PWR Steam Generator Tube Plug Assessment Document

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REPORT SUMMARY

In February 1989 at Virginia's North Anna 1 nuclear plant, an Alloy 600TT steam generator tube plug failed. The plug punctured the U-bend region of its parent tube and caused a forced leaker outage. As a consequence of this experience, which was referred to as a plug-top release (PTR), the utility industry undertook a review of steam generator plugs and associated issues and proposed utility action plans.

Background

The PTR event at North Anna 1 and generalized occurrences of leaking plugs due to cracking in a number of steam generators caused the utility industry to undertake a broad, formalized review of steam generator plugging issues. The review came under the auspices of an ad-hoc committee made up of utility industry personnel. EPRI's Steam Generator Project Office (SGPO) ultimately coordinated the review and published this document.

Objectives

To present a review of all known tubesheet plug designs made of alloy 600 and INCO 82 material presently installed in pressurized water reactor (PWR) steam generators; and, to provide a utility industry-recommended defect management plan.

Approach

Under the coordination of EPRI, an ad-hoc utility review committee was assembled. The committee met with vendors providing steam generator plugs and identified all plugs that have been used. The committee developed utility-industry consensus recommendations and informed the Nuclear Regulatory Commission (NRC) how the industry planned to manage this issue.

Results

Over thirty different types of plugs with varying degrees of cracking susceptibility have been installed in operating PWR steam generators. The review recommended that utilities institute a tube plug defect management plan consisting of the following:

- Identify all plug types installed in their steam generators.
- Identify plug heat pedigrees.
- If necessary, (1) work with plug vendors to develop tube plug-life time prediction and (2) develop nondestructive evaluation (NDE) inspection plans
- Repair and/or replace those plugs that do not meet pre-established acceptance criteria.

EPRI Perspective

The approach documented in this report was successful in convincing the NRC that the industry had adequately developed an action plan to address the steam generator plug issues raised by the North Anna PTR event. The action plan allowed each utility freedom to work with its vendors in an orderly manner to resolve any concern over future PTR events.

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Interest Categories

Steam generators

Keywords

Nuclear steam generators
Nuclear steam generator plugs
Nuclear steam generator repair

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Introduction

Primary Water Stress Corrosion Cracking (PWSCC) cracking of steam generator tubesheet plugs has occurred in the field. In one case a steam generator tube plug severed due to a 360° circumferential crack above the expander portion of the plug. The crack was essentially through-wall with approximately a 2 mil ligament reamining before a plant transient caused sufficient reduction in fit between the top of the tube plug and tube inner diameter resulting in complete ligament failure and plug-top release (PTR). The plug top accelerated to high velocity up the tube and punctured the tube in the vicinity of the U-bend transition producing approximately 75 gpm primary to secondary leakage. Because of this (PTR) event and generalized occurrences of leaking plugs due to cracking in a number of steam generators, the utility industry undertook a boad formalized review of steam generator plugging issues under the auspices of an ad-hoc committee made up of utility industry personnel. This review was ultimately coordinated by the Steam Generator Project Office (SGPO) of EPRI resulting in this document.

Discussion

The motivation behind this document is the belief that all steam generator tube plugs made of alloy 600 or similar material will crack with time if certain stress and environmental conditions are met.

The purpose of this document is to 1) present a review of all known alloy 600 and INCO 82 tubesheet plug designs presently installed in Pressurized Water Reactor (PWR) steam generators, and 2) provide a utility industry recommended "defect management" plan for use by those utilities that have steam generators with installed plugs susceptible to cracking, which provides adequate assurance that the plants reactor coolant system pressure boundary integrity will be maintained under normal operating, transient and postulated accident conditions.

The specific strategy for plug assessment and industry response was to:

1. assess all data related to utility steam generator plug cracking,

2. evaluate vendor approaches, experience and recommendations as to plug inspection/repair,

3. evaluate utility assessment approaches and experiences to date,

4. develop consensus recommendations as to plug inspection/repair plans, submit recommendations to steam generator vendors for review and to appropriate utility personnel for review and approval, and

5. present conclusions and recommendations to the NRC.

Conclusions

Over thirty different types of tubesheet plugs with varying degrees of susceptibility to PWSCC have been installed in operating PWR steam generators.

It is recommended that utilities with PWR steam generators institute a tube plug defect management plan that consists of the following:

1. Identification of plug types and where they are installed in the steam generator (this may involve in-field interrogation),

2. Identification of plug heat pedigree for all installed plugs,

3. If necessary:

   — working with the plug manufacturer and/or steam generator vendor to develop tube plug lifetime prediction. Acceptance criteria for plug integrity must be established. For those plugs that physically can not fail and result in a North Anna 1 plug-top type release event, such criteria could for example, involve prevention of plug cracking and/or leak during plant operation. Special consideration must be given to plugs with stabilizers intended to restrain failed tube sections resulting from vibration induced tube wear and/or fatigue cracking. Integrity of the stabilizer in some cases may take precedence over plug integrity from a leak standpoint,

   — NDE inspection of plugs and/or selective plug removal with destructive examination according to a sample plan

   — visual inspection plan of plugs for signs of leaking either due to inadequate plug installation or plug cracks, and

4. Action

Repair and/or replacement of those plugs that do not meet pre-established acceptance criteria or are leaking as noted by visual examination.

1

PURPOSE OF DOCUMENT

The purpose of this document is to (1) present a review of all known tubesheet plug designs made out of alloy 600 and INCO 82 material presently installed in Pressurized Water Reactor (PWR) steam generators and, (2) provide a utility industry recommended “defect management” plan, for use by those utilities that have steam generators with installed plugs susceptible to cracking, which provides adequate assurance that the plants reactor coolant system pressure boundary integrity will be maintained under normal operating, transient and postulated accident conditions.

2

INTRODUCTION

2.1 History and Need for Steam Generator Tube Plug Evaluation

The motivation behind this document is the belief that all steam generator tube plugs made of alloy 600 or similar material will crack with time if certain stress and environmental conditions are met. A review of industry events which provide a basis for this conclusion is presented below.

2.1.1 Historical Background

In February 1989 at the North Anna-1 plant, a steam generator tube plug at Row 3, Column 60 severed due to a 360° circumferential crack above the expander portion of the plug. The crack was essentially through wall with approximately a 2 mil ligament remaining before a plant transient caused sufficient reduction in fit between the top of the tube plug and tube inner diameter resulting in complete ligament failure and plug-top release (PTR). Because of differential pressure forces, the plug top accelerated to high velocity up the tube and punctured the tube in the vicinityof the U-bend transition producing approximately 75 gpm primary to secondary leakage. Additionally, the plug top, which partially extended through the affected tube, impacted adjacent tube Row 4, column 60 and “dinged” it so that a 0.650 in. diameter probe would not pass the affected tube location.

The tube plug was a mechanically expanded plug manufactured by Westinghouse and machined ou of thermally treated Alloy 600 bar material. This material exhibits a characteristic microstructure which makes it susceptible to Primary Water Stress Corrosion Cracking (PWSCC) under certain environmental conditions of water chemistry and operating temperature when the material’s applied stress state, including the combination of operating and residual stresses, approaches the material’s yield stress. In this respect, cracking susceptibility of Alloy 600 tube plugs is similar to that associated with Alloy 600 tubing used in steam generators.

In response to the North Anna-1 tube plug release event, the NRC issued Information Notice 89-33 and Bulletin 89-01, “Failure of Westinghouse SG Tube Mechanical Plugs.” Based on Westinghouse input, Bulletin 89-01 requested that plants determine if mechanical plugs from four different heats had been installed. If so, an action plan is to be defined by the affected utility to ensure that susceptible plugs to PWSCC would continue to provide adequate reactor coolant system (RCS) pressure boundary integrity under normal operating, transient, and postulated accident conditions.

This action plan essentially provided a repair and/or replace schedule developed in accordance with a lifetime prediction algorithm developed by Westinghouse. This algorithm identifies plugs susceptible to cracking before the next scheduled plant outage. Plugs identified by this algorithm are to be repaired and/or replaced. It was based on plug lifetime field experience obtained from Misstone Unit 2. Installation of Westinghouse mechanical plugs manufactured from these identified heats was discontinued.

The bulletin also suggested that any Westinghouse mechanical plugs removed from service regardless of heat from which they were obtained be examined for PWSCC on a sample heat basis and results provided to Westinghouse for inclusion in the PWSCC database supporting the tube plug lifetime prediction agorithm. Utilities removing plugs are routinely making them available to Westinghouse for analyses.

On November 14, 1990, the NRC issued Bulletin No. 89-01, Supplement 1, "Failure of Westinghouse Steam Generator Tube Mechanical Plugs." This bulletin alerted utilities that the Westinghouse tube plug lifetime prediction algorithm had evolved to include predictive capability of all Westinghouse Alloy 600 heats (not just those four discussed in NRC Bulletin 89-01) used in tube plug manufacture. Lifetime estimates for these additional heats were determined using as a reference one of the original susceptible heats noted in the Bulletin 89-01 and heat specific "performance factors" developed from corrosion testing which provided a relative difference in crack growth rates between the heats. Additionally, it noted that PWSCC occurrences of tub plugs at two plants (Sequoyah and North Anna-2) indicate that this predictive algorithm was not conservative and that adjustments to lifetime estimates for these heats would be forthcoming from the vendor.

It should be noted that in 1988, Babcock and Wilcox had repoted to the NRC that there was the possibility that some of their rolled plugs could suffer PWSCC. The McGuire-1, Summer, and Oconee-1 plants identified cracking of these plugs in their steam generator units. In 1989, additional B&W rolled tube plugs suffered cracking at the McGuire-2 plant.

Subsequently, the NRC issued Information Notice 89-65, which covered the B&W plug problem. No specific utility action was requested in this notice. At that time only a few Alloy 600 heats were identified as origins for the susceptible material used in the B&W plugs. All B&W plugs utilized this material including rolled, ribbed, and taper-welded designs.

2.1.2 Utility Industry Response

Because of events noted above, some utilities involved with PWRs initiated in 1989 a review of steam generators plugging issues and its current status with Babcock & Wilcox and Westinghouse. A meeting was held in Chicago hosted by Commonwealth Edison. Based on information provided at that meeting, the Steam Generator Project Office of EPRI concluded that the plugging issue was being adequately handled by the vendors with information exchange occurring through utility/vendor owners' groups and with periodic vendor updates provided to the NRC.

During 1989–1990 a number of utility/vendor information exchange meetings were held which addressed to varying degrees the plugging problem as it evolved in time. Utility tracking of this developing issue resulted in an industry directive to the Steam Generator Project Office (SGPO) to initiate a formal review of mechanical tube plugs. Specifically, the SGPO was directed to:

- provide an overview of the issue for the industry
- develop utility consensus on mechanical plug repair
- assure efficient and accurate information exchange
- incorporate European plug experience into the data base

The specific strategy for plug assessment and industry response chosen by the plug review committee was to:

1. assess all data related to utility mechanical plug cracking.
2. evaluate vendor approaches, experience and recommendations as to plug inspection/repair,
3. evaluate utility assessment approaches and experiences to date,
4. develop consensus recommendations as to plug inspection/repair plans, submit recommendations to vendors for review and to SGRP utility members for review and approval, and
5. present conclusions and recommendations to the NRC.

The review committee was made up only of EPRI member utilities. Utility representatives serving on this committee are listed in Appendix A.

It is noted that based on earlier discussions between the Westinghouse Owners Group (WOG) and the NRC Staff, the WOG conducted a meeting with the NRC on November

5th which summarized the current industry response to NRC Bulletin 89-01. The SGPO strategy to address the mechanical plug issue was also presented at this meeting.

At the first SGPO directed meeting (12/3–4/90) addressing the mechanical plug issue it was concluded that formal industry review must cover all plug designs and methods of installation. This borader assessment was necessitated because of a recognition that other Alloy 600 plugs, not just Westinghouse and B&W mechanical plugs, because of their design characteristics, may be susceptible to PWSCC.

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PLUG ASSESSMENT METHODOLOGY AND OUTPUT OF SGPO PLUG REVIEW COMMITTEE

The review committee invited the three domestic steam generator vendors to present all relevant details of their plug designs including installation practices and identification of plug material utilized.

These presentations occurred at two separate meetings on 12/3–4/90 in Chicago, IL. at the Commonwealth Edison offices and on 1/23–24/91 at the Florida Power & Light offices in West Palm Beach, FL. SGPO personnel investigated through independent contact, the design characteristics and other relevant details associated with plugs installed and presently offered by foreign steam generator vendors.

The review committee identifies and documents in this paper all known plug designs presently in the field. It presents a recommended "defect management" plan for the industry to implement which will provide adequate assurance of the plant's reactor coolant system pressure boundary integrity under normal operating, transient, and postulated accident conditions. This "defect management" plan is intended to ensure compliance with General Design Criteria 14 and 41 of 10CFR50, Appendix A, and the quality assurance requirements of 10 CFR 50, Appendix B.

This plan identifies plug characteristics that may make a specific plug susceptible to PWSCC, and therefore over time compromise the integrity of the reactor coolant pressure boundary. The plan provides recommendations on tube plug inspection techniques and how the lifetime of these plugs may be predicted such that they are replaced/repaired in a timely fashion while pressure boundary integrity is continuously maintained under all plant conditions.

This tube plug assessment report recommends that utilities with PWR steam generators determine and in some cases verify at their next outage the type of plug designs presently installed in their steam generators and develop an effective "defect management plan" for tube plugs as outlined in this document.

4

DISCUSSION

This section lists plug types presently known to be installed in the field, identifies plug specific design details, classifies these details as to their effect on plug susceptibility to PWSCC, potential modes of degradation from PWSCC, plug specific field performance to date, and consequences associated with degradation and plug failure.

4.1.1 Steam Generator Plug Designs

Steam Generator plugs can be classified in two general categories: shop plugs and field plugs. A listing of known plug designs is presented in Table 4-1 with reference to their individual design characteristics presented in Appendixes B and C. It is noted that "leakage limiting" plugs (i.e., so called PIP or PAP plugs) made out of Alloy 600 may also be susceptible to cracking. These specific plug designs are not addressed in this document.[1]

Shop plugs are usually utilized by the vendor before the steam generator is shipped from the manufacturing facility. Such plugging may be due to, for example, plugging tubesheet holes that do not contain tubes. Since in most cases a steam generator tubesheet is "gang-drilled" without concern for planned untubed regions, tubesheet holes may be present in specific tube bundle locations where tubes will not be placed because, for example, blowdown pipe placement. These tubesheet holes are then plugged by shop plugs.

[1] PIP and PAP plugs are intended to mitigate a North Anna-1 plug-top-release (PTR) event by their placement in susceptible Westinghouse mechanical plugs using a threaded connection with possibly some localized spot welding. Their purpose is to limit leakage and should not be classified as an ASME class 1 pressure boundary.

Table 4-1[1,2]

Vendor/Plug Type[3]	Westinghouse Electric Corp.	Babcock & Wilcox Inc.	ABB Combustion Engineering
Shop Plugs			
Welded			
• Expanded tube	Fig. B-1	Fig. B-3	Fig. B-2
• Bar - straight - tapered	 Figs. B-4 and B-5 Fig. B-6	 Fig. B-8(a) Fig. B-8(b)	 Fig. B-7
Field Plugs			
Expanded			
• Mechanical	Figs. C-1, C-4, C-5, and C-6	Figs. C-2 and C-3	
• Explosive	Fig. C-7		
Welded			
• Fusion	Fig. C-8	Figs. C-9, C-10, and C-11	Figs. C-12, C-13, and C-14
• Explosive		Fig. C-15	

Notes: (1) Item number refers to details of plug design, plug material classification and heat treatment utilized in Appendixes B and C.
(2) Table does not include field plugs made of Alloy 690.
(3) Various plug types can have variations in lengths and designs for the attachment of stabilizers.

4.1.1.1 Shop Plug Designs

There are various shop plug designs as shown in Appendix B. Note that one particular design is essentially a tube with a "blinded" end, using for example, a weld cap. The tube can extend several inches above the top face of the tubesheet. Westinghouse, Combustion Engineering and Babcock & Wilcox (B&W) have utilized this design. The Westinghouse design is formally called a "stub-tube" and is presented in Appendix B. A comparable design by Combustion Engineering and B&W is also shown in Appendix B.

The so-called "stub tube" shop plugs may not be specifically identified in the steam generator design information package provided to the utility by the steam generator vendor. The information package may identify all shop plugs on a tubesheet map. This should be verified by the utility. If they are not listed, the utility should contact their steam generator vendor and obtain the information. Classification of shop plugs as to design type may not be presented in the information package. A utility should institute a procedure that identifies the types of shop plugs utilized in their steam generators. This procedure may consist of either historical document retrieval that identifies plug type and location or in-field identification.

Because of the PWSCC susceptibility of tubesheet plugs, which is discussed in greater detail in the next section, particular attention should be directed at the so-called "stub tubes," noting their extension into the secondary side of the steam generator. They, like all tubesheet plugs except PIPs and PAPs, are categorized as an ASME class 1 pressure boundary.

Additionally, shop plugs in general may be of a specific design that the occurrence of PWSCC in these plugs cannot be ruled out. It is recognized that the industry has not placed emphasis on shop plugs, probably because of no reported problems. Because of the heightened concern associated with field plug defects, similar effort should be directed at shop plugs since in some cases they may be susceptible to PWSCC.

4.1.1.2 Field Plug Designs

Field plugs are plugs installed in the tubesheet after the steam generator has been delivered to the site. In most cases a field plug is installed to take a specific steam generator tube out of service. Field plug designs cover a broad range which is summarized in Table 4-1 with details presented in Appendix C. Generally they can be classified as to whether they have been expanded (either mechanically or hydraulically), explosively expanded, and/or welded in place. In some cases they may exhibit some degree of interference fit between a portion of itself and the tube end in the tubesheet. Their susceptibility to PWSCC is dependent on residual stresses induced by the installation method operating stress and plug material. For the majority of plugs in the field mill annealed or thermally treated Alloy 600, or INCO 82 has been the plug material used. INCO 82 is essentially Alloy 600 weld metal. Its elemental composition is similar to Alloy 600, but element amounts vary relative to Alloy 600. Specifically, it has less nickel, more chromium, less carbon and more carbon stabilizing elements (Cb-Ta). Neither published laboratory data nor available field experience data show INCO 82 to be susceptible to PWSCC. The authors of this document caution the reader by noting that if stressed high enough one can expect this material to suffer PWSCC.

Plugs presently being installed in steam generators as replacements for installed plugs susceptible to defects or for new plugging requirements are made of thermally treated Alloy 690, material shown to be resistant to PWSCC.

It is noted that some plug designs (for example, Figures C-7 and C-4 in Appendix C) are integrally designed with a tube stabilizer rod or cable (stabilizer attached to plug top, not shown). The purpose of the stabilizer rod is to restrict movement of the tube if it suffers a complete through wall 360° crack. Utilities need knowledge of where integral stabilizer plugs have been employed, particularly if plug replacement plans include their removal. In Babcock & Wilcox's once through steam generators the integrity of the plug/stabilizer must be maintained. Tubes were plugged because of tube vibration induced fatigue cracking. Since the vibration of concern in these units is located in the upper spans of the steam generator tube bundle, the stabilizer is hung from the top tubesheet plug. If the integrity of the plug is compromised through PWSCC resulting in complete circumferential through wall cracking and disengagement of the stabilizer from the plug, the stabilizer may fall down the tube striking the bottom tubesheet plug. In this situation, the integrity of the tube or portions thereof in the upper span without the stabilizer must be addressed.

Finally, there are special plugs that have been field installed for isolated, site-specific cases. One such plug is shown in Figure C-14, Appendix C. This multi-plug element was utilized in steam generators that had suffered tubesheet ligament damage.

4.1.2 Susceptibility of Plug Designs to PWSCC and to Potential for Plug Top Release

Each of the plug designs are identified as either being shop installed or field installed plugs. Shop installed plugs are described in Appendix B in detail, and field installed plugs are described in Appendix C.

All shop installed plugs are wleded but have variations as to whether tubing or bar stock material was used and whether the plug was tapered or required some expansion. Field installed plugs are either of an expanded or welded type. The expansion method is generally by mechanical means using either a roller or a mandrel. However, explosive expansion has also been used. Welding of plugs is generally done by a tungsten inert gas (TIG) process, however one vendor has also used an explosive welding method.

Determining whether a specific plug design would be susceptible to PWSCC is in some cases quite subjective unless there is field or laboratory data available to help make the judgement. In the forthcoming paragraphs each design is rated for (1) the risk of PWSCC in service, and (2) the risk of plug-top-release (PTR). A risk rating is qualitatively assigned as either low, moderate (designated as "mod") or high. This was done by considering the estimated installed residual stresses and the material and heat treated condition. The stresses developed by the various installation methods are qualitatively ranked as shown in Table 4-2. Expansion methods were generally rated as high while fusion welding methods were rated as moderate.

Table 4-2
Qualitative Ranking of Residual Stress Level

Method/Treatment	Estimate of Stress	Ranking
• Expansion		
Roller	>yield	high
Mandrel	>yield	high
hydraulic	~yield	mod
explosive	>yield	mod
• Welding		
TIG	~yield	mod
explosive	>yield	high
• Stress relieved	<yield	low

All alloy 600 material whether tubing, bar or Inco 82 weld metal was considered potentially susceptible to PWSCC if stressed high enough. However, qualitatiely, mill annealed tubing was considered more susceptible than say thermally treated tubing or 82 weld metal as indicated in Table 4-3. Thermal treatment (TT) does not always produce low susceptibility if the treatment (hot roll temperature or anneal) prior to TT is not high enough to dissolve chromium carbide. Thus, hot rolled (HR) bar stock given a TT is given a ranking of low to moderate in an attempt to account for this potential variability.

Table 4-3
Qualitative Ranking of Material and Heat Treatment

Material	Susceptibility
Alloy 600 Tubing	
- LTMA (low tem. mill annealed)	high
- HTMA (hi temp mill annealed)	mod
- LTMA + thermal treatment (TT)	high
- HTMA + TT	low
- HTMA + stress relieved (SR)	low
- Welded	mod

Table 4-3
(*Continued*)

Material	Susceptibility
Alloy 600 Bar	
- HR (hot rolled)	mod - high
- HR + TT	low - mod
- Welded	mod
82 Weld Metal	
- wrought	low
- welded	low

4.1.2.1 Shop Installed Plugs

Details of all the shop installed plugs are given in Appendix B. As indicated in Table 4-4, shop installed plugs all have welds and are classified as expanded tubes or as bar plugs. Table 4-4 also classifies each plug as to the risk of PWSCC and the potential consequence of cracking.

Table 4-4
Classification of Shop and Field Installed Steam Generator Plugs for Risk and Potential Consequence of PWSCC

	Appendix Figure No.	Risk of PWSCC/ Location[(a)]	Potential Consequence of PWSCC[(b)]
Shop Installed			
• Welded			
Expanded Tubes			
- W expanded stub tube	B-1	mod-hi/et, sr	leakage
- CE expanded tube	B-2	mod/haz, et	leakage
- B&W stub tube	B-3	low/et, haz	leakage
Bar			
- W half length bar	B-4	hi/et	leakage
- W full length bar	B-5	hi/et	leakage + PTR
- W tapered	B-6	mod/haz	leakage
- C-E tapered	B-7	modhaz	leakage
- B&W button	B-8(a)	low/haz	leakage
- B&W tapered	B-8(b)	low/haz	leakage

Table 4-4
(*Continued*)

	Appendix Figure No.	Risk of PWSCC/ Location[(a)]	Potential Consequence of PWSCC[(b)]
Field Installed			
• Expanded			
- Mechanical			
W mechanical	C-1	hi/et	leakage + PTR
W rolled tube	C-4, C-5	hi/et	leakage
W rolled sleeve	C-6	hi/et	leakage
B&W Ribbed	C-2	hi/et	leakage + PTR
B&W Rolled	C-3	hi/et	leakage + PTR
- Explosive			
W Explosive	C-7	hi/et	leakage + PTR
• Welded			
- Fusion			
W tapered	C-8	low/haz	leakage
B&W Tapered	C-11	low/haz	leakage
B&W Cap	C-10	lowhaz	leakage
B&W U-cup	C-9	mod/haz	leakage + PTR
C-E Tapered	C-13, C-14	low/haz	leakage
C-E Straight	C-12	low/haz	leakage
- Explosive			
B&W	C-15	hi/et	leakage + PTR

(a) et - expansion transition
haz - heat affected zone
sr - skip rolls
(b) PTR - plug top release

Expanded Tube Plugs

There have been two expanded tube plugs identified by the vendors which have been installed which have been rated as having at least a moderate risk of PWSCC. The Westinghouse design shown in Figure B-1 has a cap welded on the end of a piece of steam generator tubing which was the same as that used for the remainder of the steam generator. Depending on the type of generator (i.e., model D, E or F) the tubing can be either mill annealed (LTMA) or thermally treated (TT). The welded end portion of very early plugs may have been shop peened on the OD. However, most were given a stress relief treatment in a furnace. But a portion of the tube did not get the same thermal cycle as the cap porton did because it stuck outside the furnace. If the tubing was mill annealed and was subsequently hard rolled into the tube sheet, then the tube material has a moderate to high risk of PWSCC with leakage or possible PTR. If the tubing was thermally treated and the expansion process was done by hydraulic then a moderate ranking was assigned. A similar design by C-E as shown in Figure B-2 of Appendix B has a cap welded on C-E type steam generator tubing (HTMA), but with no stress relief treatment. The tube plug was then explosively expanded into the tube sheet. This design was ranked as having a moderate susceptibility to PWSCC because the weld residual stresses at the cap and the high stresses because of the explosive expansion. The B&W stub tube (Figure B-3) was rated as a low risk of PWSCC since both the welded cap and expanded portion of the plug was stress relieved during the full bundle stress relief treatment. All these designs should leak if PWSCC occurs in service.

Bar Plugs

Bar stock plugs as identified in Figures B-4 through B-7, use alloy 600 hot rolled or hot rolled annealed bar stock. Two Westinghouse designs identified as a half length and full length bare hole designs are given a rating of high PWSCC susceptibility in Table 4-4, because they were rolled into the tube sheet before they were welded. The half length design should just leak if PWSCC occurs. The risk of PTR is low since it has a cap welded to the secondary face of the tube sheet which should have low operational stresses which should reduce the chance of SCC at that location. Having a cap at the secondary tube sheet face would prevent the lower plug from penetrating the secondary side should the lower plug eject. The full length bar, however, if leakage does not occur with PWSCC does have a risk of PTR because it could crack circumferentially at the toe of the rolled transition without leakage and be propelled out of the tubesheet hole. The other welded bar designs identified in Figures B-6 and B-7 are ranked in Table 4-4 as a moderate risk of PWSCC since the plugs are made from bar stock (either hot rolled or annealed) and have weld residual stresses estimated to be at least equivalent to the yield stress level. These plugs should only leak if PWSCC occurs. The B&W button and tapered plugs are rated as a low risk of PWSCC since they received a full bundle stress relief treatment.

In summary the shop installed plugs all have welds at various locations. The expanded tube type plugs do require some special attention from the utility since there is a moderate risk of PWSCC. The bar plugs that were roller expanded at the end do have a high risk of cracking in service and should also be inspected. Many of these plug designs have never received any inspection. It looks as if the majority of them can be done by some sort of visual or dye penetrant evaluation.

4.1.2.2 Field Installed Plugs

Field installed plugs can be classified as being either of the expanded type or welded type. The expanded type can be done either by some mechanical method or by an explosive method. The welded plugs are generally fused at the primary tube sheet face by a TIG process or in the case of one vendor, the welding was performed by an explosive method.

Details of each field installed plug are presented in Appendix C.

Expanded

As indicated in Table 4-4 the expanded type plugs have been rated as having a high risk of PWSCC in the expansion transition zones. This high risk is based principally on the fact that the expansion process whether done by rollers, mandrels, or explosive methods produce high residual tensile stresses somewhere in the plug. The high stresses are required in order to develop a leak-tight seal. The Westinghouse mechanical and explosive designs shown in detail in Figures C-1 and C-7, have also been judged to have a risk of plug top release if cracking is circumferentially oriented with no leakage. Of course, the mechanical type has already demonstrated the phenomena in the field. The Westinghouse explosive plug was rated high since cracking can be circumferential in the expansion transition region. Examination of field installed plugs do, however, indicate that circumferential cracks tend to go throughwall first and leak which reduces the chance of plug top release. However, should the exception to this trend exist the design is considered to be at high risk of PTR.

The B&W ribbed plug, Figure C-2, is similar to the Westinghouse mechanical plug and might result in a PTR event. It has been argued by B&W that the expansion mandrel never travels beyond the ribs in this plug, and consequently should PWSCC occur, it would not cause PTR. The ranking principal taken here is to accept in general the B&W argument, but also to allow for the exception where the mandrel could extend below the ribbed region allowing a circumferential crack to grow in a manner similar to the Westinghouse mechanical plug.

The roll expanded plugs which include Westinghouse rolled tube (Figures C-4 and C-5) and rolled sleeve plugs (Figure C-6), and the B&W rolled plug (Figure C-3), while having a high risk of PWSCC should experience leakage. In general, cracking is considered to be principally axial at upper toe transition and circumferential plus axial at the lower heel transition. However, as with roller expanded steam generator tubing there can be a rare case of pure circumferential cracking seen in the upper toe transition, and for this reason a roller expanded plug could be at a risk of PTR.

Fusion Welded

As indicated in Table 4-4, all but one of the fusion welded plugs have been rated as having a low risk of PWSCC. This is based on (1) the experience to date that PWSCC has not been observed in a) Alloy 600 or INCO 82 weld deposits, or heat affected zones, and (2) that the plugs are tapered and have an interference fit. The one fusion welded plug considered to have a moderate risk of PWSCC is the B&W U-cup design shown in Figure C-9. It is considered that because the fusion weld is performed at the end of the protruding tube, that weld shrinkage could put a bending stress on the plug. Should circumferential cracks develop, then the risk of PTR increased because the plug is straight and extends beyond the expanded portion of the tube.

The last field installed welded plug in Table 4-4 is the B&W explosive welded plug. This plug has been given a high risk of PWSCC because of the high axial residual stresses developed which can produce circumferential cracks. Depending upon the location of these cracks, the tip of the plug may be propelled up the tube during the situations leading to a PTR type event.

5

TUBE PLUG DEFECT MANAGEMENT PROCEDURES

5.1 Introduction

The goal of defect management is to identify tube plugs that have an unacceptable probability of violating acceptance criteria associated with maintaining the integrity of the reactor coolant pressure boundary and repair or replace these plugs before they violate pre-established acceptance criteria. Defect management involves the determination of a plugs' cracking and/or leak potential exceeding acceptance limits during a future operational run of the steam generator. Defect management procedures may involve tube plug lifetime[2] predictive methodologies, NDE procedures, mechanical probing to verify plug integrity, and plug visual inspection.

5.2 Tube Plug Lifetime Prediction Algorithms

Because of the original cracking problem with Westinghouse mechanical plugs the steam generator vendor developed a plug lifetime predictive algorithm implemented by utilities and found acceptable to the NRC. This algorithm uses a plug cracking acceptance criteria defined as the remaining effective full power days (EFPD) required until the mechanical plug reaches a remaining ligament thickness insufficient to resist steam generator feed line break pressure of 2650 psi. The intent of the criteria is to prevent a North Anna 1 top of plug release event which is not preceded by plug leaks[3] into the tube. If the number of days is less than the plant's operational run time required to reach its next scheduled outage, the plug is repaired or replaced. The

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[2] The definition of plug lifetime is dependent on the acceptance criteria chosen to ensure that the integrity of the reactor coolant pressure boundary is maintained for all plant conditions.

[3] According to reference 1, "typically for mechanically expanded plugs, when cracking occurs it is mostly axially oriented or, if circumferentially oriented, the cracking has been limited in azimuthal extent in the plug shell when it progresses through wall. Moreover, for mechanically expanded plugs, the expected result of potential PWSCC is that leakage would occur past the plug into the active tube." Therefore leak-before-break criteria is expected to be satisfied in the majority of mechanical plug degradation. When leakage does occur, pressure equalization across the plug tens to mitigate a top-of-plug release event similar to the North Anna 1 occurrence.

algorithm can employ apparent crack growth rates determined from Westinghouse mechanical plugs removed from operating steam generators and results of Westinghouse corrosion tests. This algorithm was originally applicable to mechanical plugs manufactured from four separate Alloy 600 heats exhibiting a microstructure deemed to be highly susceptible to PWSCC. Its application to plugs made from heats exhibiting a microstructure deemed less susceptible to PWSCC was accomplished by developing crack growth rates as a function of individual heats., The algorithm also incorporated a growth rate temperature dependence using the Arrehenius relationship to account for the steam generator hot leg versus cold leg temperature difference.

The algorithm, its applicability, justification and postulated inherent conservatism are well documented in reference 1. It is not the purpose of the present document to provide details of this algorithm and application methodology. But it should be noted that the algorithm, as applied to satisfy NRC Bulletin 89-01, predicts remaining tube plug life based on the worst plug crack growth rate as measured on one plug removed from Misstone Unit 2. Subsequent to application of this algorithm to Westinghouse mechanical plugs taken from heats originally noted in NRC Bulletin 89-01, crack growth estimates documented in reference 1 for tube plugs taken from heats not identified in NRC Bulletin 89-01 were found to be in significant error based on examination of cracked tube plugs removed from field steam generator units. At the time of writing this document, the steam generator vendor was in the process of modifying the algorithm to account for these new data. Such continuous updating of the algorithm is anticipated as the data base of cracked plugs increases. One would expect, because of the paucity of data, a predictive lifetime algorithm of this nature would utilize the largest measured growth rate experienced in the field and possibly modified by an engineering safety factor for additional margin.

Reference 1 also presents a methodology that attempts to put the top-of-plug release event on a more probabilistic basis. It uses a method of hazard plotting as discussed in reference 2, along with assumed crack growth rates in Alloy 600 taken from laboratory testing of tube roll transitions typically found in steam generator tubesheets. Reference 1 does not suggest that this type of statistical approach be used to define mechanical plug failure on a site specific basis. But rather, it uses it's probabilistic predictions to support the argument that mechanical plug failue during relatively long plant operational runs is a low probability event. This paper does not judge the correctness of the approach and its intended application, but is simply noting that a viable probabilistic methodology to predict tube plug lifetime is a desirable technique to utilize if statistically sufficient data exists. Using this approach one can establish meaningful confidence levels with quantifiable conservatism on the reliability of tube plugs over time. In this way plant safety can be maximized while minimizing unnecessary plug inspection and/or plug replacement.

In regards to probabilistic assessment of tube plug lifetime, Northeast Utilities at Millstone Unit 2 has instituted just such an approach which has been accepted by the NRC. Details of the methodology and its application are presented in Appendix D.

It is noted these algorithms have been developed to prevent the North Anna 1 top-of-plug release event that is associated with Westinghouse mechanical plugs[4,5]. But there are plugs in the field that are made out of susceptible Alloy 600 material which possibly over time will crack resulting in a plug leak, but not result in the type of event which occured at North Anna 1. From an operational viewpoint these plugs should be repaired or replaced in a timely and economically acceptable maner. Probabilistic algorithms, as described above, provide the methodology by which this can occur. Site specific application of such a technique for each susceptible plug design may be possible if sufficient data are available as was the case at Millstone Unit 2. It is apparent that the industry could benefit from a database consisting of relevant failed plug information and their heat pedigree for all such plugs removed from service at all affected plants. It is therefore recommended that utilities identify and document all plug designs presently installed and the heats from which they were produced.

5.3 Steam Generator Tube Plug Inspection Techniques

Steam generator tube plugs made of susceptible Alloy 600 material under specific stress conditions may suffer PWSCC at some point in time. Tube plug lifetime prediction algorithms as described in the previous section can help determine when cracking of these plugs is expected to occur. Without a statistically significant data base of for example, time to crack or fail, taken from the field and/or laboratory tests these algorithms must resort to utilizing the worst case failure event experienced as an indicator of when future events will occur. Such an approach usually dictates conservative plug lifetime estimates. This leads to unnecessary plug repair and/or replacement.

Inspection of plugs can augment lifetime prediction algorithms and reduce unnecessary plug replacement. NDE/eddy current inspection techniques can be utilized for some plug designs with confidence in being able to detect cracking. Unfortunately inherent design characteristics of some plugs preclude the use of these techniques.

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[4] According to reference 1, a North Anna 1 tube leak due to top-of-plug release event is not expected to occur for part rolled tubes in tubesheets or for tubes having a U-bend radius above a critical value.

[5] Other vendor plug designs are susceptible to top-of-plug release, although they may not produce a North Anna 1 type event.

It is noted that the Babcock & Wilcox (B&W) rolled tube plugs can be inspected by eddy current techniques for detection of cracks in both the toe and heel locations. Circumferential cracks have occurred in the heel location but not at the toe portion of the plug. To date only axial cracks have been detected at the toe portion of the plug. It is unlikely that cracking can be detected by eddy current techniques in B&W ribbed plugs. Also, an eddy current probe cannot be extended through and beyond the mandrel expander of this plug type. Mechanical probing to verify plug placement during plant outages is recommended. B&W welded plugs may be visually inspected during an outage for drips of secondary water or boric acid crystal accumulation in the vicinity of the weld indicating the existence of thru-weld cracks. Eddy current testing of B&W explosive plugs using a rotating pancake probe (RPC) is also available. It is recommended that at plant outages, mechanical probing to verify plug placement be performed, especially for those that are integral with a tube stabilizer.

Westinghouse has developed an eddy current technique for inspection of mechanical plug designs and has limited field implementation experience for this technique. It is believed that eddy current interrogation of the plug using a RPC can identify cracks in their explosive or rolled plugs over most of their length. Welded plugs can be inspected for failure through visual examination as noted for the B&W welded plugs.

All presently field installed INCO 82 ABB/Combustion Engineering plugs are welded plugs that can be visually inspected for weld crack evidence.

Shop plug inspection presents difficulties for eddy current inspection. Solid bar plugs have insufficient open space to allow an eddy current probe to interrogate the potential region for cracking. Stub tubes may not be fully inspectable over their length. The top weld cap of the stub tube is not inspectable by an eddy current probe.

5.4 Inspection Sample Plan

An inspection sample plan is dependent on an individual utility’s assessment of the applicability and use of a tube plug lifetime prediction algorithm, historical evidence of cracking and pulled plug examination results. Additionally, economic conditions may warrant repair and/or replacement of all susceptible tube plugs in a time frame that may preclude the necessity of NDE inspection. An inspection plan is therefore site specific, dependent on the type of plug designs utilized in the steam generator and their manufacturer. An inspection plan should be formulated in concert with recommendations of the plug manufacturer.

5.5 Tube Plug Defect Management Plan Summary

It is recommended that utilities with PWR steam generators institute a tube plug defect management plan[6] that consists of the following:

1. identification of plug types and where they are installed in the steam generator (this may involve in-field interrogation),

2. identification of plug heat pedigree for all installed plugs,

3. If necessary:

   — working with the plug manufacturer and/or steam generator vendor to develop tube plug lifetime prediction. Acceptance criteria for plug integrity must be established. For those plugs that physically can not fail and result in a North Anna 1 top-of-plug type release event, such criteria could for example, involve prevention of plug cracking and/or leak during plant operation. Special consideration must be given to plugs with stabilizers intended to restrain failed tube sections resulting from vibration induced tube wear and/or fatigue cracking. Integrity of the stabilizer in some cases may take precedence over plug integrity from a leak standpoint,

   — NDE inspection of plugs and/or selective plug removal with destructive examination according to a sample plan,

   — visual inspection plan of plugs for signs of leaking either due to inadequate plug installation or plug cracks, and

4. Action

repair and/or replacement of those plugs that do not meet pre-established acceptance criteria or are leaking as noted by visual examination.

[6] Defect management procedures may involve tube plug lifetime predictive methodologies, NDE procedures, mechanical probing to verify plug integrity, and plug visual inspection.

6

REFERENCES

1. Westinghouse report WCAP-12245 (non-proprietary version), “Steam Generator Tube Plug Integrity Summary Report,” Revision 2, June 1989.

2. Nelson, W., “Hazard Plotting for Incomplete Failure Data,” Journal of Quality Technology, Vol. 1, No. 1, January 1969.

A

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B

SHOP INSTALLED ALLOY 600 STEAM GENERATOR PLUGS

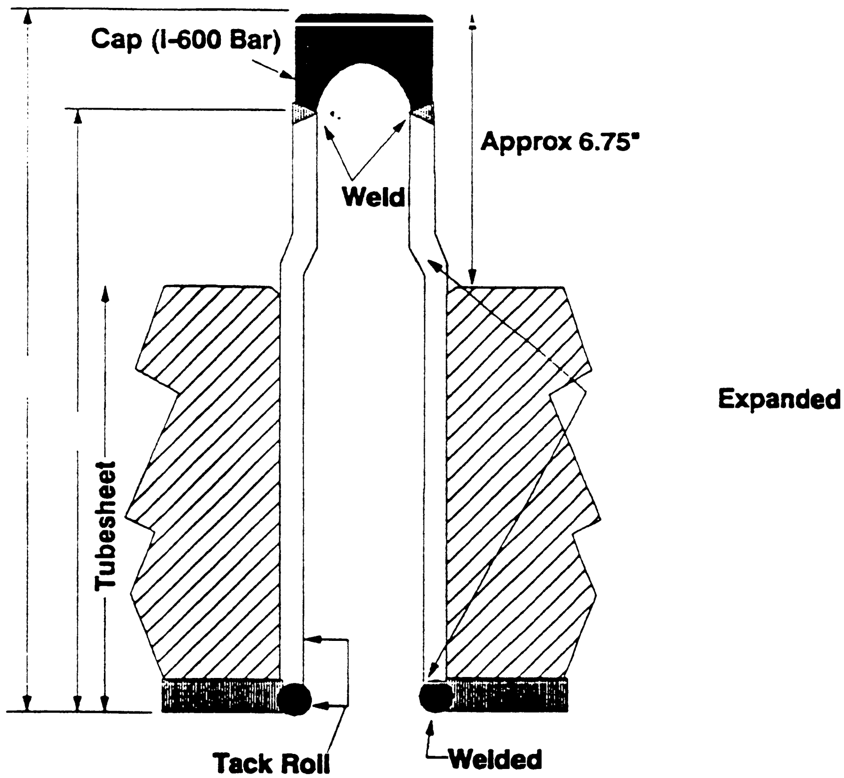


Figure B-1
Westinghouse "Stub Tube" Plug

Material/Heat Treatment: Alloy 600 MA or TT tubing and bar + Welded Stress Relieved at cap end by OD peening or thermal stress relief.

Residual Stress Level: Low in cap, mod-hi in expanded tube which can be hard rolled or hydraulic expanded

Field Cracking/Location: None reported

Inspectability: Never tried, should be possible by MRPC in expanded tube section but difficult in welded zone

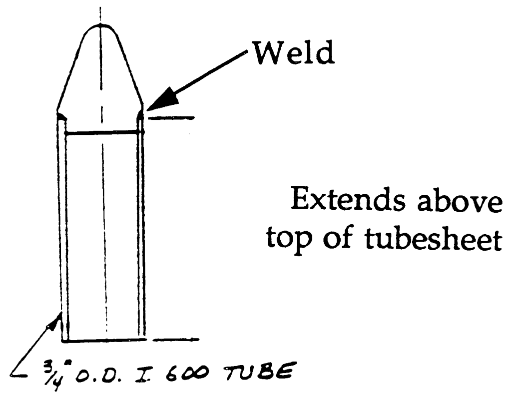


Figure B-2
ABB/C-E Welded Straight Tube Sheet Plug

Material/Heat Treatment: Nose - Alloy 600 Bar/hot rolled
Tubing - Alloy 600/HTMA
Residual Stress Level: Moderate at weld joint (no stress relief) high at explosive expansion transitions
Field Cracking/Location: None reported
Inspectability: Never tried, should be possible by RPC in expanded tube section but difficult in welded zone

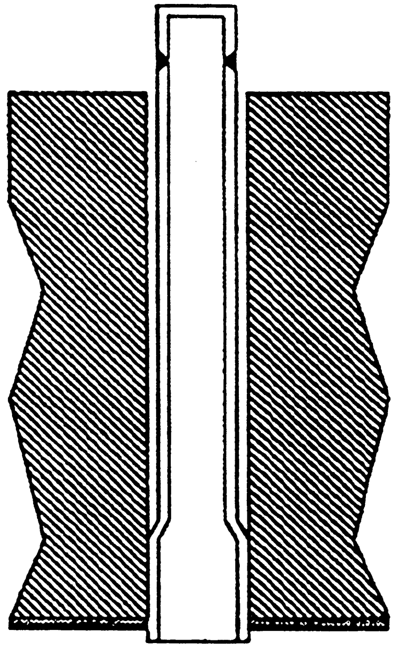


Figure B-3
B&W 'Stub Tube' Plug

Material/Heat Treatment: (Alloy 600 tubing/HTMA + bar/welded/expanded + welded) + full bundle stress relief.
Residual Stress Level: Low
Field Cracking/Location: None reported
Inspectability: Never tried, should be possible by RPC in expanded tube section but difficult in welded zone.

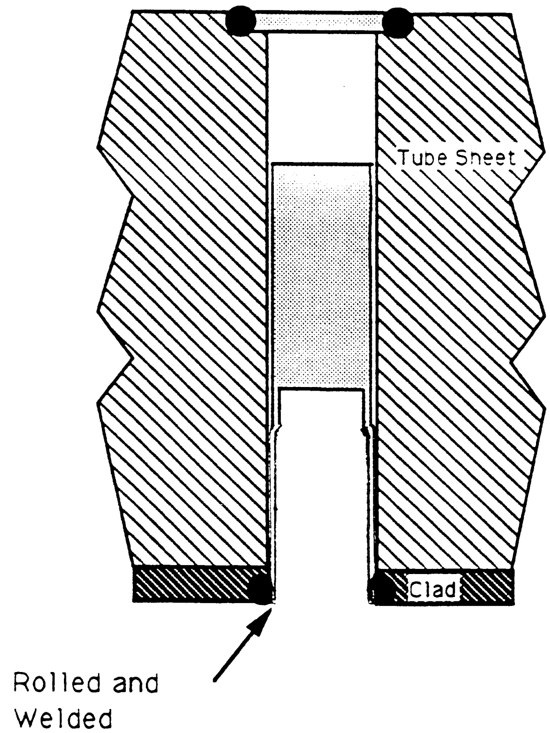


Figure B-4
Westinghouse Half Length Solid Bar/Capped Top Bare Hole

Material/Heat Treatment: Solid Plug - Alloy 600 Bar/MA + Welded to Weld Clad Sec. face of tubesheet
Residual Stress Level: Mod in weld to high in roll transition
Field Cracking/Location: None reported
Inspectability: Never tried, should be possible by MRPC in expansion zone; impossible at cap.

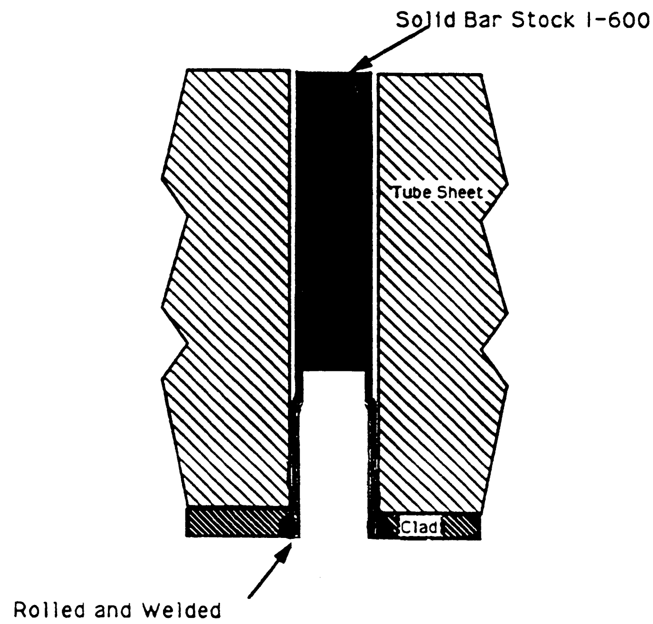


Figure B-5
Westinghouse Full Length Solid Bar Plug

Material/Heat Treatment: Alloy 600 Bar/MA
Residual Stress Level: high in roll transition
Field Cracking/Location: None reported
Inspectability: never tried, should be possible by MRPC in expanded zone

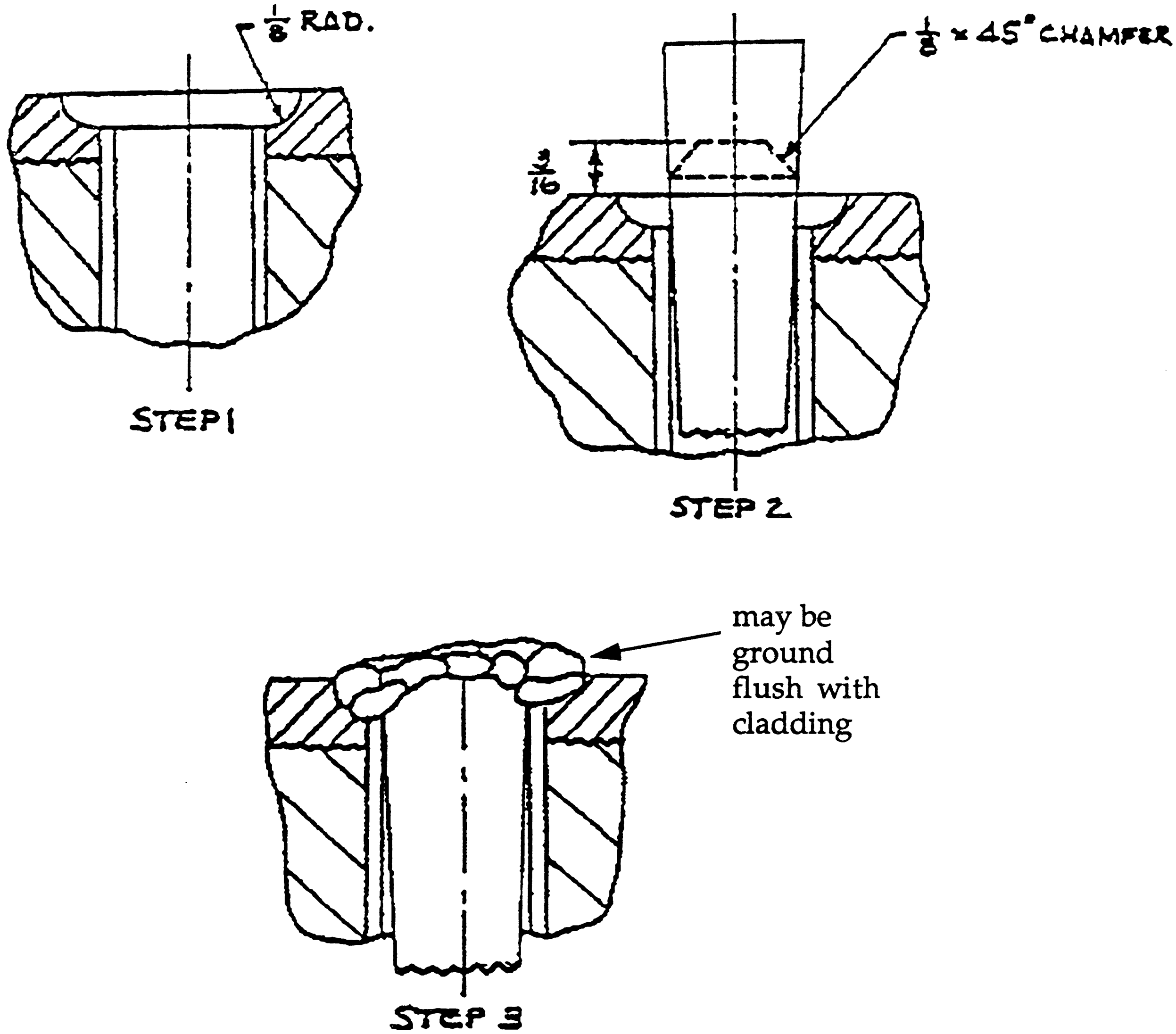


Figure B-6
Westinghouse Welded Tube Plug (Step 1 Required only for Defective Tube Weld)

Material Heat Treatment: Alloy 600 Bar/MA
Residual Stress Level: Mod.
Field Cracking/Location: Leakage reported
Inspectability: Visual

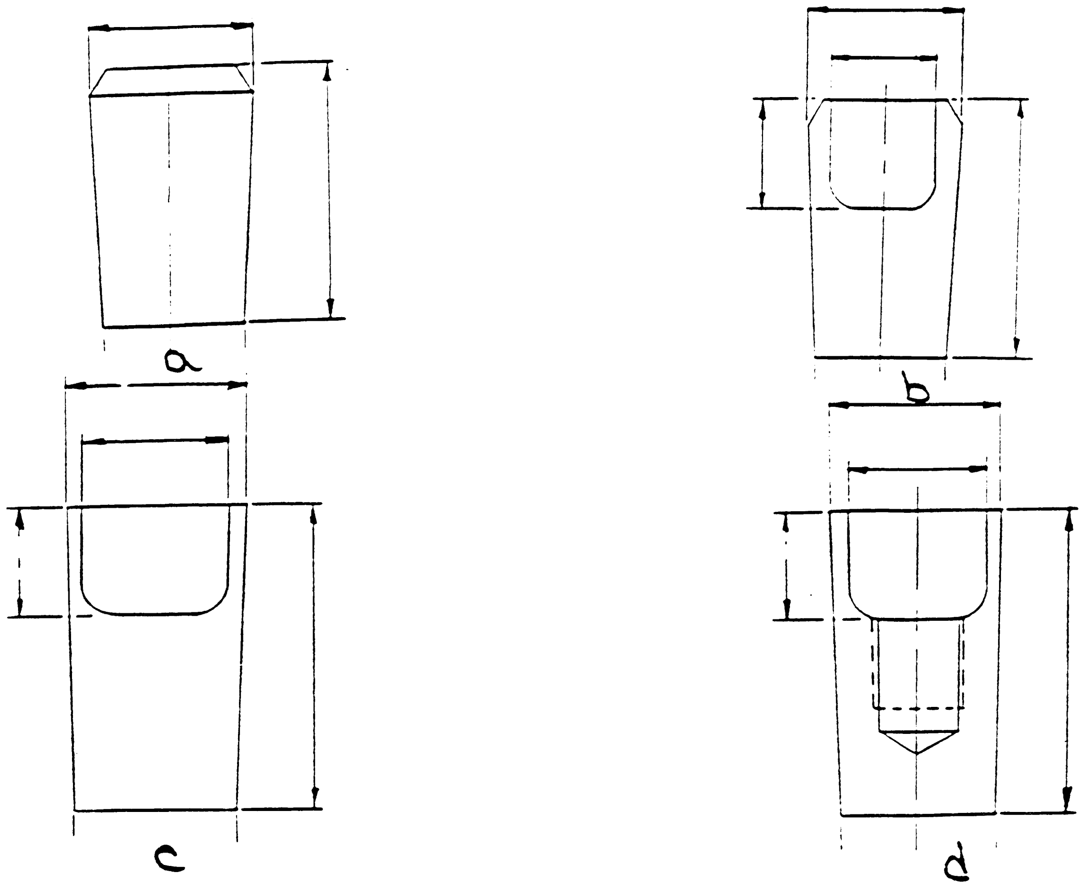
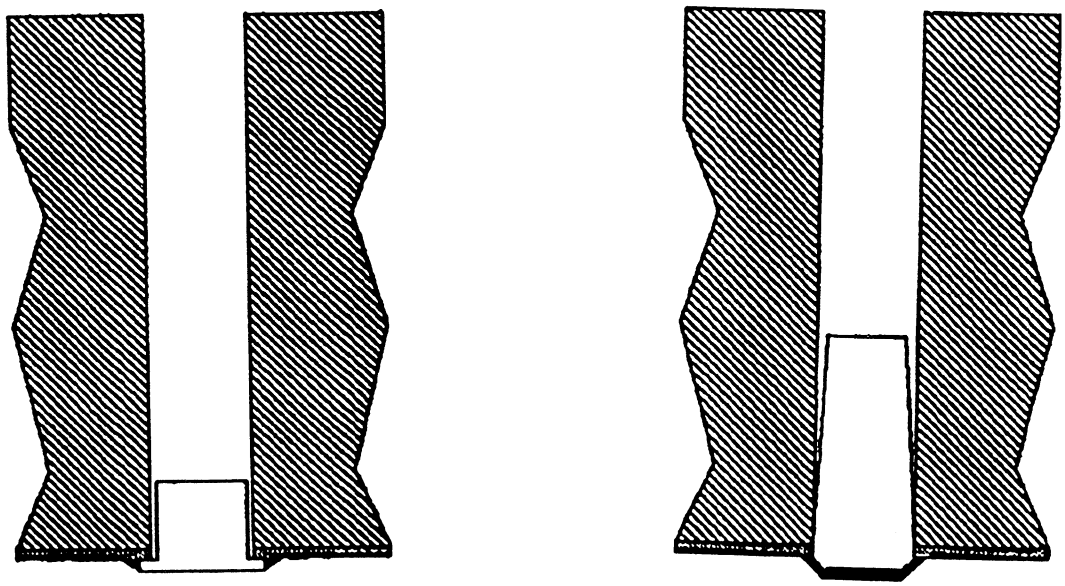


Figure B-7
ABB/C-E Welded Tapered Plugs

Material/Heat Treatment: Alloy 600 Bar/Hot Rolled
Field Cracking/Location: None reported
Inspectability: Visual



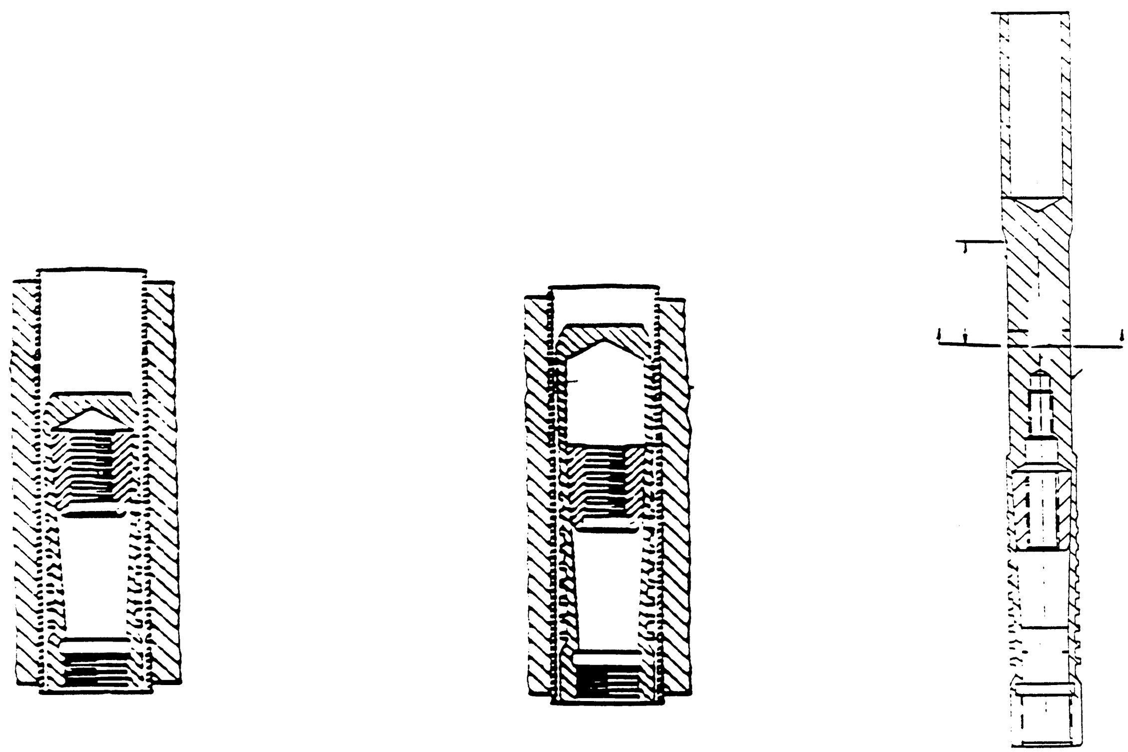
a) Button b) Tapered

Figure B-8
B&W Welded

Material/Heat Treatment: Alloy 600 Bar/HR/Welded/full bundle stress relieved
Field Cracking/Location: None reported
Inspectability: Visual

C

FIELD INSTALLED ALLOY 600 AND INCO 82 STEAM GENERATOR PLUGS



a) Standard Mechanical Plug b) Extended Length Mechanical Plug c) Stabilizer Plug

Figure C-1
Westinghouse Mechanical Plugs

Material/Heat Treatment: Alloy 600 Bar/TT
Residual Stress Level: Mod to high
Field Cracking/Location: Yes/Expanded Ribbed portion at and above expansion mandrel
Inspectability: By MRPC but difficult

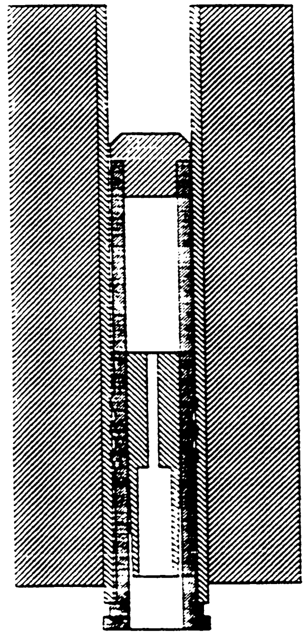


Figure C-2
B&W Ribbed Plug

Material/Heat Treatment: Alloy 600 Bar/TT
Residual Stress Level: Mod to high
Field Cracking/Location: SCC found under mandrel
Inspectability: Visual leakage

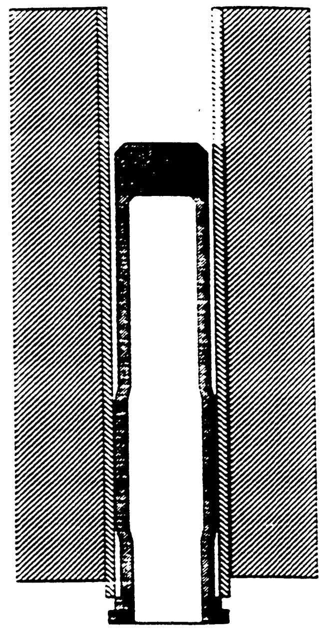


Figure C-3
B&W Rolled Plug

Material/Heat Treatment: Alloy 600 Bar/TT
Residual Stress Level: High
Field Cracking/Location: Yes/axial cracks in top (toe) transition and circum. in bottom (heel) transition
Inspectability: By RPC or visual leakage.

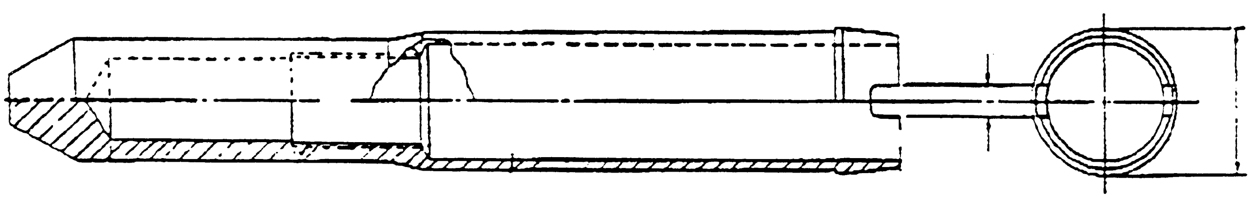


Figure C-4
Westinghouse Rolled Tube Plug for TMI-1

Material/Heat Treatment: (Unknown)
Residual Stress Level: High
Field Cracking/Location: (Unknown)
Inspectability: (Unknown)

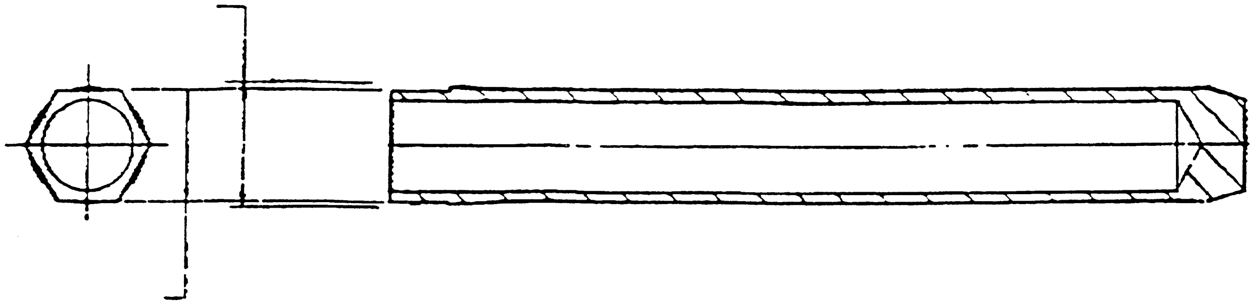


Figure C-5
Westinghouse Rolled Tube Plug for SCE

Material/Heat Treatment: (Unknown)
Residual Stress Level: High
Field Cracking/Location: (Unknown)
Inspectability: (Unknown)

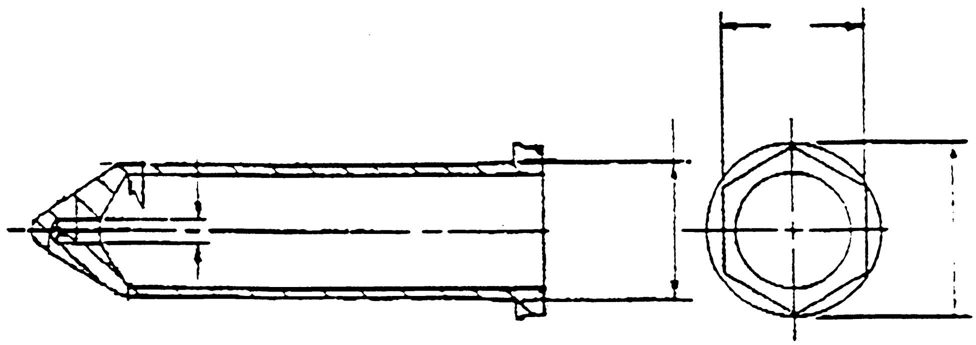


Figure C-6
Westinghouse Rolled Sleeve Plug for SCE

Material/Heat Treatment: (Unknown)
Residual Stress Level: High
Field Cracking/Location: (Unknown)
Inspectability: (Unknown)

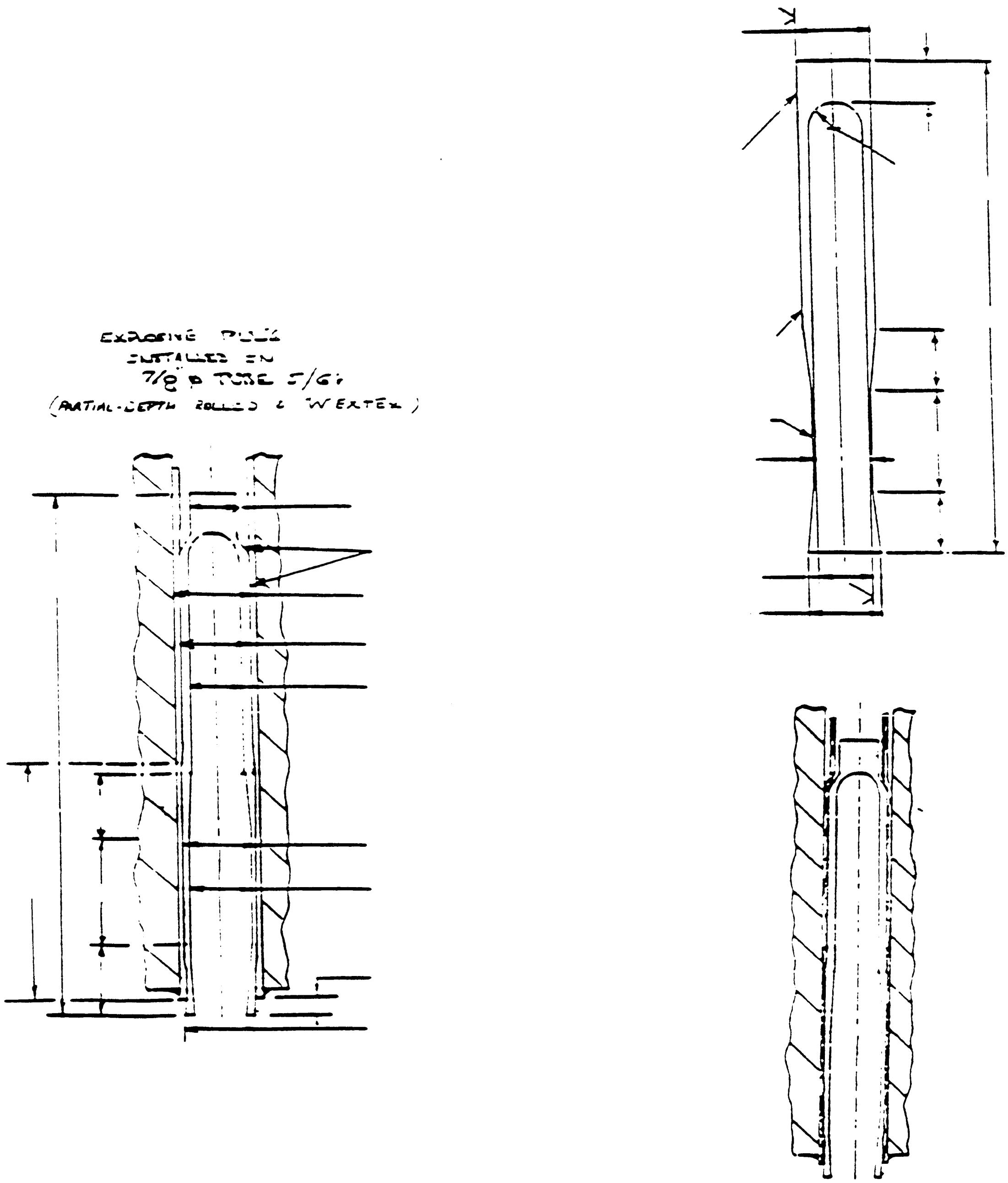


Figure C-7
Westinghouse Explosive Plug

Material/Heat Treatment: Alloy 600 Bar/MA
Residual Stress Level: Mod to high
Field Cracking/Location: Yes/Circ. in Expansion Transition zone(s)
Inspectability: Visual leakage and possibly by MRPC

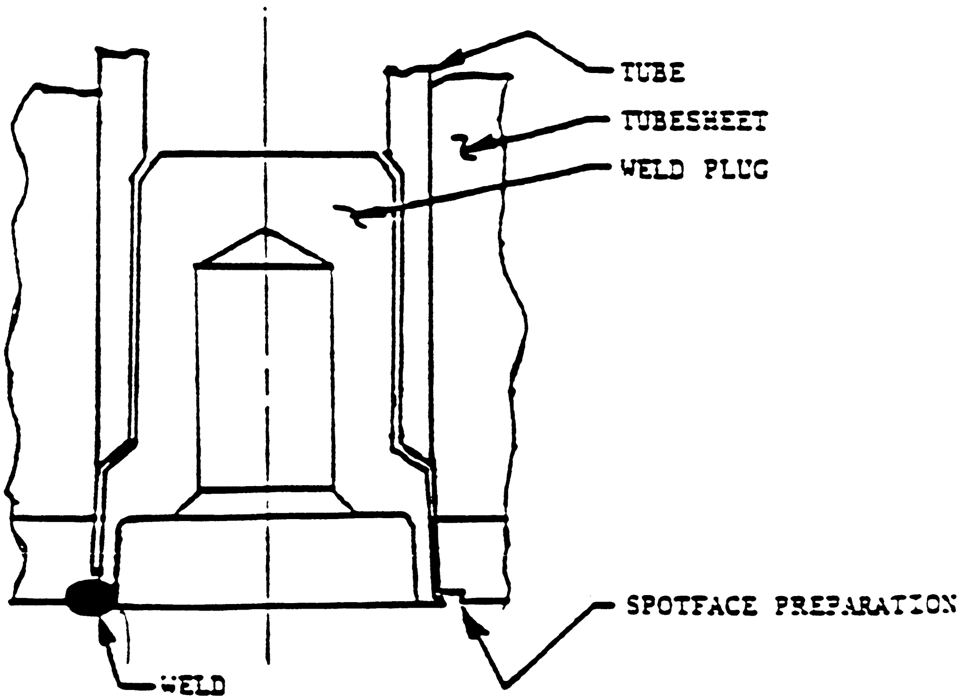


Figure C-8
Westinghouse Welded Tapered Plug

Material/Heat Treatment: Alloy 600 Bar/MA or Alloy 690 Bar/TT
Residual Stress Level: Mod
Field Cracking/Location: none reported
Inspectability: Visual leakage of dye penetrant

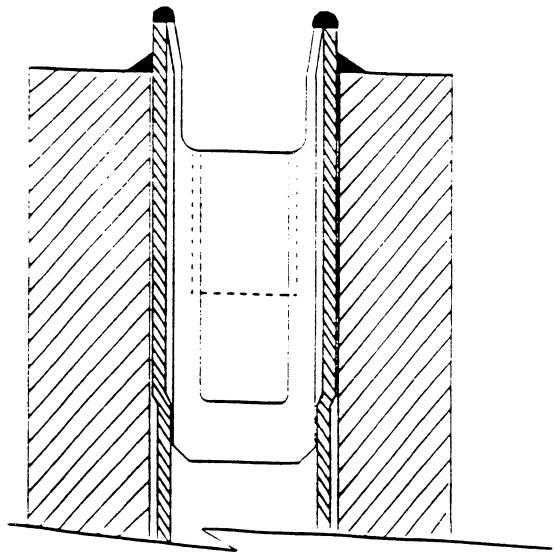


Figure C-9
B&W Welded U-Cup Plug

Material/Heat Treatment: Alloy 600 Bar/TT
Residual Stress Level: Moderate
Field Cracking/Location: None reported
Inspectability: Visual leakage

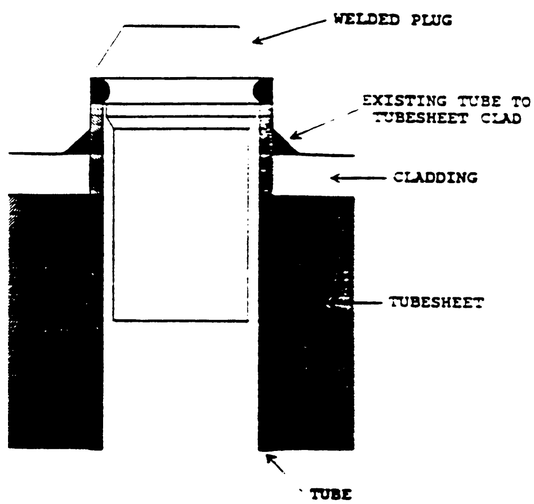


Figure C-10
B&W Welded Cap Plug

Material/Heat Treatment: Alloy 600 Bar/TT
Residual Stress Level: Moderate
Field Cracking/Location: None reported
Inspectability: Visual leakage

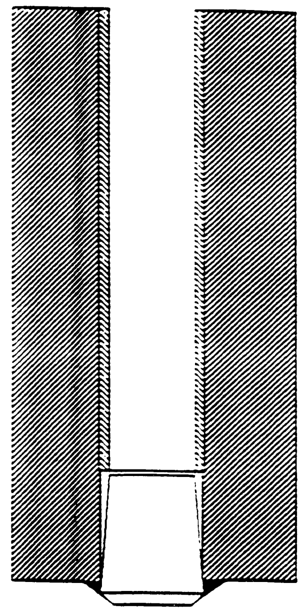


Figure C-11
B&W Taper Welded Plug

Material/Heat Treatment: Alloy 600 Bar/TT
Residual Stress Level: Moderate
Field Cracking/Location: None reported
Inspectability: Visual leakage or dye penetrant

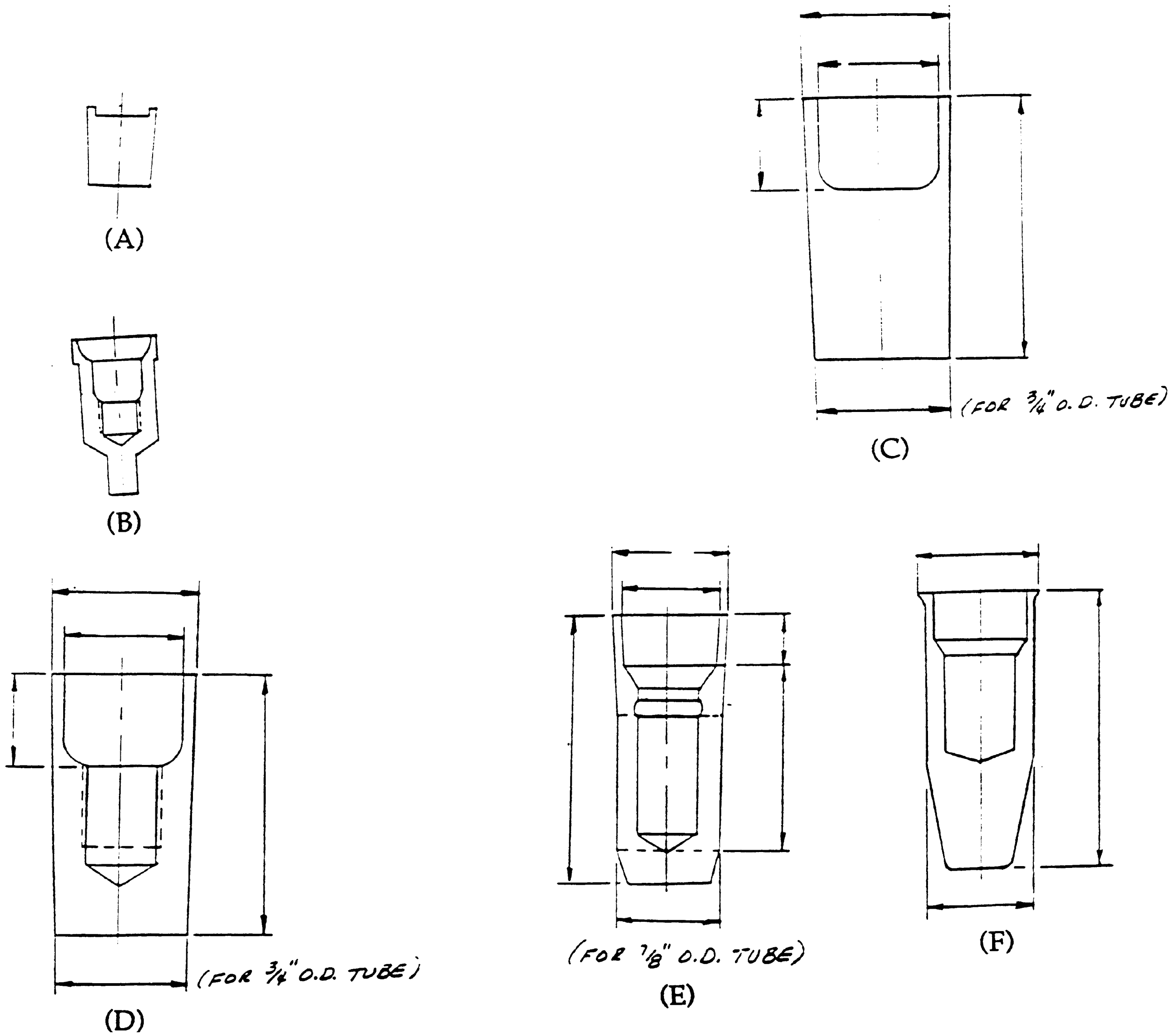


Figure C-12
ABB/C-E Welded Tube Plugs

Material/Heat Treatment: INCO 82 Bar/HR ?
Residual Stress Level: Mod
Field Cracking/Location: None reported
Inspectability: Visual

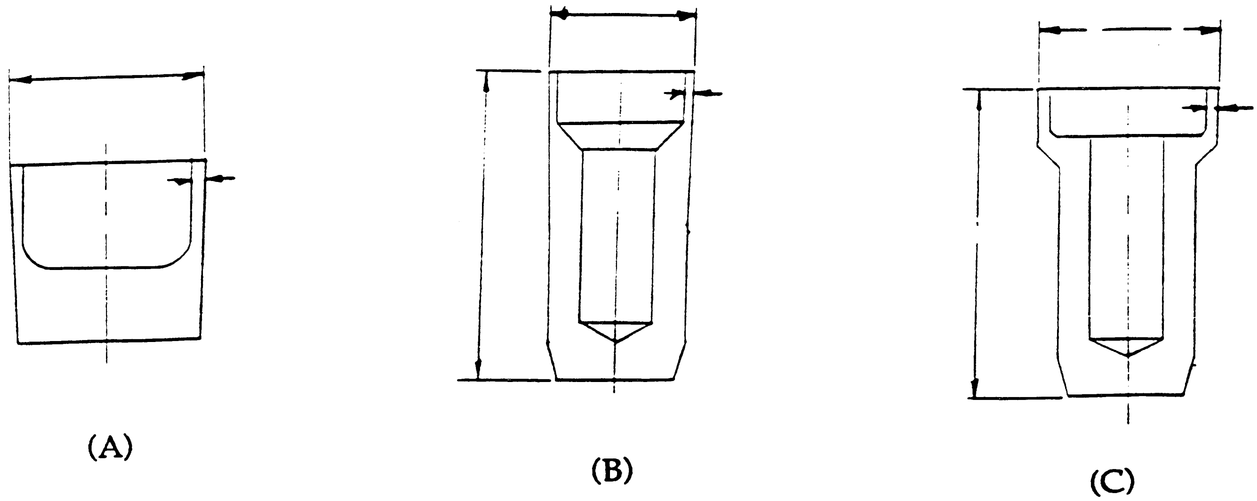


Figure C-13
ABB/C-E Welded Tapered Tube Sheet Plugs

Material/Heat Treatment: INCO 82 Bar/HR
Residual Stress Level: Moderate
Field Cracking/Location: None reported
Inspectability: Visual

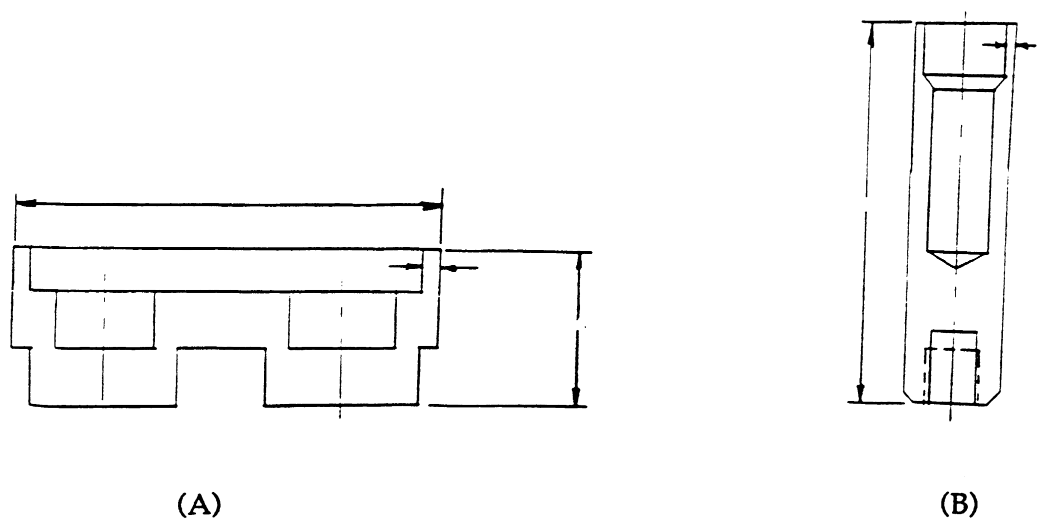


Figure C-14
ABB/C-E Welded Special Plugs

Material/Heat Treatment: INCO 82 Bar/HR
Residual Stress Level: Moderate
Field Cracking/Location: None reported
Inspectability: Visual

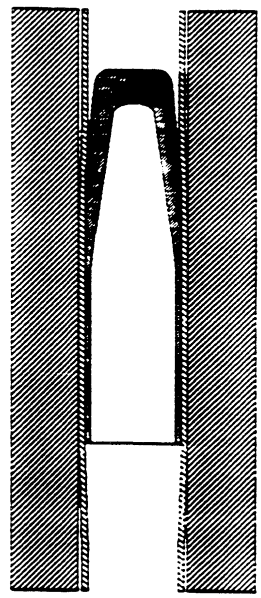


Figure C-15
B&W Explosive Welded Plug

Material/Heat Treatment: Alloy 600 bar/TT
Residual Stress Level: High
Field Cracking/Location: Yes/Circ. in Expansion Transition Zone(s).
Inspectability: Specialized RPC and visual leakage.

D

ALTERNATE METHODOLOGY FOR PREDICTING PLUG CRACKING[7]

An alternate methodology for predicting cracking of steam generator (SG) tube plugs has been developed and applied at Northeast Utilities (NU). The bases of this predictive methodology are that primary water stress corrosion of Alloy 600 follows an Arrehenius relationship with temperature and a log normal statistical distribution with time. Adjustments are made to account for differences in operating temperature, exposure times, and material susceptibility in order to determine the time to failure for a give population of plugs. Failure in this case is defined as any evidence of cracking. This evidence can be in the form of visually leaking plugs or by other nondestructive means. No attempt is made to distinguish the location or orientation of the cracks in the plugs. This methodology has been used to predict the cracking of Westinghouse (W) mechanical plugs, but should be applicable to other types of plugs or plugs from other vendors once sufficient test data or field data is available.

In order to predict plug lifetimes using this method, available plug failure data are plotted as cumulative failures as a function of log time in effective full power days (EFPD). Failure points are adjusted through the use of ranks to account for differences in sample sizes. Plotted in Figure D-1 are the failure data obtained during the February 1989 refueling outage for a specific heat of mechanical plugs which had been installed in the Millstone 2 (MP2) SGs. These plugs had been installed in two batches, one batch of 197 plugs in 1988 and another batch of 101 plugs in 1986. Failure was defined as visible evidence of leakage or boric acid stains, which was assumed to be indicative of a throughwall crack. The visual criteria for determining plug failure was standardized for the NU plants and is shown in Figure D-2. A line drawn through these data points establishes the expected performance of this heat of material with time. The slope of the line indicates variability in the material, with a steeper slope indicating more variability in the time to failure.

[7] Fred Anderson, Northeast Utilities

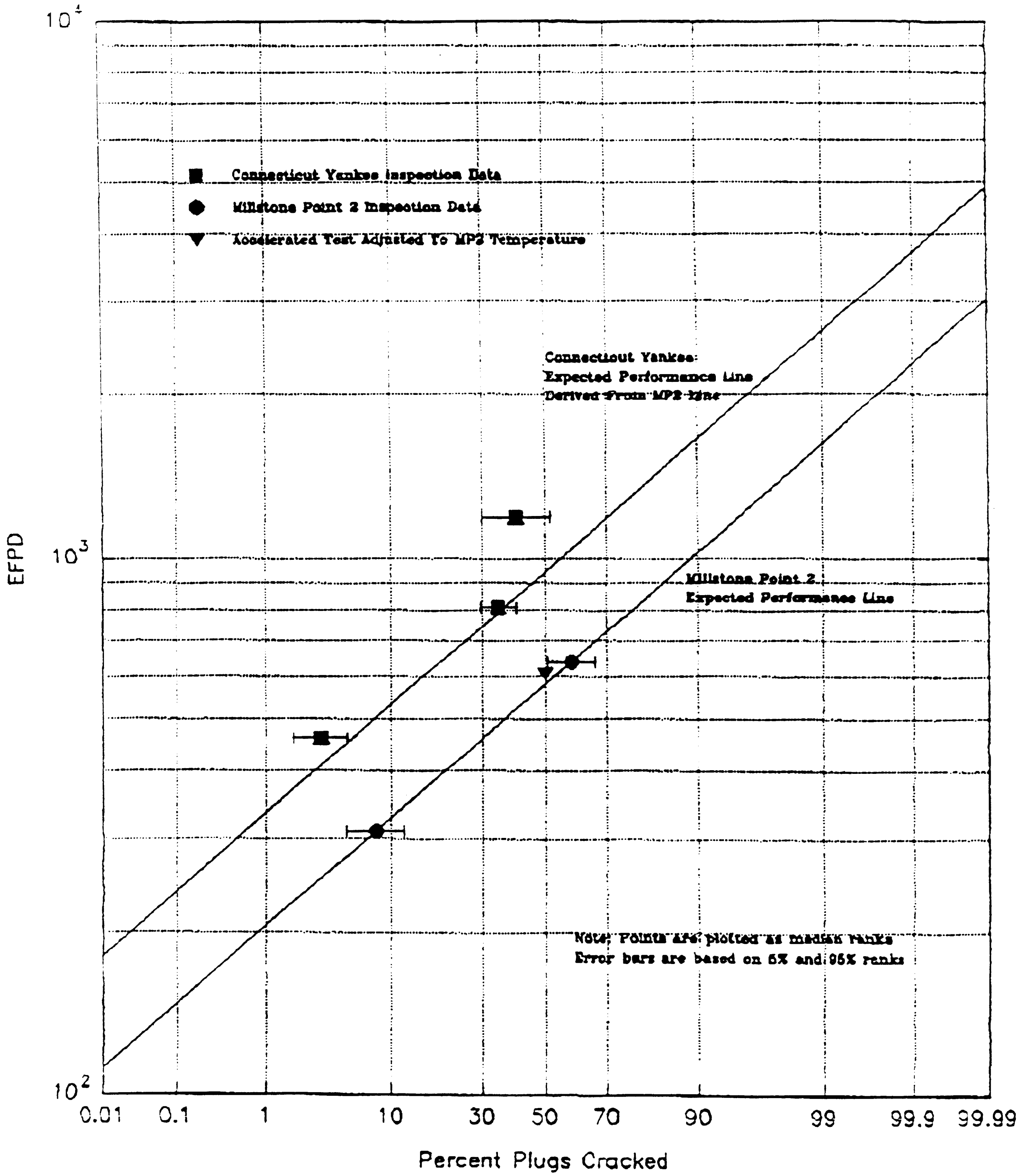
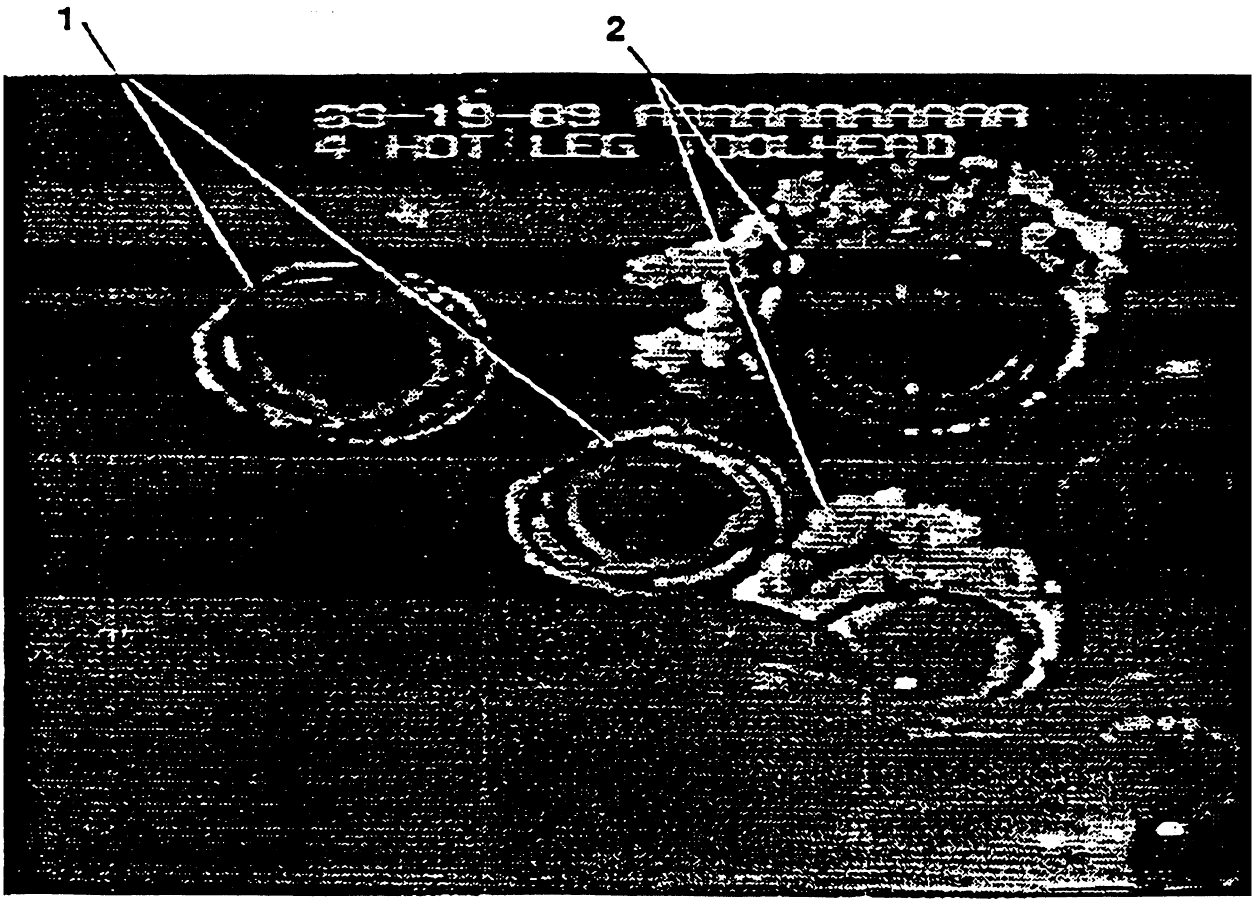


Figure D-1
Steam Generator Tube Plugs Visual Inspection Data



This picture provides the following information:

1 = Acceptable Plugs with minimal boric acid residue

2 = Unacceptable Plugs with excess boric acid residue or evidence of constant leakage

Figure D-2
1989 Connecticut Yankee RFO, Steam Generator #4 Westinghouse Mechanical Plug Visual Examination

As a sanity check, the 50 percent failure point from laboratory accelerated tests of this heat of material was compared with the MP2 field data. The test results were adjusted to the MP2 operating temperature using the Arrehenius relationship with an activation energy of 53.4 kcal/mole. The testing used a similar failure criteria, since the tests were continued until leakage was detected in the specimens. The adjusted test data point is plotted in Figure D-1 and shows excellent correlation with the field data.

Plugs from the same heat of material also had been installed in Connecticut Yankee (CY). The plugs were installed in three batches: 344 in 1984, 187 in 1986, and 53 in made for the September 1989 refueling outage. The median rank of the actual failures observed during the refueling outage, based on visual observations, is also plotted in Figure D-1 and show close agreement with the expected performance as indicated by the adjusted line.

Figure D-3 illustrates a step-by-step development of the predicted useful lifetime of 50 plugs from a hypothetical Heat "B." The useful lifetime of the plugs is defined as the exposure time that the first failure would be expected to occur. The plugs would be removed from service prior to that time. Field data is available for Heat "A" and is plotted in Figure D-3. Based on laboratory test data, heat "B" is known to be a factor of 10 better than Heat "A" with the same degree of variability. The Heat "A" expected performance line is adjusted by the factor of 10. A second adjustment is made using the Arrehenius relationship (Time proportional to EXP (-Q/RT) to account for any difference in the temperature the data was obtained and the desired SG conditions. The adjusted line is the expected performance of Heat "B" at the desired SG temperature. Since the objective is to identify the time to the first failure, the median and 5 percent ranks for a sample of 1 out of 50 is either calculated or looked up in a table. The values are 1.3 percent for the median and 0.1 percent for the 5 percent rank. The intersection of the Heat "B" expected performance line and the median rank is the expected time to the first failure. The intersection of Heat "B" expected performance line and the 5 percent rank is a more conservative time to first failure since 95 percent of the time the first failure would be expected to occur at a longer time. For conservatism, it is recommended that the 5 percent rank be used to determine useful lifetime.

This predictive methodology has demonstrated good agreement between predicted and actual field results. The usefulness of the methodology should increase as additional field and test data become available. Accurate predictive methods are beneficial to ensuring safety and limiting unnecessary repairs.

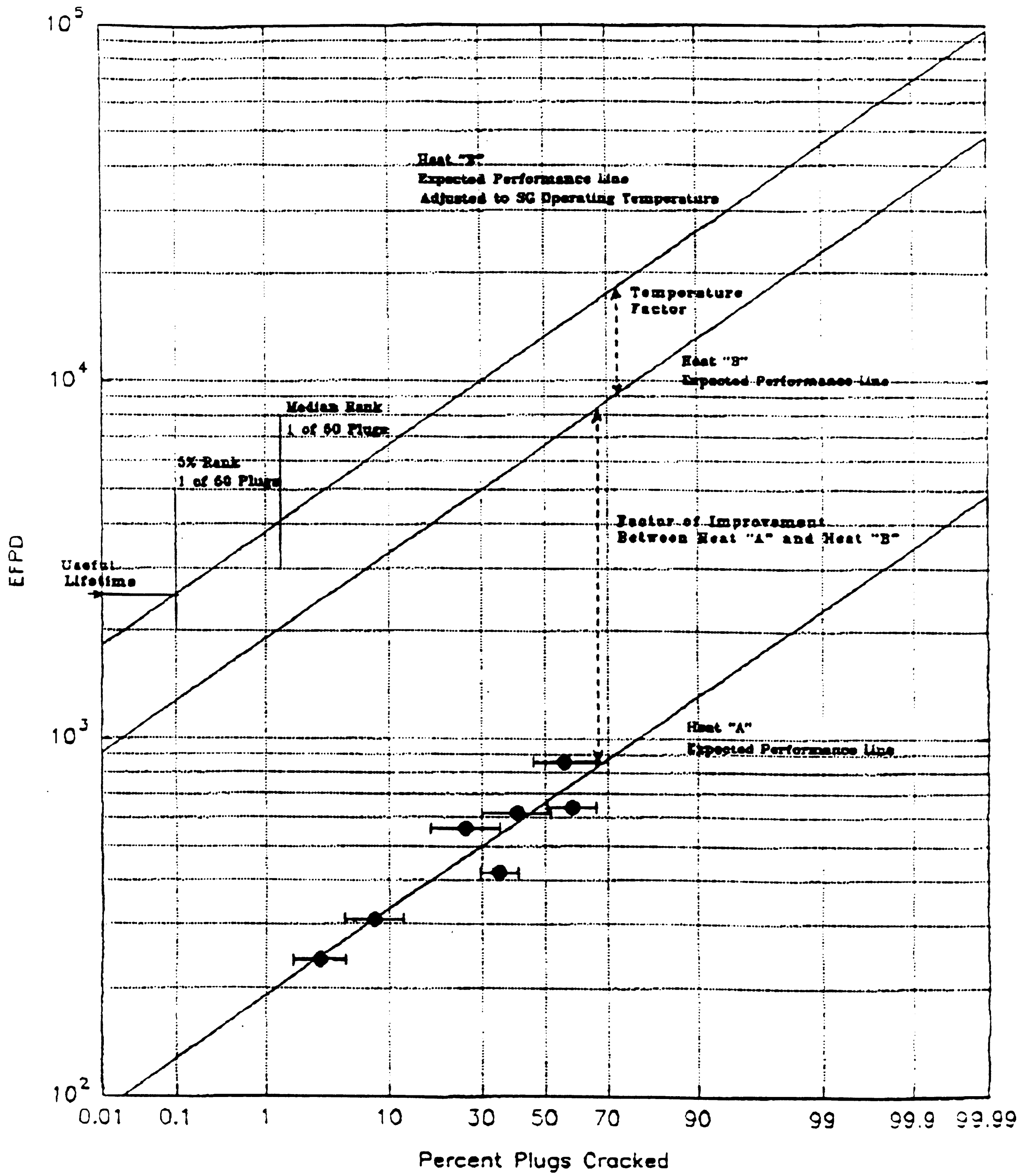


Figure D-3
Steam Generator Tube Plugs, Methodology for Determining Plug Lifetime