FAILURE ANALYSIS AND STRUCTURAL INTEGRITY EVALUATION OF LEAKING ALUMINUM-BRONZE CAST VALVE BODIES AND FITTINGS IN THE ECW SYSTEM

Report for
Houston Lighting and Power Company
South Texas Project

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ABSTRACT

This report presents the metallurgical failure analysis and the structural integrity evaluation of the leaking aluminum-bronze castings in the Essential Cooling Water system (ECW) at the South Texas Project (STP) Unit No. 1.

The failure analysis of two valves (one leaker, one non-leaker) and one fitting consisted of metallurgical cross sections, heat treatment studies, chemical and X-ray diffraction studies, microstructure analysis and the verification that the field replication procedure is satisfactory on aluminum-bronze. The failure analysis revealed that the leaks are caused by dealloying corrosion. The plain aluminum-bronze alloys in use (952 and 954) are susceptible to this form of corrosion.

The structural integrity evaluation consisted of cross sectioning and mapping the dealloying in 32 additional castings, performing miniature tensile tests on castings with known dealloying, performing proof tests on three fittings, two containing through wall leakage, and a statistical analysis of the extent of the dealloying plus fracture and limit load analysis.

The metallurgial and structural integrity analysis has demonstrated that the material has significant margin against failure for the design loading conditions. Proof tests of actual components with dealloying demonstrated load capacity on the order of 50 times the design pressure.

Key Words

dealloying
aluminum-bronze

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1.0 FAILURE ANALYSIS OF FIRST THREE SAMPLES

1.1 Introduction

On April 1, 1988, weeping type leaks were found in valves and fittings in the 2 inch and smaller piping in the Essential Cooling Water System (ECW). This was in unit number 1 of the South Texas Project (STP). To date, 90 of the approximately 800 valves and fittings have signs of weeping. The weeping is limited to the valves and fittings, which are all aluminum-bronze castings. The aluminum-bronze piping and welds show no sign of weeping. This is consistent with the literature that shows that alloys with less than 8 percent aluminum (wrought pipe and weld metal) are resistant to dealloying and alloys with greater than 8 percent aluminum (valve and fitting castings) are subject to dealloying under certain conditions.

Bechtel's Materials and Quality Services was initially requested to perform a failure analysis of a weeping valve and a fitting. The intent of this initial analysis was to identify the mechanism that is causing the weeps and the underlying metallurgical, design and environmental factors that led to the failures.

1.2 Conclusions of the First Diagnostic Phase

A. The leaks are caused by dealloying corrosion going through the wall of the cast valve or cast fitting.

B. Only castings have any sign of dealloying.

C. There is no sign of dealloying corrosion in either the weld metal or the wrought Al-bronze pipe.

D. The greatest amount of through-wall corrosion occurs in the region of the crevice and gap between the pipe and valve or pipe and fitting (socket end).

E. The metallurgical microstructure of the valves and fittings is a mix of three phases: alpha, beta and $gamma_2$. It is the aluminum in the $gamma_2$ phase that is preferentially corroded. The microstructures examined to date have a complete network of $gamma_2$ so that there is a path through the casting for dealloying to cause leaks.

F. Forced air cooling as specified by the supplier's procedure does not prevent the formation of the $gamma_2$ phase, which is susceptible to dealloying.

G. The chemistry of one valve body was check analyzed and was in conformance with the specification, ASME SB-148 CA 954.

H. The corrosion products are as expected. They contain aluminum, iron, calcium, and copper. There is some evidence of Gallionella in the corrosion products. To date, we have found no evidence that this known iron bacteria has any effect on Al-bronze.

I. The identification of the phases (alpha, beta and $gamma_2$) is based on:

1. Sample photomicrographs provided by the material supplier (see Figure 1.2a).

2. Heat treating three samples from a valve, and cooling them in water, air and in the furnace, and comparing their microstructures.

J. Metallurgical plastic replicas were taken from a laboratory specimen and directly from an elbow. A comparison of the photomicrographs taken at 480X of the lab specimen and the two replicas shows them to be essentially the same.

K. Field replicas can be used to nondestructively determine the microstructure of Al-bronze castings.

L. The pH of the residual water inside valve EW-0269 (serial No. 61-382) was 6.0.

M. The fittings and valves are experiencing dealloying corrosion because:

1. The microstructure contains the $gamma_2$ phase which is susceptible to dealloying.

2. The pH in the crevices due to the electrochemistry of the crevice is acidic, which promotes dealloying.

N. The biocides and other water treatment chemicals do not appear to have promoted the dealloying. (See Appendix A for typical cooling water chemistry logs.)

1.3 Materials

A. The valve bodies are specified to be cast aluminum-bronze to specification SB-148 CA 954 (10 - 11.5 percent aluminum).

B. The fittings are specified to be cast aluminum-bronze to specification SB 148 CA 952 (8.5 - 9.5 percent aluminum).

C. The pipe material conforms to SB 169 C61400 (6-8 percent aluminum).

1.4 Evaluation Methods

A. The as-received pieces were photographed and are shown in Figure 1.1.

B. In order to properly interpret the microstructure of Al-bronze, two actions were taken. The supplier of the raw castings was asked to send us photomicrographs of the typical microstructures of Al-bronze. Figure 1.2a is the information from them. Second, three small samples from Valve EW-0269 (serial No. 61-382) were heated above 1100°F for one hour. One sample was cooled in water, one in air and one was left in the furnace and slow cooled by turning off the power. Figure 1.2b shows the microstructure of the three specimens.

C. Cross sections were taken through the valve that leaked, the fitting (elbow) that leaked and the valve that did not leak. Table 1.1 compiles all the information obtained from this work and references the applicable figures that show the microstructures and macrostructures.

D. The chemistry of Valve EW 269 was determined. The results are listed in Table 1.2.

E. The residue in the socket weld crevice in the elbow was analyzed by EDAX for elements and by X-ray diffraction for compounds. The residue was also analyzed for bacteria that are known to be active in microbiologically influenced corrosion. The results are in Table 1.2.

F. When Valve EW 269 was unpacked, it was found to have been sealed up by plastic bags and tape. There was still a slight amount of moisture trapped in the valve. The pH was measured with litmus paper and was pH 6.0.

G. It is common practice to use a technique called replication at a field location, when a metallurgist wants to know the microstructure of a piece of equipment but can't cut out a sample of material. This method is well understood for carbon and stainless steels. In case it was needed in the field, a test was made to be sure that the techniques also work for Al-bronze. The standard field replication techniques for grinding, polishing and etching work quite well. Replicas were taken from a laboratory specimen and from an elbow polished and etched as if it was being done in the field. The photomicrographs of the two replicas and of the actual piece of material are almost identical (see Figure 1.6).

H. The chemistry as well as the pH of a saturated solution of welding flux were taken to determine if the flux might have been the source of the low pH.

1.5 Discussion of Results

A. The study to determine the visual appearance of the three phases (alpha, beta and $gamma_2$) was completed in a satisfactory manner. A comparison of the sample photograph from the supplier and the photomicrographs prepared by Bechtel show how to identify the three phases. The cross sections show several things:

1. The valves and elbows contain gamma$_2$ phase, which indicate that the forced air cooling per the supplier's procedure did not prevent its formation.

2. The microstructure of a fitting that was tempered and forced air cooled by Bechtel was identical to the as-received material. This confirms that forced air cooling does not prevent the formation of gamma$_2$.

3. Dealloying is the corrosion mechanism that is causing the leaks.

B. The chemistry of the base metal is as expected, as was the analysis of the corrosion products. The influence of MIC on this problem is unknown. <u>Gallionella</u> was found in moist residue in the crevice of the elbow.

C. The pH of the sample of residual water found in Valve EW 269 was slightly low. The site records show a pH of 8 to 9 for the system. However, it was reported that a pH of 4 was measured in the water weeping from a leaking valve. This low pH is most likely a result of the electrochemical effect of the crevice.

D. EDAX analysis of the welding flux reveals significant amounts of fluorine and sodium and lesser amounts of aluminum and silicon. Wet chemical analysis revealed 1.01 percent boron. The pH of a saturated solution both of as-received and of high temperature baked flux dissolved in distilled water (pH 6) was pH 7.2, i.e., the flux is basic.

TABLE 1.1

ANALYSIS OF CROSS SECTIONS OF
INITIAL SAMPLES

SERIAL NO. PROJECT ID NO.	VALVE OR FITTING, HEAT NO.	TYPE OF CROSS SECTION	WORST CASE LOCAL PENETRATION OF DEALLOYING	METALLURGICAL STRUCTURE	LOCATION OF CROSS SECTION	PHOTOMICROGRAPH	MOUNT NO.
61-382 EW 269	Valve H5174-44	Circumference 100 to 200 degrees	27% 0.12 in.	Alpha and ga. [illegible] 50%/50%	Fig. 1.3 Leaking ends	Continuous network of $gamma_2$ dealloying and minor pits	7040
61-382 EW 269	Valve H5174-44	Longitudinal @ 180 degrees	100% plus 0.025 in. on the OD and ID	Alpha and $gamma_2$ 50/50%	Fig. 1.3 leaking end	Dealloying is "U" shaped. Continuous network of $gamma_2$ in valve. Pipe and weld no $gamma_2$	7041
61-382 EW 269	Valve H5174-44	Longitudinal @ 180 degrees thru bronze valve and carbon steel pipe (drain connection)	None	Alpha and $gamma_2$ and small grey dots in both phases 50/50	Fig. 1.3 No leak	No dealloying continuous network of $gamma_2$	7042
466-185 EW 315	Valve H5174-36	Longitudinal @ 180 degrees Bronze valve to bronze pipe	50% Some were to 25%	Alpha $gamma_2$ and beta. Small grey dots in both phases 50%/50%	Fig. 1.4 No leak	Dealloying continuous $gamma_2$ network	7043

TABLE 1.1 (cont'd)

SERIAL NO. PROJECT ID NO.	VALVE OR FITTING, HEAT NO.	TYPE OF CROSS SECTION	WORST CASE LOCAL PENETRATION OF DEALLOYING	METALLURGICAL STRUCTURE	LOCATION OF CROSS SECTION	PHOTOMICROGRAPH	MOUNT NO.
	Elbow	Longitudinal @ 180 degrees Bronze elbow to bronze pipe	100% @ socket weld gap.	Alpha and & $gamma_2$	Fig. 1.5	$Gamma_2$ network semi-continuous. Dealloying @ gap	7044
	H9528-31			70%/30%	Leaking end		
	Elbow	Circumference 100 to 200 degrees	60%	Alpha and $gamma_2$		Dealloying o ID on the [illegible] specimen.	7045
	H9528-31			70% alpha/ 30% $gamma_2$	Leaking end		
	Elbow	Longitudinal 90 degrees away from leak and back from gap	40%	Alpha and $gamma_2$		Dealloying on the ID around the gap and down toward weld	7046
	H9528-31			70% alpha/ 30% $gamma_2$	Leaking end		
	Elbow	Circumference extrados	40% Small spot ----------- Remainder is one or two grains deep ID	Alpha and $gamma_2$		Dealloying on ID	7047
	H9528-31			70% alpha/ 30% $gamma_2$	No leak		

TABLE 1.2

CHEMICAL ANALYSES

1. Base metal of Valve EW-269 by emission spec.

Element	Cu	Al	Fe	Mn	Ni
% Weight	84.9	10.6	4.25	0.11	0.06

2. Corrosion product analysis by EDAX

Element	Al	Fe	S	Ca	Cl	Si	Cu
% Screen Height	100	100	20	20	15	10	8

3. Corrosion product compound analysis by x-ray diffraction

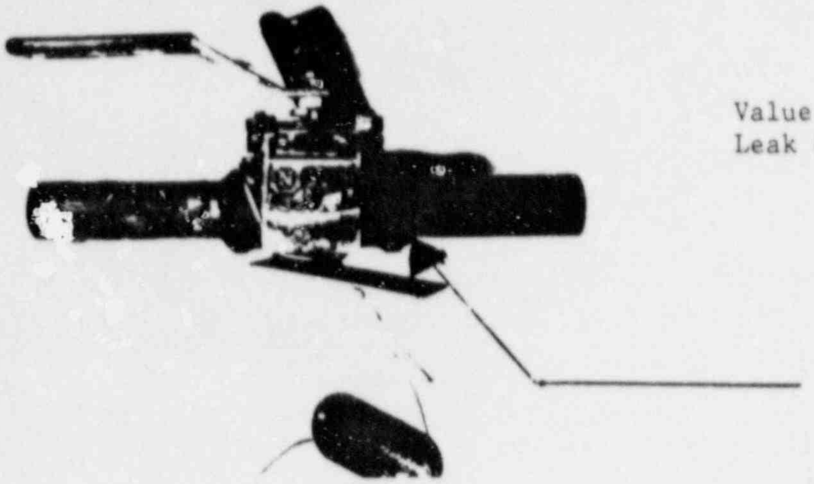
   1/2 (Fe_2O_3 - H_2O)

   $CaCO_3$

   These are the only compounds with strong patterns. Since the EDX results show a strong line for aluminum, the only aluminum compound that has a very weak crystal pattern is $Al(OH)_3$. It should be noted that this compound is most commonly the result of the corrosion of aluminum.

4. Bacterial analysis of the corrosion product revealed evidence of Gallionella, which is one of the bacteria known to be involved in the corrosion of steel and stainless steel.

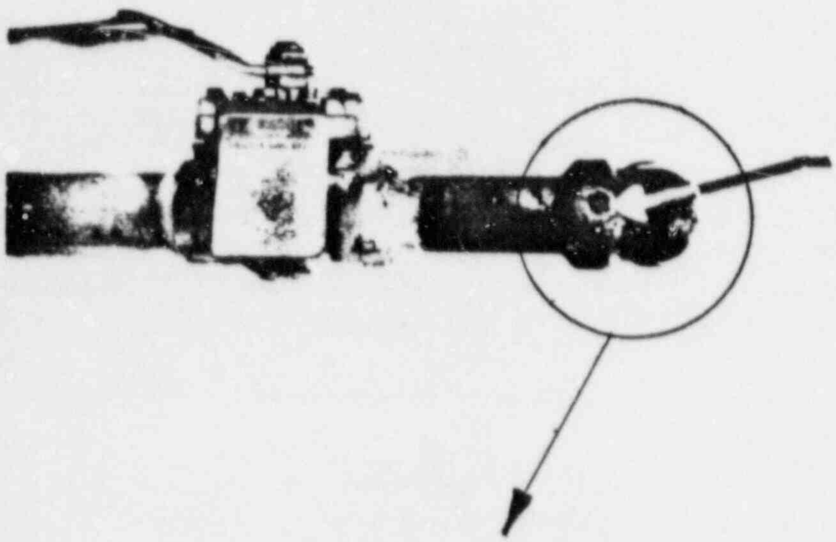
Valve EW 269
Serial No. 61-352



Value handle @ 0°
Leak @ 180°

LEAK

Valve EW 315
Serial No. 466-185



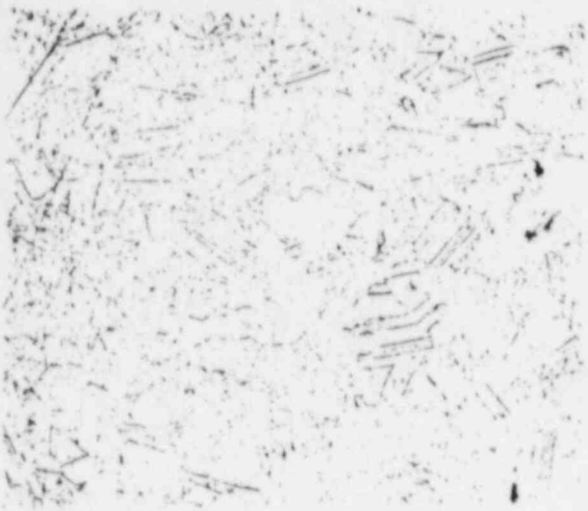
Value handle @ 270°
No Leak in Valve
Leak in Fitting @ 180°

Elbow Heat No. H9528-36

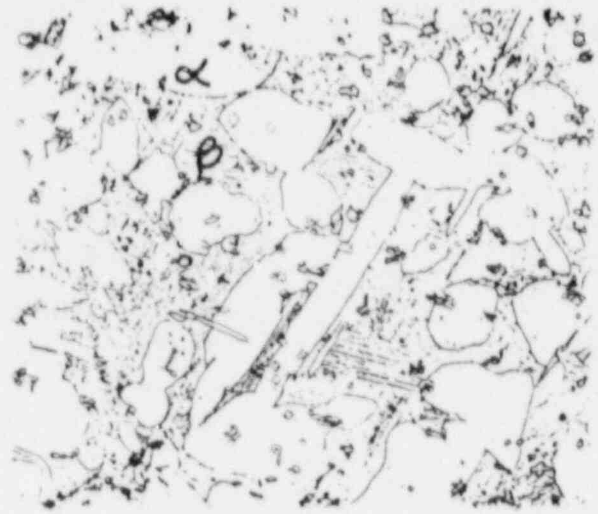
LEAK

FIGURE 1.1 As Received

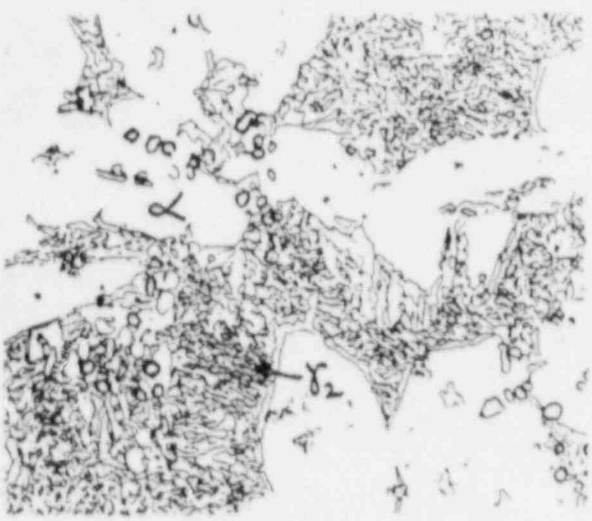
METALLOGRAPHIC STRUCTURES - ALUMINUM BRONZE ALLOYS



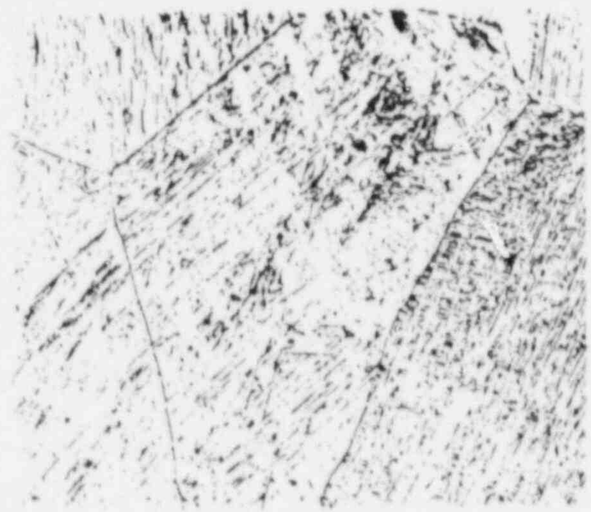
1. Wrought Structure
   Alpha Phase



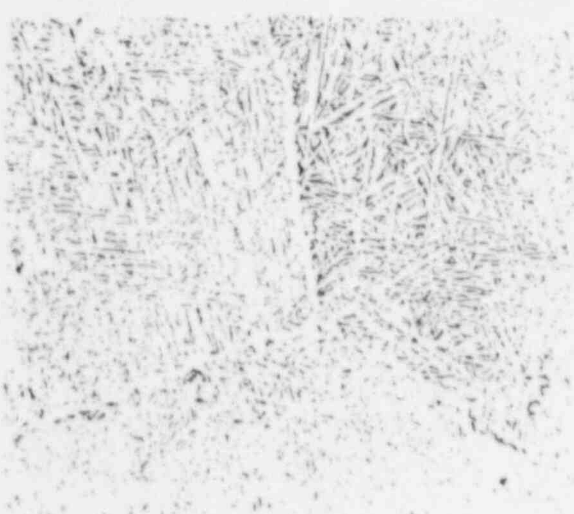
2. Slowly Cooled
   Alpha Plus Beta Phases



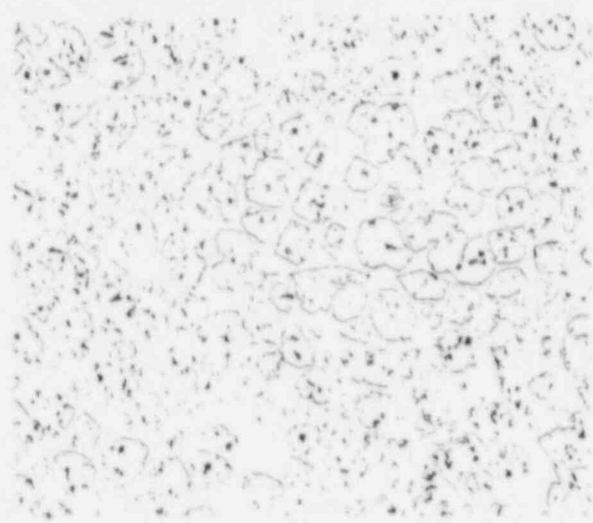
3. Slowly Cooled
   Alpha Phase Plus Eutectoid



4. Rapid Quench
   Martensitic Beta

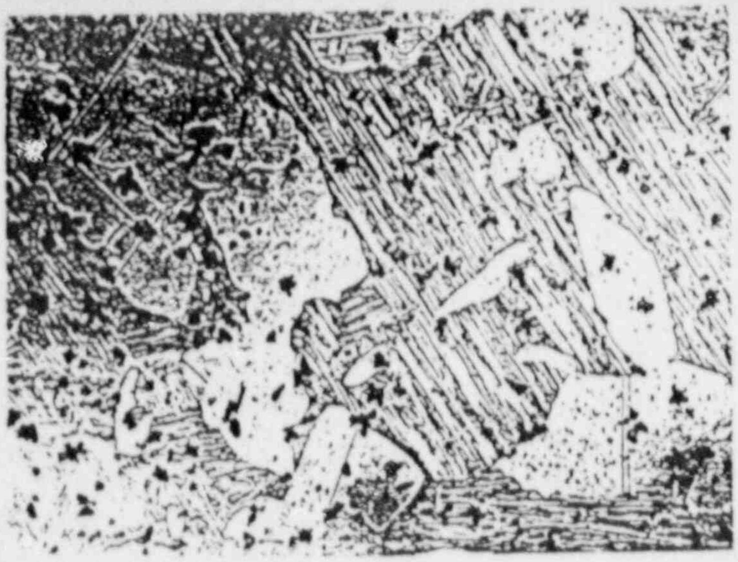


5. Rapid Quench Plus Anneal
   Martensitic Beta Plus
   Acicular Alpha



6. Slow Cool
   Beta Plus Gamma Phases

FIGURE 1.2a Typical Microstructures

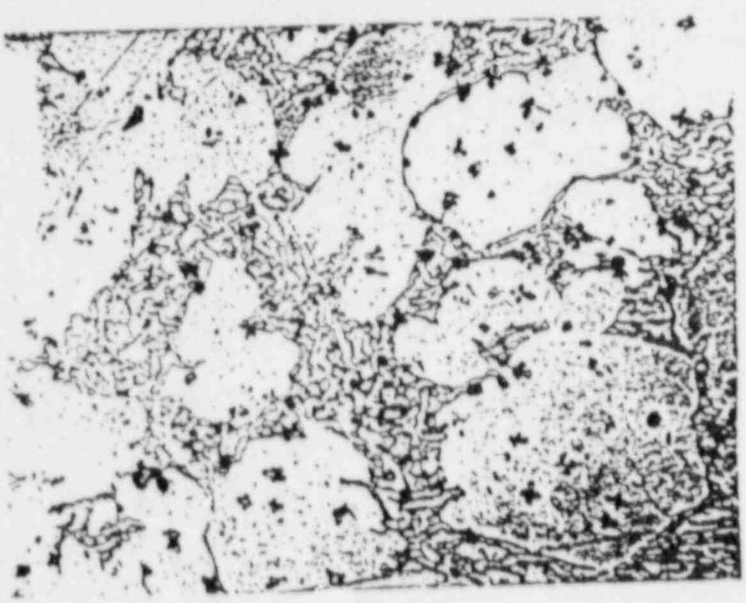


Heat at 1150°F one hour
Water Quench

Source: Bechtel Valve 269

Heat at 1220°F one hour
Air Cool - Fan

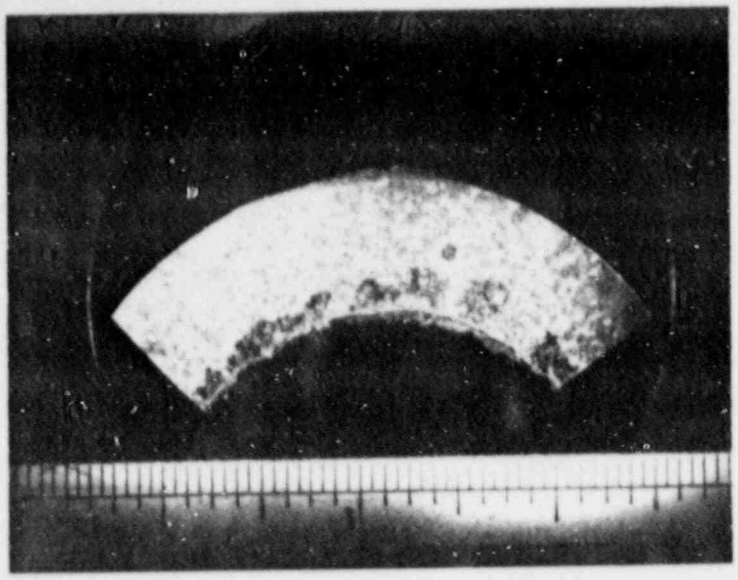
Source: Bechtel Elbow
Heat No. H95-28-36



Heat at 1250°F one hour
Furnace Cool

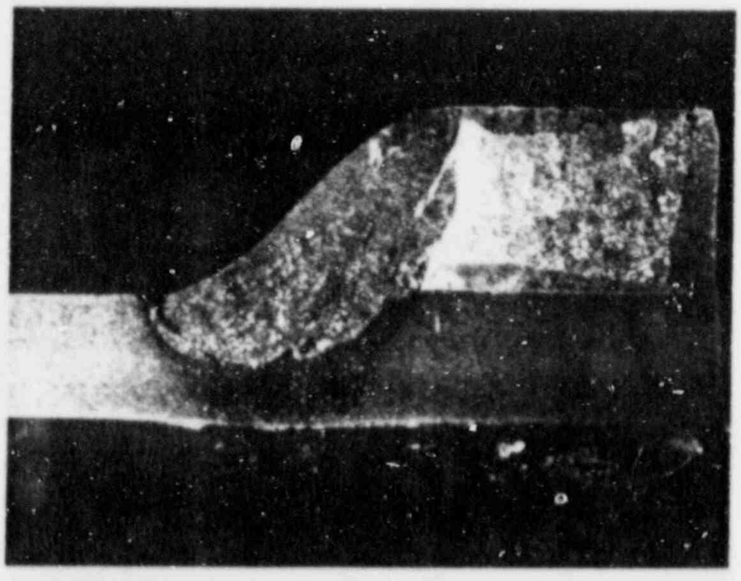
Source: Bechtel Valve EW 269

FIGURE 1.2b Typical Microstructures



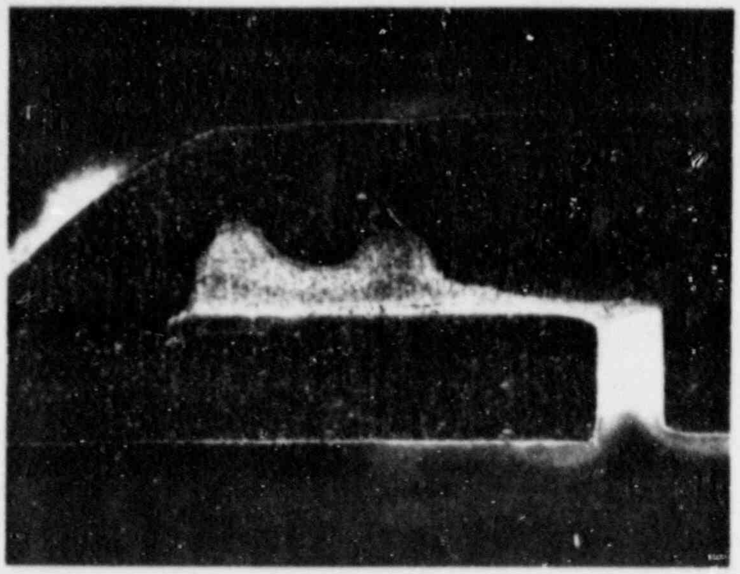
Mount 7040
2X
NH_4OH - H_2O_2 etch

Mount 7040
480X
NH_4OH - H_2O_2



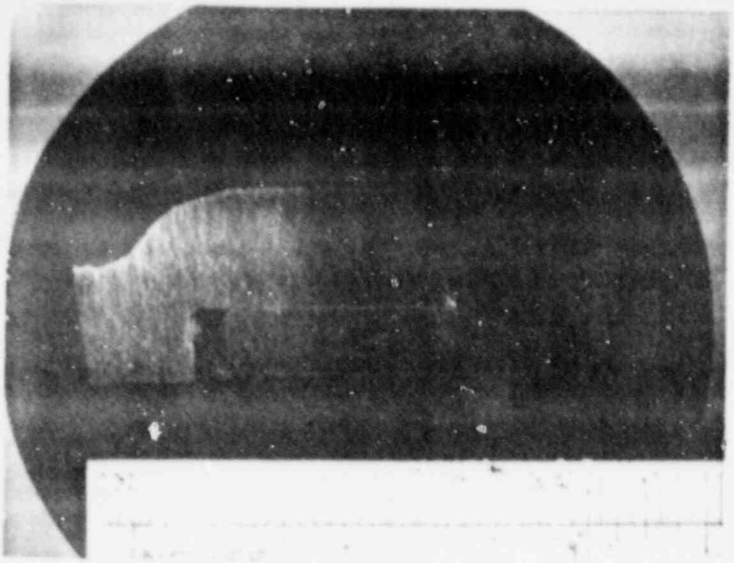
Mount 7041
5X
NH_4OH - H_2O_2

FIGURE 1.3 Valve EW 269



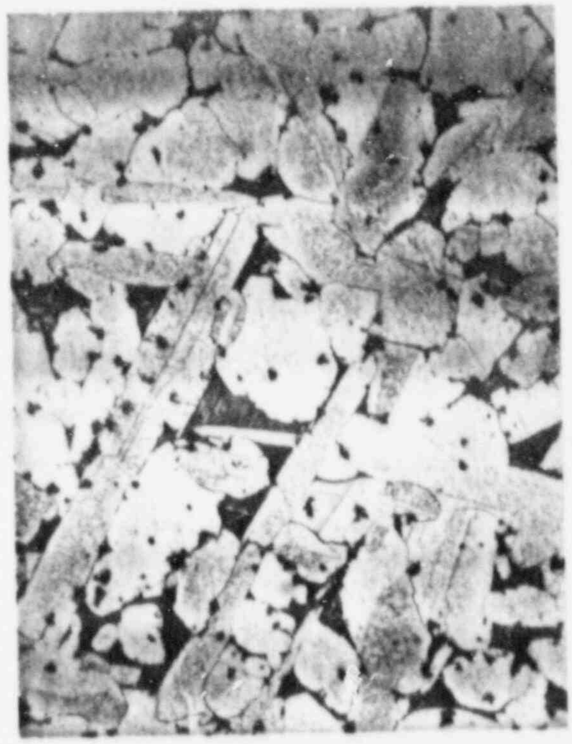
Mount 7043
5X
$NH_4OH - H_2O_2$

FIGURE 1.4 Valve EW 315



Mount No. 7044
2X
$NH_4OH - H_2O_2$

Mount 7047
500X
$NH_4OH - H_2O_2$



Mount No. 7045
2X
$NH_4OH - H_2O_2$

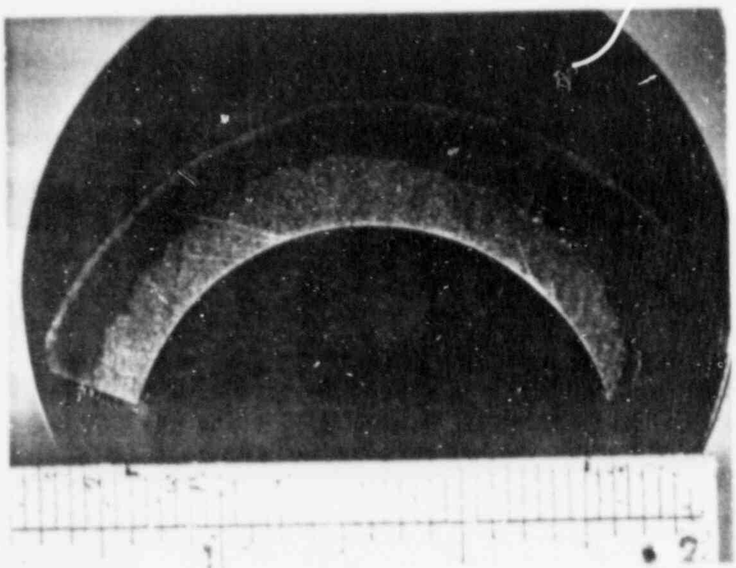
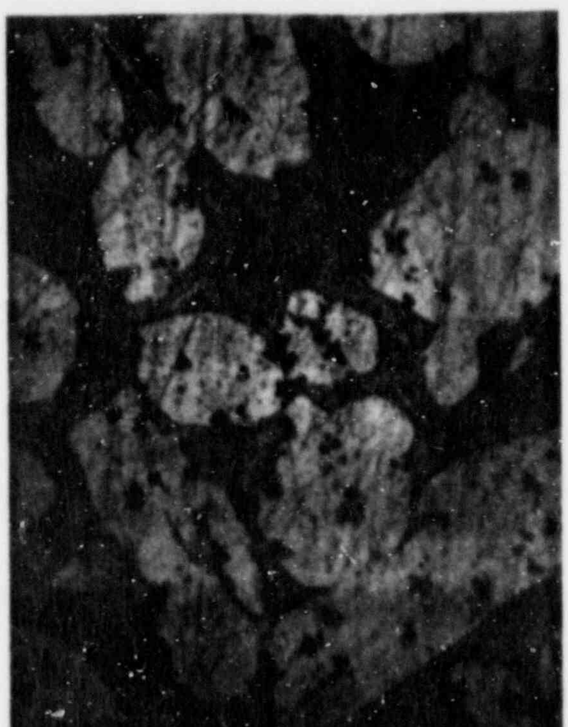


FIGURE 1.5 Elbow Heat No. H9528-36

480X Replica 7040

Replica

480X 7040



Laboratory Mount

FIGURE 1.6 Comparison of replica micrograph with laboratory micrographs, Valve EW 269

2.0 STRUCTURAL INTEGRITY

2.1 Introduction

During the period prior to completion of replacement, STP asked Bechtel to do an analysis of the system in the current and future corroded condition on the basis of statistical probability of the condition of the system based on analysis of samples of leaking and non-leaking joints. In addition, Bechtel was asked to analyze the system from an ASME Code standpoint and from a fracture mechanics standpoint. Finally, proof tests were conducted to determine the inherent margins.

2.2 Statistical Analysis

In order to obtain data for statistical analysis, 65 component ends were sectioned circumferentially and longitudinally. Longitudinal cross sections were used to confirm the observation that the worst dealloying areas were the socket weld crevices. Additional circumferential cross sections were used to determine the maximum amount of dealloying. This was accomplished by making circumferential cross sections of the crevice area and polishing until the greatest amount of dealloying was found. Typical circumferential and longitudinal cross sections are shown in Figures 2.1 and 2.2. A summary of the data obtained is contained in Table 2.1.

The data in Table 2.1 were used to perform a statistical analysis. The procedure used and results obtained are described in the following sections.

2.2.1 Classification of Samples

The circumferential cross section for each end of the sampled fitting was classified from observations as a leaker or a non-leaker. Thus, the extent of dealloying for the leaker ends sampled represents the condition of any valve or fitting socket that was currently found leaking on the ECW system. The extent of dealloying for the non-leaking ends sampled represents the extent of dealloying of the current ends after the leakers were removed.

The results of the samples, presented on Table 2.1, are also shown on Figure 2.3.

2.2.2 Confidence Level

It is necessary to insure that the sampled fittings adequately represent the whole population of fittings. Therefore, the degree of confidence has been estimated.

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From the sample, a probability p of finding a certain fraction dealloyed in a socket end is determined. This probability is then used to estimate the probability P of finding a certain fraction dealloyed in the population. The standard error of proportion is determined using the following relation:

$$sp = \sqrt{\frac{p(1 - p)}{n}} \sqrt{\frac{N - n}{N - 1}} \qquad \text{(equation 2-1)}$$

where:

N is the population size,
n is the sample size, and
p is the probability of finding a certain fraction dealloyed.

The error of estimation E for a 95% confidence level is found by using:

$$E = 1.96 \cdot sp \qquad \text{(equation 2-2)}$$

Therefore, the probability P of finding a certain fraction dealloyed in the population of fittings is given by:

$$P = p \pm E \qquad \text{(equation 2-3)}$$

From Equation 2-1 it is seen that as either the sample size approaches the population size or the probability approaches zero, or one, the error band will approach zero. To assure a 95% confidence level for a 95% probability we will solve equation 2-1 such that $p + E = 0.05$. The proportion of non-leaking socket ends exceeding 59.08% dealloying is estimated to fall between 0% and 5% (1.044% ± 3.956%) while the proportion of leaking socket ends exceeding 92.25% dealloying is estimated to fall between 0% and 5% (1.243% ± 3.757%).

2.2.3 Sample Distribution

The data presented on Table 2.1 were used to generate Figure 2.4. In this figure, the percent of exceeding a certain fraction of the cross section being dealloyed is plotted for all samples taken. The leakers and non-leakers are plotted separately along with the combination of all samples. As shown on this figure, the leaking ends have a higher percent of the cross section dealloyed than the non-leakers. Thus, it can be deduced that replacement of the leaking socket ends will remove the number of fittings with high dealloying and the remaining population will be characterized by the non-leaking data.

2.2.4 Leakage as a Function of Dealloyed Cross Section

As shown above, the leaking socket ends have correspondingly more of the cross section dealloyed than the non-leaking socket ends. Therefore, an attempt to determine the fraction of leaking socket ends as a function of dealloyed cross-sectional area is made. For this purpose, the probability distribution function of socket ends as a function of dealloyed cross section area needs to be determined.

Some assumptions must be made concerning the possible shape of this probability distribution function. Originally, the socket ends had little or no dealloying, thus the distribution function was narrow near zero. As time went on and corrosion set in, more and more socket ends were being dealloyed. This process can take the shape of an exponential or Weibull distribution function. As more and more fittings are dealloyed, the median shifts towards higher values and the shape changes towards a normal or log-normal distribution. From the data obtained from the sample, it can be seen that the non-leaking socket ends can be characterized by a Weibull distribution, while the leaking socket ends approximate a normal distribution.

The above distribution functions were then used to determine the percentage of leaking socket ends that can be observed as a function of cross section dealloying as shown on Figure 2.5.

2.3 Stress Evaluation

To establish the margins existing in the original design a review of the stress analysis of the small bore ECW system was performed.

In addition to this review further calculations were performed to determine the margins that exist when the stresses are compared with the minimum properties of the dealloyed material as determined by testing.

2.3.1 Objectives

The specific objectives of this task were as follows:

1) to review the original design calculations and establish the original design margins.

2) to demonstrate existing margins for dealloyed fittings using ASME Section III methods and the minimum properties of dealloyed materials as established by tests.

2.3.2 Analysis Assumptions

The original design bases for the small bore Al-bronze piping are established through ASME Section III Subsections NC 3600. In this particular analysis method stress multipliers or stress intensification factors (SIF) are used to account for geometric discontinuities. All stresses in the original design analysis are referenced to the section properties of the piping material. For purposes of the stress review, the results of the original analysis for equations 9 and 11 of ASME Section III were reviewed and compared to allowable design stresses.

For equation 9B, the primary stress equation due to pressure weight and Operating Basis Earthquake (OBE), the allowable stress is 21.6 ksi and for equation 11, the effect of pressure, weight, other sustained load and thermal expansion, the allowable stress is 45.0 ksi.

To evaluate the margins that exist between design loads and actual material properties tensile tests were performed on material that was up to 100 percent dealloyed. The average ultimate tensile strength for the 100 percent dealloyed material was 30 ksi.

In the evaluation of actual stresses that exist in these fittings a value for SIF has been applied to the crevice location. The values for SIF have been established from the Reference 2 and Reference 3. In all cases the larger value (conservative case) from either reference was used.

Finally for the stress evaluation, ASME III Appendix III was used to establish a value for S_M, a value of the quarter of the ultimate tensile strength of 100 percent dealloyed material (7.5 ksi) was used.

The ASME Code equations with stress multipliers to account for geometry discontinuity due to dealloyed material are outlined below:

$$EQ9: C_p \frac{P_p D}{4t_f} + 0.75(C_m) \frac{M_b}{Z_f} \quad 9B < 1.2S_H$$

$$EQ11: C_p \frac{P_p D}{4t_f} + 0.75(C_m) \frac{M_a}{Z_f} \quad 9D < 2.4S_H$$

P_d:Design Pressure = 120 PSI
P_p:Peak Pressure = 40 PSI
t_f:Minimum Fitting Wall Thickness Per ANSI B16.11
Z_f:Minimum Section Modulus of Fitting = R^2TF
D: Outside Diameter of Fitting
C_p:Stress Multiplier for Pressure Stress (= 2.74) Per Reference 2
C_m:Stress Multiplier for Pressure Moment Stress (= 3.42) Using Greater Value From Reference 2 or Reference 3
S_H:1/4 (30.0 ksi) = 7.5 ksi per ASME Section III Appendix III
M_A:Resultant Moment Due to Weight
M_b:Resultant Moment Due to Earthquake and Occasional Loads
M_c:Range of Resultant Moments Due to Thermal Expansion

2.3.3 Analysis and Results

The original ASME Section III analysis was reviewed and stress values compared to allowable values for the original material. These results are shown in Figure 2.5. The stress ratios presented in the Figure 2.5 illustrate the fraction of the total allowable stress that exists in each fitting under the design conditions of sustained plus secondary loads.

It can be seen from these data that there are significant margins existing in the original design. The highest stress in the ECW small bore piping is about 77 percent of the code allowable stress. It can be seen from Figure 2.5 that in all cases these stress ratios show adequate stress margins.

An alternative design criteria was established with which to compare the calculation results of equations 9 and 11. In this case the allowable stress was based on the average ultimate tensile strength of 100 percent dealloyed material. This valve is 30 ksi. Consistent with ASME Section III Appendix III, a value for S_H was established as one quarter of this value or 7.5 ksi. The stress allowables for equation 9, using ASME III Sections NC 3600 are 1.2 S_H or 9 ksi and for equation 11 the value is 18.75 ksi. Re-analyzing the system with this design basis gives the results shown in Table 2.4 and Figure 2.4. In this table and figure the calculated stress values have been compared to the average ultimate tensile strength as defined by tests. Again it may be seen from Table 2.4 and Figure 2.4 that in all cases significant margins exist between the sustained plus secondary loads and the available material tensile properties.

2.3.4 Conclusions

Based on the margins that exist in the original design condition, the reevaluation of stresses using fitting section properties and tensile properties from dealloyed material tests, all fittings are acceptable from the stress point of view. This is the case even when the worst case Stress Intensification Factors (SIF) values for fittings are used from the published literature. This result stems from the initial design margins illustrated in Figure 2.5, the effect of the increased section properties of the fitting (as compared to the pipe properties that were used in the original design analysis) and the low operating pressures at the ECW system.

2.4 Fracture Mechanics Integrity Analysis

2.4.1 Introduction

The ASME Code design rules for piping provide margins against failure for loading conditions encountered during normal service as well as postulated conditions such as seismic loads and abnormal events. In assessing the structural integrity of partially dealloyed aluminum bronze piping components, a conservative evaluation has been performed to assure that adequate margins still remain. This was accomplished by evaluating the condition where the dealloyed region is assumed to have lost its load carrying capacity and will behave like a crack-like flaw. Under these conditions, flaw evaluation procedures similar to Section XI of the ASME Code have been applied.

Unlike some carbon steels and low alloy steels, aluminum bronze is inherently ductile and tough. This stems from its crystal structure which is like that of Type 304 stainless steel. Thus, the fracture resistance of aluminum bronze is expected to be high and the affected fittings will be relatively insensitive to material flaws such as cracks.

2.4.2 Linear Elastic Fracture Mechanics

Although aluminum bronze is not expected to behave in a non-ductile manner, linear elastic fracture mechanics techniques (LEFM) were used to establish the load carrying capacity of partially dealloyed fittings when the dealloyed region is treated as a crack-like flaw. When LEFM principles are applied, the flaw tolerance of the component can be quantified in terms of applied stress, flaw size and shape, and the fracture toughness of the material. By defining any two of these parameters, the third parameter can be quantified by fracture mechanics relationships. Selection of conservative values for fracture toughness, and a conservative representation of the size and extent of dealloying as a flaw, will give a conservative determination of the structural capacity for a partially dealloyed fitting. In terms of LEFM, crack instability (or propagation) is predicted if the following condition is satisfied:

$$K_I \geq K_{Ic}$$

where K_I = applied stress intensity factor (a function of stress and flaw and part geometry)

and K_{Ic} = critical stress intensity factor (or fracture toughness)

K_{Ic} is a material property which can be determined through testing, like a yield strength in a tensile test. In this case, K_{Ic} data or any other toughness data (such as Charpy V-notch impact properties) for aluminum bronze are not readily available. However, based on test data of aluminum bronze welds in 10- and 30-inch diameter cooling lines given in Reference 4, it is estimated that K_{Ic} for aluminum bronze is in the 150 - 200 ksi$\sqrt{in}$ range. The cast product form has somewhat lower toughness. It is conservatively estimated that the lower bound toughness is 65 ksi$\sqrt{in}$. based on discussions with several sources.

K_I can be expressed, in simplified terms, as follows:

$$K_I = \sigma F \sqrt{\pi a}$$

where σ = nominal stress
a = crack size
F = functional relationship that accounts for flaw shape, body geometry and type of loading.

The relationship between critical bending stress and dealloyed area was determined for the case of two limiting conditions: a complete 360 degrees circumferential dealloyed region originating from the inside surface, and a through-wall dealloyed region extending part way around the circumference. In directly applying LEFM to these conditions, the dealloyed regions were conservatively modelled as flaws, debonded and without any load carrying capacity. The methods contained in Reference 5 and 6 were used to establish the stress intensity factors for these flaw geometries. The capacity of the remaining uncracked section for the two limiting cases is shown in Figure 2.1 as a function of the extent of dealloying (cracked cross-section) and two lower bound estimates of fracture toughness. Even for the lowest value of K_{Ic} assumed (i.e. 65 ksi $\sqrt{in}$), significant load-carrying capacity remains for through-wall flaws exceeding 50% of the circumference or 4.6 inches in surface flaw length.

For the summary stresses given in Table 2.3, the computed through-wall flaw lengths that can be tolerated in the system are as follows:

Nominal Pipe Size (inch)	Socket		Tolerable Size	
	Diam.	Circumference	Percent	Degrees
1	1.75	5.50	>65	>234
2	2.75	8.64	59	212

It is reasonable to assume, given the conservative nature of the LEFM evaluation assumptions, that non-ductile failure of partially dealloyed material is not an issue of concern. It is therefore concluded that adequate toughness exists to prevent fracture of ECW system fittings and plastic collapse is the governing failure mode.

2.4.3 Limit Load Analysis

Because sufficient fracture resistance exists in partially dealloyed fittings to allow for utilization of the inherent tensile strength margins in the ECW system design, the structural integrity for a net-section plastic collapse failure mode was evaluated. The two previous limiting cases of part-through and through-wall partially dealloying were again analyzed by assuming no load carrying capacity of fully-dealloyed regions. The bending stress for net-section plastic collapse was established from Reference 7. Reference 7 provides the technical basis for the flaw evaluation procedures of Paragraph IWB-3640 and Appendix C for austenitic piping given in Section XI of the ASME Code.

For a material flow stress defined as the average of the specified minimum yield strength and ultimate tensile strength for the lowest strength alloy, the tolerable levels of part-through dealloying uniformly distributed around the circumference are shown in Figure 2.2. Ample bending capacity is observed up to dealloy depths in excess of 80 percent even when the residual strength of 100 percent dealloyed material has been neglected. When the strength of dealloyed material is used, the bending load capacity of the fitting is computed to be approximately five times the worst case design loads. This is shown by the horizontal line in Figure 2.2.

The through-wall dealloyed model, as shown in Figure 2.3, gives a lower prediction of bending stresses to cause plastic collapse than the 360 degree part-through model; however, significant margins are still calculated for through-wall dealloying extending 180 degree around the circumference. Again, because the strength of the fully dealloyed material is significant, the available bending load capacity will be greater than these conservative calculations and will not fall below the case of the fully dealloyed condition (See again Figure 2.3).

2.4.4 Summary

Based on LEFM analysis under the conservative assumption that dealloyed regions are debonded and will behave as cracks, very large amounts of dealloying can be tolerated in small bore fittings without a concern for non-ductile failure. Similarly, on a plastic collapse basis there is adequate strength even in the fully dealloyed condition to support the intended design loads with sufficient safety margins. It is reasonable to conclude that, based on the above analyses, the components will have significant integrity and margin against failure, for the design loading conditions.

2.5 Proof Tests

A leaking coupling, a leaking tee and a non-leaking elbow were selected for tests to failure. Steel plates were welded onto the open ends and then they were subjected to increasing water pressure. The two leakers failed by leaking faster than the pump (200 cubic cm/minute) could keep up with it rather than by breaking. The non-leaker failed by the end plate blowing off. The pressure to cause failure was as follows:

Item	Condition	Percent of Cross Section Dealloyed at Area of Maximum Attack Area (percent)	Failure Pressure (psi)
Coupling	Leaker	38	8950
Tee	Leaker	52	5900
Elbow	Non-Leaker	0	6500

The failure of the tee was at the weld we made to seal the casting. The welder noticed the casting material was difficult to weld (presumably because it was dealloyed at that point) and indicated he felt it would fail at that closure. Therefore, we feel the coupling failure where the closure welds were made on wrought pipe is most representative of the pressure carrying capacity of the leaking dealloyed Al-bronze. For a pressure of 8950 psi in the 3.03 diameter coupling, the stress in the 0.255 inch wall to cause failure is 49.54 ksi. This is three times the design stress of 15.7 ksi. A conservative reference burst pressure was calculated by the following equation from Reference 8:

$$P_B = \sigma_u' \quad F_{cyl} \quad \ln W$$

The calculated burst pressure was 6800 psi. Therefore, the "proof" strength of the coupling exceeded the reference burst strength of a sound casting.

2.6 Dealloying Rate Studies

The dealloying rates reported by Upton in reference 9 are as follows:

Heat Treatment	Twelve month tests Maximum Corrosion Rate (mpy)
Water quenched	0.02 - general 0.03 in crevices
As-received bar stock	0.03 general 0.15 in crevices
Furnace cooled	2.0 mpy

Ferrara and Caton report in reference 10 a maximum dealloying rate of 30 mpy after one year and 22.5 mpy after two years. Both Upton's and Ferrara's results are lower than the 44 mpy average and 83 mpy maximum estimated at STP. The maximum rates are based on the assumption that dealloying occurred in 3 years to 100 percent of the wall and the average rate assumes 50 percent. The STP socket data are plotted in Figure 2.6 based on the commonly used expression for corrosion rate:

$$V = K_1 t^{-K_2}$$

where V = corrosion rate in mpy
K_2 = 1/2
K_1 experimentally determined = 1.36×10^4 for STP sockets

t = time in hours

The data from Ferrara and Caton and from Upton were used to validate the form of the equation.

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REFERENCES

1) ASME Boiler and Pressure Vessel Code Section III 1974 with Winter, 1975 Addenda

2) "Stress indices for girth welded joints, including radial weld shrinkage, mismatch and tapered-wall transitions". NUREG/CR-371 (ORNL/SUB-2913) by E. C. Rodabaugh and S. E. Moore.

3) "Stress indices for ANSI Standard B16.11 socket-welding fittings". ORNL-TM-4929 by E. C. Rodabaugh and S. E. Moore.

4) "Structural Integrity Analysis for Essential Cooling Water Lines", July 1983 by G. R. Egan and S. R. Paterson.

5) "Elastic-Plastic Fracture Analysis of Through-wall and Surface Flaws in Cylinder" EPRI Report NO-5596 January 1988 by V. Kumar and M. D. German.

6) "Evaluation of Flaws in Carbon Steel Piping", EPRI RP 1757-65, Draft Final Report, March 1988.

7) "Evaluation of Flaws in Austenitic Steel Piping", EPRI Report NP-4690-SR (April 1986)

8) C. P. Royer and S. T. Rolfe, Effect of Strain-Hardening Exponent and Strain Concentrations on the Bursting Behavior of Pressure Vessels, ASME Paper 74-MAT-1 (1974).

9) B. Upton, Corrosion (June 1963) 204t.

10) R.J. Ferrara and T.F. Caton, Materials Performance (February 1982)

Table 2.1

Statistical Sampling of ECW System Fittings

Valves		Percent of Cross-Section Area Lost to Dealloying: Leakers	Non-Leakers
EW102	A	43	
	B	47	
EW103	A	24	
	B		0
EW104	A	54	
	B		10
EW105	A	30	
	B		10
EW335	A		14
	B	37	
EW337	A	59	
	B		21
EW338	A		10
	B		22
EW369	A	24	
	B		3
EW116	A	9	
	B		6
EW126	A	52	
	B	82	
EW415	A	8	
	B		29
EW323	A	54	
	B		13
EW235	A		46
	B		12
EW031	A	35	
	B		37
EW332	A		5
	B		17
EW214	A	88	
	B		20
EW115	A	59	
	B		38
EW017	A	67	
	B		18
EW114	A		0
	B		0
EW351	A		1
	B		11
EW215	A	68	
	B		3
A8	A		0
	B		0
DA5	A	80	
	B		19

Table 2.1 (continued)

Statistical Sampling of ECW System Socket Ends

		Percent of Cross-Section Area Lost to Dealloying	
		Leakers	Non-Leakers
Valves (continued)			
102	A		19
	B		36
MA13	A	57	
	B	44	
A2	A	62	
	B		64
L0582	A		29
	B		28
Tees			
T337	A		0
	B		0
	C		0
T338	A		47
	B		37
	C		32
Burst	A		52
Test	B		38
	C		48
Couplings			
C-6	A	38	
MA12	A	50	
Total Sampled		24	41
Mean Percent Dealloyed		48.79	19.39
Standard Deviation		21.02	17.39

Table 2.2

Design and Operational Data for the Aluminum Bronze Cooling Water Piping

(1)	Materials:	Pipe and Couplings	CA61400 (SB 169 or 150)
		Valve bodies	CA95200 (BA 148 or 271)
(2)	Pipe size:	2-inch NPS and smaller, Schedule 40	
(3)	Temperatures:	150°F maximum design; 160°F operating	
(4)	Pressure:	120 psi maximum design; 41 psi operating	
(5)	Fluid:	Brackish Water	
(6)	Design Code:	ASME Section III, Class 3	

TABLE 2.3

SUMMARY OF FITTING DIMENSIONS AND HIGHEST STRESS LEVELS

NOMINAL FITTING SIZE (IN)	DESIGN PRESSURE (PSIG)	OPERATING PRESSURE (PSIG)	DIMENSIONS Do (IN)	DIMENSIONS t (IN)	FITTING STRESSES* (ksi) Pm	Pb	Pe
1/2	120	40	1.223	0.184	0.20	0.72	--
1	120	40	1.778	0.224	0.24	4.27	1.16
1-1/2	120	40	2.415	0.250	0.29	1.96	2.11
2	120	40	2.952	0.273	0.32	4.26	1.81

*NOTE: Fitting stresses listed are the highest (worst case) stresses calculated without distinction among service level (i.e., normal, upset, emergency or faulted). The stresses are summarized in categories of primary membrane (Pm), primary bending (Pb), and thermal expansion (Pe) with SIFs removed (i.e. unconcentrated) to be consistent with evaluation definitions of IWB-3640 and proposed IWB-3650.

TABLE 2.4

STRESS EVALUATION

FITTING SIZES	TOTAL NUMBER OF FITTINGS	TOTAL NUMBER OF FITTINGS MEET ALLOWABLES **	STRESS RATIO: $\frac{\text{MAX STRESS}}{\text{30 KSI}}$
½"	13 *	13 *	EQ.9 .074 EQ.11 .039
1"	56	56	EQ.9 .289 EQ.11 .192
1-1/2"	60	60	EQ.9 .181 EQ.11 .283
2"	154	154	EQ.9 .326 EQ.11 .276
TOTAL	283	283	

NOTES:

1. * ONE OF THESE FITTINGS IS ¼"
2. ** S_H = ¼ (30 KSI)
3. EQUATION 9 ALLOWABLE IS 1.2 S_H
4. EQUATION 11 ALLOWABLE IS (S_A + S_H)
   S_A = (1.25S_C + 0.25S_H)
5. TOTAL NUMBER OF FITTINGS ABOVE REPRESENTS STRESS DATA POINTS EXCLUDING THOSE FITTINGS AND VALVES REPLACED AND/OR DELETED

NRCS29.DGN

Figure 2.1 Bending Stress Capacity for Dealloyed 2 - inch Fittings Based on LEFM

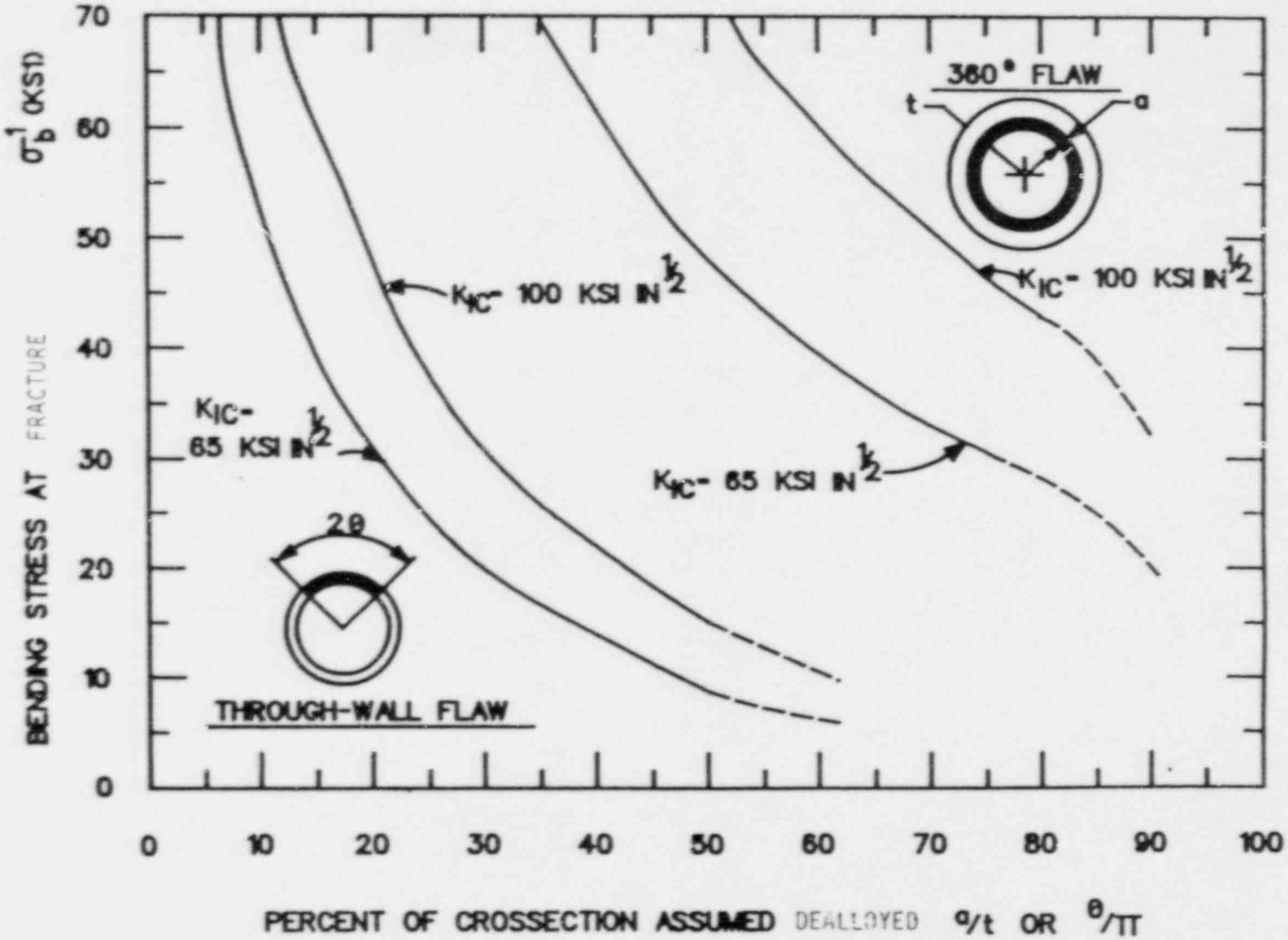


Figure 2.2 Conditions for Net-Section Plastic Collapse for 360 Degree Part-Through Dealloying

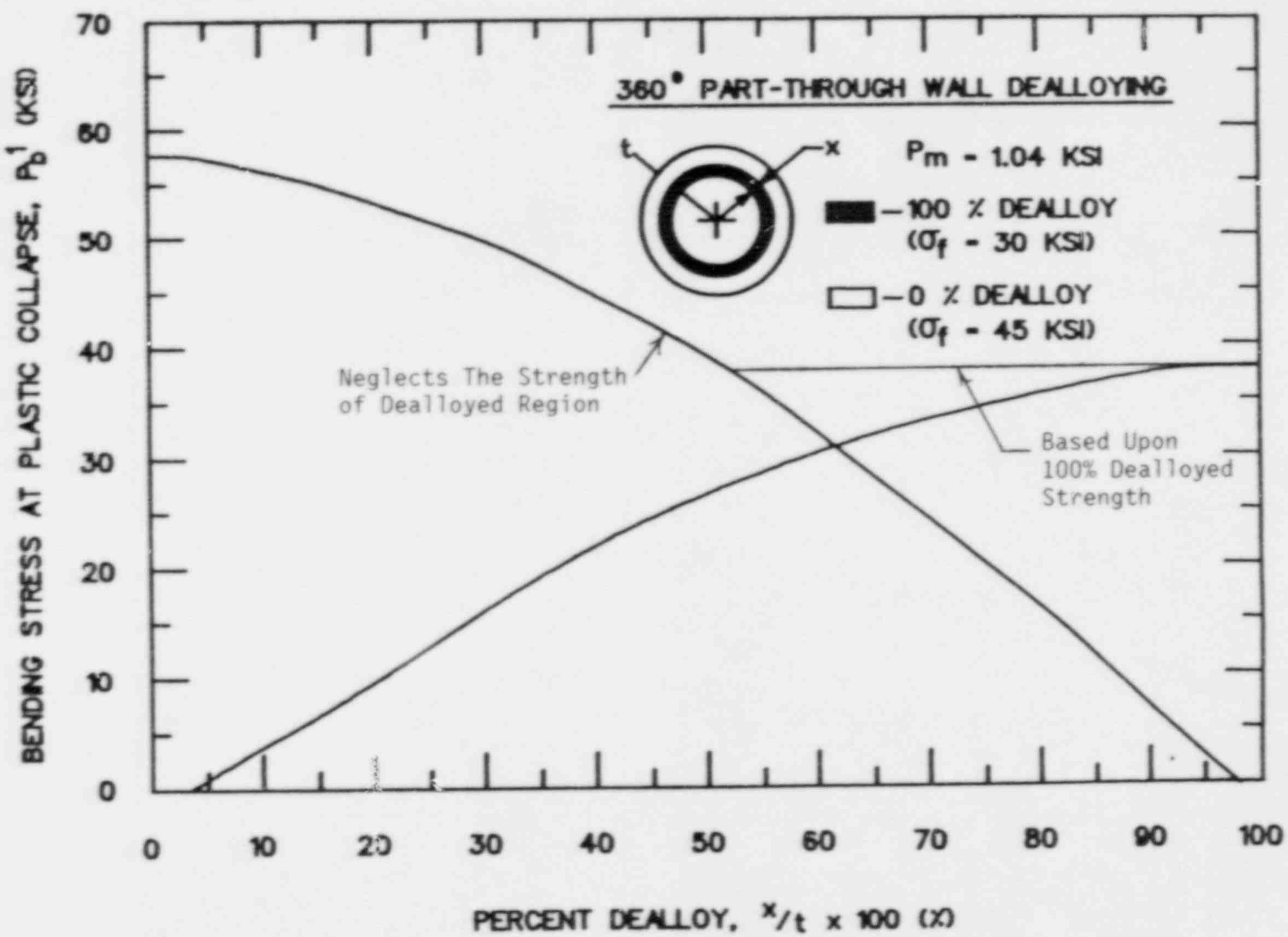


Figure 2.3 Conditions for Net-Section Plastic Collapse for Through-Wall Dealloying

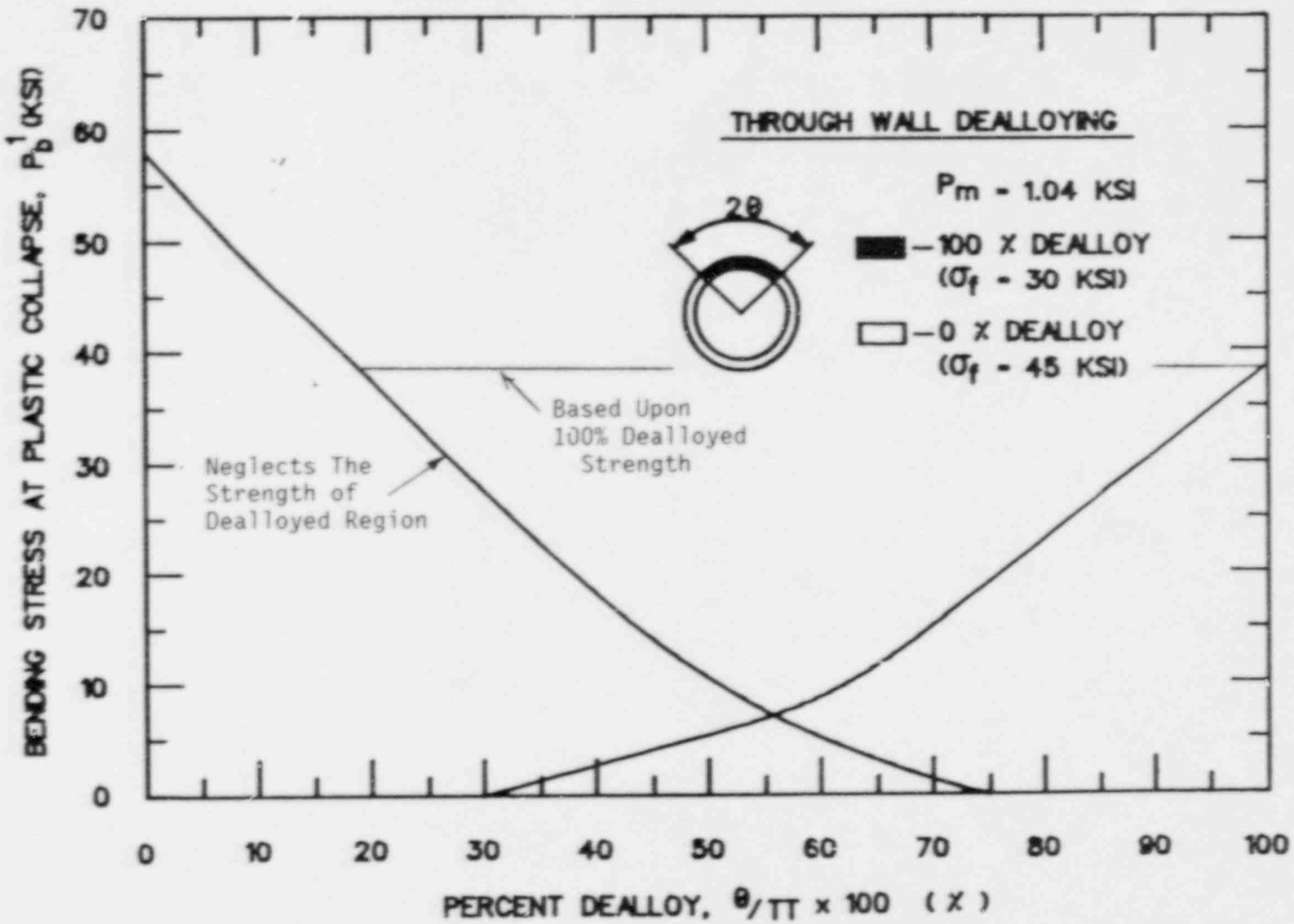


FIGURE 2.4

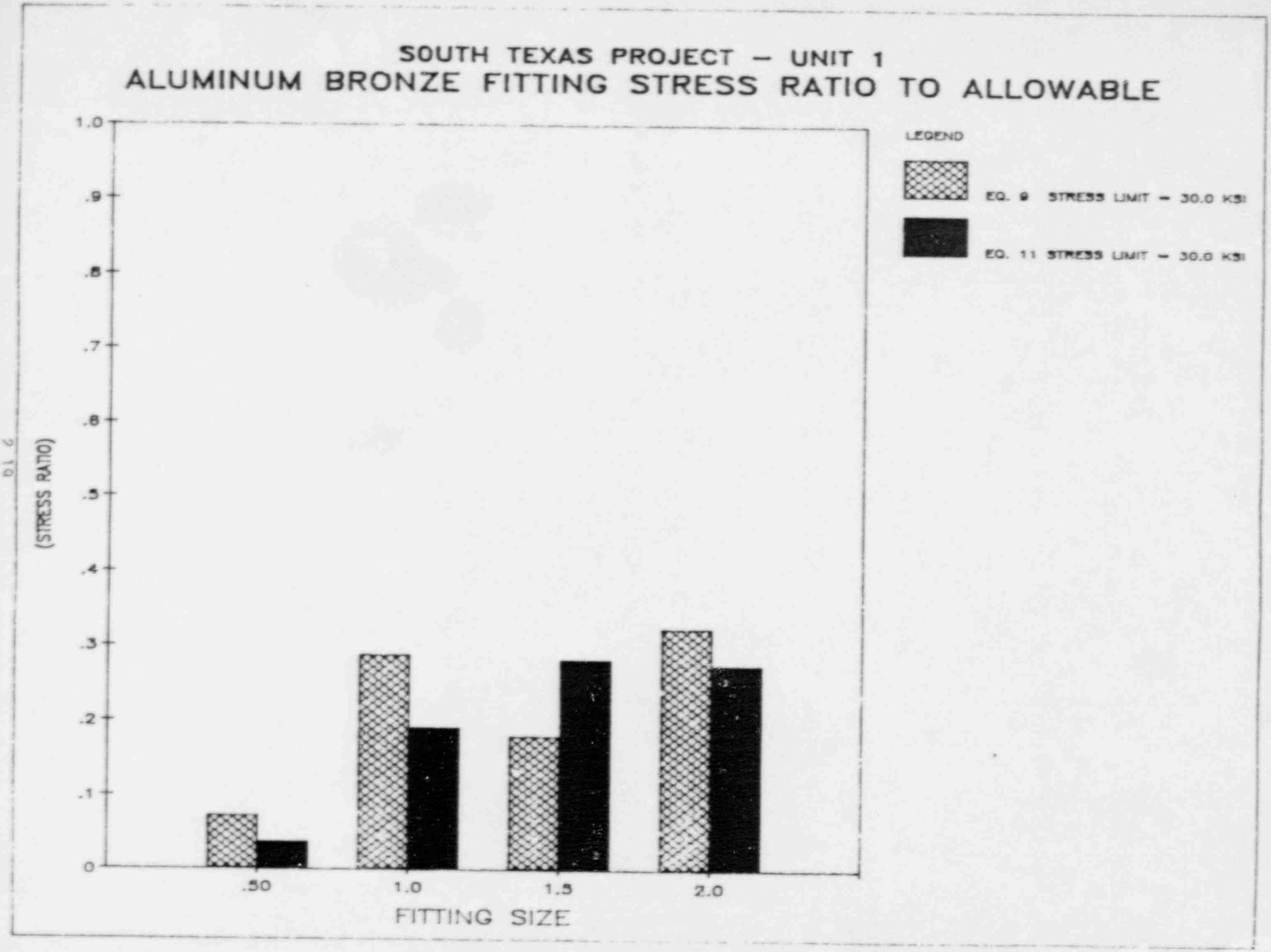
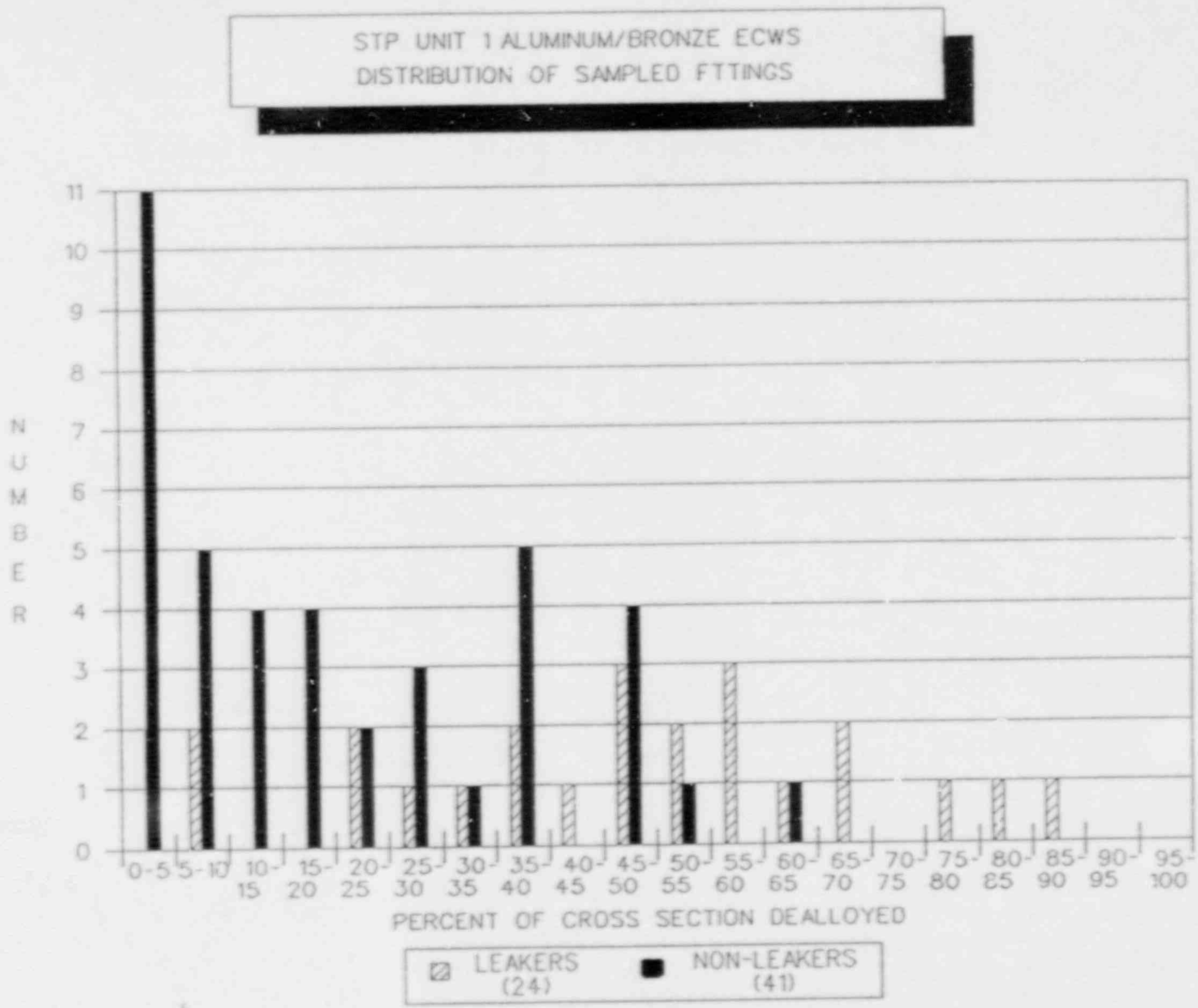

SOUTH TEXAS PROJECT – UNIT 1
ALUMINUM BRONZE FITTING STRESS RATIO TO ALLOWABLE
LEGEND
EQ. 9 STRESS LIMIT – 30.0 KSI
EQ. 11 STRESS LIMIT – 30.0 KSI
(STRESS RATIO)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
.50
1.0
1.5
2.0
FITTING SIZE

FIGURE 2.5



STP UNIT 1 ALUMINUM/BRONZE ECWS
DISTRIBUTION OF SAMPLED FTTINGS
NUMBER
0
1
2
3
4
5
6
7
8
9
10
11
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-55
55-60
60-65
65-70
70-75
75-80
80-85
85-90
90-95
95-100
PERCENT OF CROSS SECTION DEALLOYED
LEAKERS (24)
NON-LEAKERS (41)

Figure 2.6

DEALLOYING OF LEAKING ALUMINUM BRONZE SOCKETS