	"
	ZW	B41	A	HPI	"		"		"	"
RANCHO SECO	WX	B44	D	HPI	585 GPM	650 GPM	FLOW ORIFICE		3.87	52
	XY	B46	C	HPI	"	"	"		"	"
	YZ	B40	A	MU/HPI	"	"	"		"	"
	ZW	B41	B	HPI	"	"	"		"	"
MIDLAND 1	WX		A	HPI	*675 GPM TOTAL	NOT AVAILABLE	*FLOW ORIFICE	40^oF-110^oF (DEPENDING ON THE WEATHER)	0	0
	XY		B	MU/HPI					"	"
	YZ		C	HPI					"	"
	ZW		D	HPI					"	"
MIDLAND 2	WX		C	HPI	*675 GPM TOTAL	NOT AVAILABLE	*FLOW ORIFICE	40^oF-110^oF (DEPENDING ON THE WEATHER)	0	0
	XY		D	HPI					"	"
	YZ		A	MU/HPI					"	"
	ZW		B	HPI					"	"
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	600 GPM		FLOW ORIFICE		2.01	46
	XY	B61	A1	HPI	"		"		"	"
	YZ	B59	B1	MU/HPI	"		"		"	"
	ZW	B44	B2	HPI	"		"		"	"

(b) 2 pump operation for ONS-III can either be:

1 HPI Train with 2 pumps
or 1 HPI Train with 1 pump and 1 HPI Train with 1 pump

TABLE 1 MATRIX OF FACTS

PLANT SITE	RV COLD LEG	PIPE ASS'Y	CUST. IDENT.	NOZZLE TYPE	EST. MAX. HPI NOZZLE ACT.	EST. HPI TO NOZZLE	MU/HPI CONNECTION
OCONEE 1	WX		A1	MU/HPI	(20)	87	PIPE/PIPE
	XY		A2	MU/HPI		87	"
	YZ		B2	HPI			"
	ZW		B1	HPI			"
OCONEE 2	WX	B44	B1	HPI	(13)		PIPE/PIPE
	XY	B41	B2	HPI			"
	YZ	B40	A2	MU/HPI		53	"
	ZW	B46	A1	MU/HPI		53	"
OCONEE 3	WX	B44	B1	HPI	(17)		PIPE/PIPE
	XY	(See Note 4)	B2	HPI			"
	YZ	B40	A2	MU/HPI		47	"
	ZW	(See Note 4)	A1	MU/HPI		47	"
TMI 1	WX	B44		HPI	-	-	CHECK VALVE
	XY	B41		MU/HPI			"
	YZ	B40		HPI			"
	ZW	B46		HPI			"
TMI 2	WX						
	XY						
	YZ						
	ZW						
CR 3	WX	B44	A2	HPI	39		CHECK VALVE
	XY	B41	A1	MU/HPI		49	"
	YZ	B40	B1	HPI	36		"
	ZW	B46	B2	HPI	37		"
ANO 1	WX	B44	C	HPI	(17)		ELBOW
	XY	B41	D	MU/HPI		56	"
	YZ	B40	B	HPI			"
	ZW	B41	A	HPI			"
RANCHO SECO	WX	B44	D	HPI	(31)		ELBOW
	XY	B46	C	HPI			"
	YZ	B40	A	MU/HPI		52	"
	ZW	B41	B	HPI			"
MIDLAND 1	WX		A	HPI	*0	*0	SEVERAL FEET
	XY		B	MU/HPI			" "
	YZ		C	HPI			" "
	ZW		D	HPI			" "
MIDLAND 2	WX		C	HPI	*0	*0	SEVERAL FEET
	XY		D	HPI			" "
	YZ		A	MU/HPI			" "
	ZW		B	HPI			" "
DAVIS BESSE 1 (See Note 5)	WX	B56	A2	HPI	(3)		ELBOW
	XY	B61	A1	HPI			"
	YZ	B59	B1	MU/HPI		46	"
	ZW	B44	B2	HPI			"

NOTES: 1. SHOP ASSEMBLIES WERE CLEANED TO CLASS C PER SPECIFICATION S-107 E.

2. INSPECTION RESULTS NOMENCLATURE

A. SAFE END CRACKED, SLEEVE LOOSE/WORN/MISSING
B. SLEEVE INDICATED SOME LOOSENESS/WEAR - NO SAFE END CRACKING
C. CIRCUMFERENTIAL CRACK OR MARK

OK - NO ABNORMAL INDICATIONS

3. INFORMATION MUST BE OBTAINED FROM SITE RECORDS

4. INFORMATION FOR THIS MATRIX CONCERNING COLD LEG PIPE ASSEMBLY SERIAL NO'S. B41-209-50-1 AND B41-209-50-2 IS AVAILABLE BUT WHICH ASSEMBLY IS LOCATED IN THE B2 LEG AND A1 LEG MUST BE OBTAINED FROM SITE RECORDS.

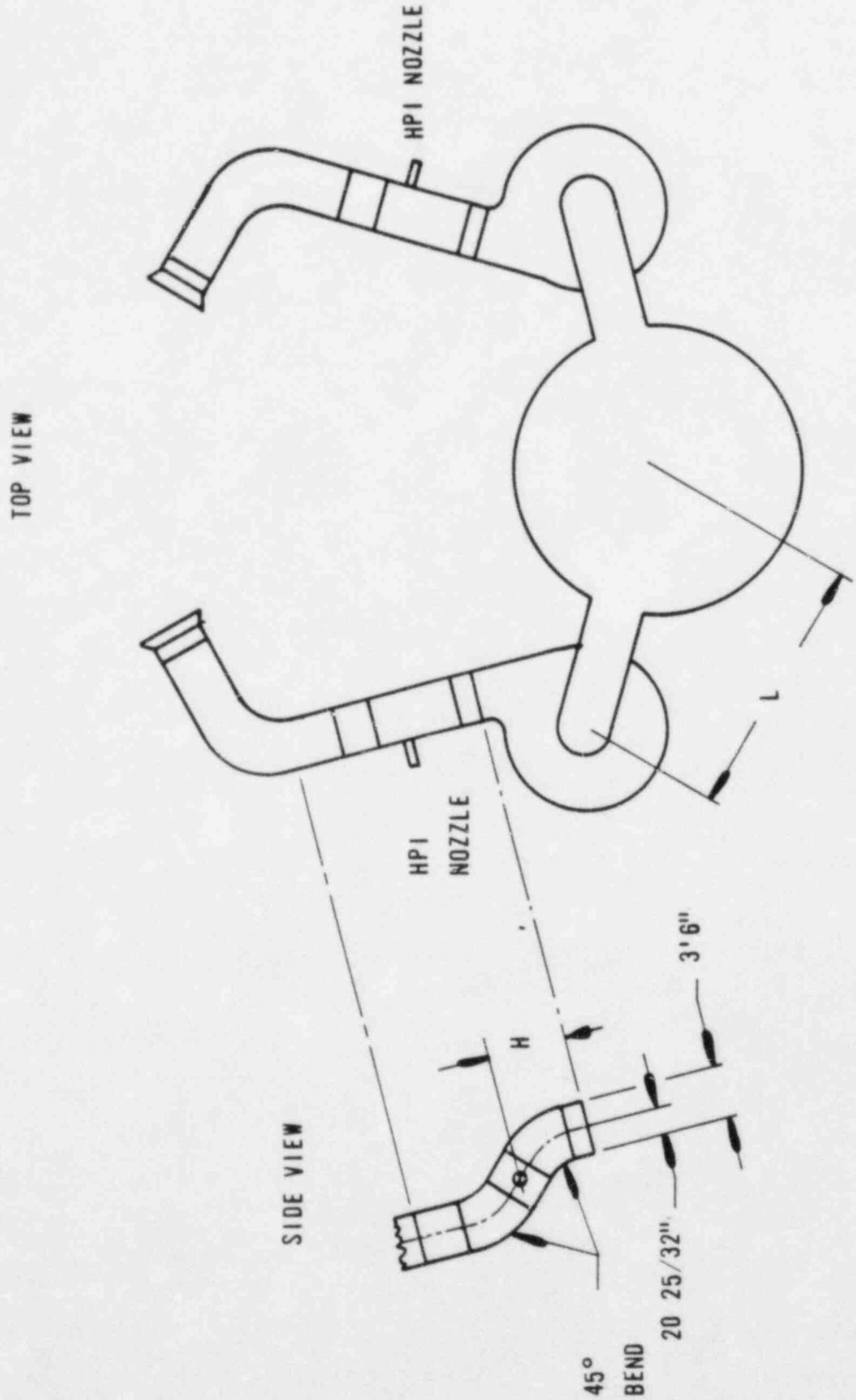
5. WHILE TAKING MEASUREMENTS OF THE A-1 RC PUMP FIXED VANES, IT WAS DISCOVERED THAT THE THERMAL SLEEVE IN THE HPI LINE NOZZLES WAS LOOSE. ALL THERMAL SLEEVES WERE REROLLED. THE FOLLOWING INFORMATION WAS RECORDED AT THE SITE.

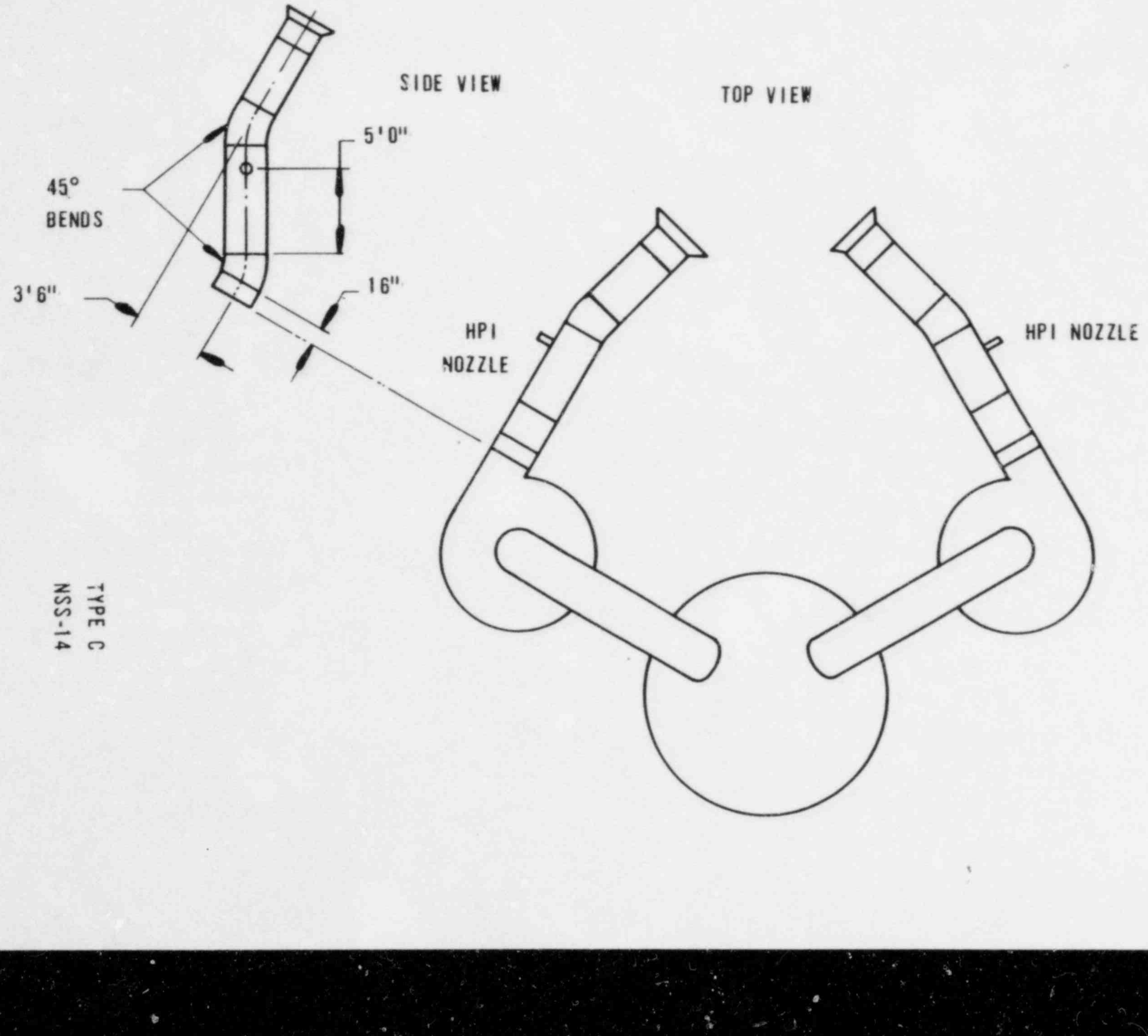
CUST. IDENTIFICATION		THERMAL SLEEVE ID IN EXPANDED AREA
A2	TH. SLEEVE TIGHT	1.5086
A1	TH. SLEEVE LOOSE	1.5060
B1	TH. SLEEVE TIGHT	1.5178
B2	TH. SLEEVE TIGHT	1.5162

	AFTER REROLLING	THERMAL SLEEVE ID IN EXPANDED AREA
A2	TH. SLEEVE TIGHT	1.5162
A1	TH. SLEEVE TIGHT	1.5190
B1	TH. SLEEVE TIGHT	1.5178
B2	TH. SLEEVE TIGHT	1.5183

TYPE A H = 4'5 3/16" L = 12'6"
FOR NSS 3,4,5,9,11

TYPE B H = 4'9 3/16" L = 13'
FOR NSS 7,8





TYPE C
NSS-14