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U. S. Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, DC 20555

South Texas Project Electric Generating Station
Units 1 and 2
Docket Nos. STN 50-498 and 499
Microbiological Influenced Corrosion in Unit 2
Standby Diesel Generator Jacket Water Cooling System

This letter documents discussions between the NRC (E. Tomlinson) and HL&P (J. Bailey) concerning the discovery of Microbiologically Influenced Corrosion (MIC) in the jacket water cooling systems (JWCS) of the Unit 2 standby diesel generators.

In Unit 2, corroded conditions were found in the JWCS during initial startup of the diesels. This piping was replaced as necessary, acid flushed and treated to prevent further corrosion. Expansion seals, which are used as a secondary seal to prevent JWCS fluid from entering the diesel lube oil sump, were later found to be damaged. Other damaged seals, identified using a pressure test, are in the process of being replaced.

An evaluation was performed (attached) which considered the storage history, material conditions, and system leakage detection capability. The evaluation also includes an analytical review of damaged expansion seals which were removed from the diesels.

In summary, the evaluation concluded that the presence of MIC was a result of the storage conditions of the Unit 2 diesels. With replacement of the identified leaking expansion seals in Unit 2, the existing seals, as well as the replacement seals, will serve their intended function. Further failures if experienced would be minor and would be detectable by normal surveillance tests in advance of diesel engine performance impact.

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In Unit 1, although identical storage records exist, no signs of excessive corrosion as seen on Unit 2 have been observed. Inspections conducted to date have identified no failures. Analytically, it has been shown that expansion seal failures are unlikely even if MIC is present. Therefore, no further actions are planned for the Unit 1 diesel generators.

If there are any questions, please contact Mr. J. N. Bailey (512) 972-8663.

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Attachment: Evaluation of Unit 2 Diesel Generator MIC cc:

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Attachment

Evaluation of Unit 2 Diesel Generator MIC

STATEMENT OF CONDITIONS ON UNIT 2

During prerequisite testing of ESF Diesel Generator No. 21, leaks were discovered in cylinder liner expansion seals on cylinders 10R, 5R, 2L, 3L and 4L. The expansion seal on 10R had a 1/4" hole and the expansion seals on 5R, 2L, 3L and 4L had pin holes.

These seals are designed to allow the cylinder liners to expand and contract while acting as the jacket water pressure boundary secondary seal between the cylinder liners and cylinder block. The primary seal is the metal to metal contact of the liner to the engine block. The exterior of the liner is plated with tin prior to being installed to assure a tight "forced" fit. Some leakage may occur into the expansion seal area especially during the standby mode.

The expansion seals on cylinders 10R and 10L were removed and shipped to the Bechtel Material Laboratory for analysis. Both seals exhibited evidence of Microbiologically Influenced Corrosion (MIC) and transgranular stress corrosion cracking. See attached report and photographs in Appendix 3, "Failure Analysis of Diesel Cylinder Liner Expansion Bellows."

A pressure test at 35 psig was performed on the expansion seals to identify any other deficiences. The pressure test on Diesel No. 21 seal bellows identified deficiences to seal bellows on cylinders 1R and 8R. Diesel No. 21 had a total of seven (7) deficient seals. Installation of new seals was completed by April 29, 1988 for all cylinders.

The pressure test on Diesel No. 23 expansion seals revealed that cylinder 3L had a pin hole in the expandable metal portion of the seal and that 4L had seepage from the weld area close to the seal upper flange. Both seals have been replaced.

No leaks were found on Diesel No. 22.

STORAGE HISTORY

All six diesel generators were fabricated in 1979. Prior to storage the cooling systems were flushed with a mixture of 50% glycol, 45% water, and 5% rust inhibitor. Five were stored outside, on rail cars, at the factory in Pennsylvania. Engine No. 7196 was stored elsewhere following testing, in an environmentally controlled warehouse and shipped directly to site.

The standby diesel generators installed in Unit 1 were shipped to the site over the period November 1981 through August 1983. See Appendix 1, "Standby Diesel Generators Storage and Shipment History." These engines were the last three manufactured.

s/WGW/b

While at the site, prior to installation in the DGB, the Unit 1 diesels were stored in accordance with ANSI N45.2.2, Level B storage (in an enclosed area with dry warm air) until installation in the Diesel Generator Building (DGB) in early 1984.

In 1983, the three Unit 2 diesels were inspected at the factory and were found to show evidence of external rusting and other deterioration. Consequently they were refurbished at the factory to correct any problems created due to the extended storage period. After refurbishment, the cooling systems were flushed with a mixture of 50% glycol, 45% water and 5% rust inhibitor and drained. The Unit 2 diesels were shipped to the site in 1984 and installed in Unit 2 in April of 1986. While at the site, prior to installation in the DGB, those diesels were also stored in accordance with ANSI N45.2.2, Level B Storage requirements.

MATERIAL CONDITIONS

The Unit 1 diesels were prepared for operation in the Summer of 1986. At that time, rust colored water was found in the jacket water coolant system, but the system exhibited no signs of deleterious corrosion. A velocity flush using water was used to clean the lines and the system.

The Unit 1 jacket water systems were filled and inspected prior to starting the diesels with no evidence of leakage at the expansion seals found.

While preparing the Unit 2 diesels for testing, their jacket water systems were found to contain severe corrosion damage. While a velocity flush was sufficient to remove the minimal rusting found in the Unit 1 cooling systems, Unit 2 required replacement of piping and an acid flush, prior to release for testing. On the Unit 2 expansion seals leakage was noted at the first filling of the jacket water system after the acid flush was completed.

STORAGE & MATERIAL CONDITION CONCLUSION

Although HL&P has been unable to determine the factor resulting in the difference, the Unit 2 diesels (but not the Unit 1 diesels) required corrective action due to corrosion both at the factory and here on site. Two of the Unit 2 engines required an acid flush at the factory prior to shipment. All three required replacement of jacket water piping and acid cleaning of the jacket water system on site. A review of Cooper-Bessemer data has not revealed any differences to account for the additional corrosion problems.

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MIC CONTROL

MIC control is an ongoing site program. Various procedures are in use which have been proven to be effective in MIC control. Due to the evidence of MIC presence, the Unit 2 jacket water systems, including the expansion seals, have been sterilized with hydrogen peroxide to kill any existing bacteria. All flush water used during startup activities has been treated to prevent MIC recontamination of the system.

During operations, Low Halogen Nitrite-Borate-Tolytriazole is added to the jacket water coolant of both units to prevent general corrosion. The high PH of this fluid, >10, will prevent growth of MIC. The nitrite in the corrosion inhibitor will reduce the tendency for stress corrosion cracking by reducing the oxygen content and creating nitrate. The deaeration mechanism is nitrite reacting with oxygen to form nitrate. The nitrate formed is also an inhibitor of stress corrosion cracking.

MEANS OF DETECTING LEAKAGE

VISUAL TESTS:

The Unit 1 expansion seals have been inspected, along with the rest of the diesel components, during the testing phase. This includes the velocity flush of the jacket water system, start and stop tests of the engine, and a 100 hour run performed on each diesel. No leakage has been noted during any of these inspections.

In comparison, leakage was identified in two of the Unit 2 expansion seals during the initial fill operations.

OIL ANALYSIS:

The diesels are test run periodically, at a minimum of once a month. Lube oil samples are taken during the monthly test run. The lube oil pump provides sufficient mixing of the oil to entrain any water contamination with a complete volume change approximately every 3 1/2 minutes. The minimum detectable concentration in the sample, as analyzed, is 0.05% water in the oil, corresponding to a total water volume of approximately 1.05 gallons. No evidence of water contamination of the oil has been found in the Unit 1 machines.

s/WGW/b

Should leakage of the cooling system fluid into the oil reservoir occur, the monthly sample of the lube oil system provides a positive method of identifying that fact. With the detectable concentration of 0.05% and per Cooper-Bessemer, an allowable contamination of 1% (21 gallons) water in the oil, sufficient tolerance exists to recognize leakage prior to impacting the operability of the diesel units.

The absence of water in the Unit 1 oil samples indicates that there is no leakage of water into the crank case. Therefore, there has been no through wall damage due to MIC in the Unit 1 diesel expansion bellows.

SUMP INDICATORS:

Seal bellows leakage is one of several leakage paths for cooling water to the lube oil. The following is a tabulation of lube oil capacities and set points.

Lube Oil Sump and System Capacity = 2,100 Gal.
Operating Level of Sump = 1,300 Gal.
Remainder of System Oil = 800 Gal.

1. Capacity Per Inch Basis:
    - (a) High Oil Level Alarm = 65.2 Gal/In. of Depth
    - (b) Normal Oper. Level = 66.1 Gal/In. of Depth
    - (c) Low Oil Level Alarm = 67.3 Gal/In. of Depth
2. Distance From the Crankshaft to Alarm Settings:
    - (a) High Oil Level Alarm = 22 5/8"
    - (b) Normal Oil Level = 24 5/8"
    - (c) Low Oil Level Alarm = 26 5/8"
3. Difference In Liquid Level By Gallons To Trip/Alarm:
    - (a) High Level = Average of 65.65 Gal. x 2 = 131.3 Gal. Addition
    - (b) Low Level = Average of 66.70 Gal. x 2 = 133.4 Gal. Loss

As shown above, the lubricating oil sump level alarms will provide only indications of gross fluid additions or losses from the sump.

JACKET WATER COOLING SYSTEM STANDPIPE INDICATIONS:

The jacket water cooling system level is measured on a standpipe. A discussion of the operating and standby modes is provided below.

s/WGW/b

The normal evaporation rate of the jacket water coolant, during the running condition of 170°F, is approximately 0.3 gph or 0.426 in/hr in the sight glass. During the coolant temperature rise of 50°F, from 120°F (standby temperature) to 170°F (operating temperature), the water level in the standpipe will rise 6.75" due to thermal growth. Because of this level increase, a low level alarm would not occur until 27 gallons of inventory has been lost during engine operation. The design of the interference fit between the cylinder liner and the engine block is such that little, if any, leakage would occur in the operating mode.

In the standby mode a coolant loss of approximately 15 gallons would cause a local alarm (JACKET WATER STANDPIPE OFF NORMAL) and a remote alarm (ESF DIESEL GENERATOR TROUBLE) to sound in the Control Room. These alarms provide adequate leak detection while in the standby mode.

CONCLUSIONS REGARDING LEAK DETECTION

MIC has not been observed in the Unit 1 diesels during testing. Additionally, lube oil samples to date have shown no trend to indicate increasing leakage. Adequate systems exist, i.e. the lube oil sump level and jacket water cooling standpipe level, to alarm a catastrophic introduction of water into the crankcase or a significant loss of jacket water cooling system fluid. Therefore, continued operation of the Unit 1 diesels is justified.

ANALYTICAL REVIEW

Two expansion seals were removed from the Unit 2, Diesel No. 21 and sent for evaluation. One of the seals had already been observed to leak. The other was removed from the opposite side of the engine but was not leaking. (It was removed because of the accessibility due to the removal of the leaking seal on the opposite side). A combination of MIC pitting and corrosion cracking was observed in the leaking seal while the other seal had evidence of the bacteria but no pitting or cracking. The acceptability of the remaining expansion seals was evaluated on the basis of design parameters provided by the diesel supplier and expansion seal manufacturer, and observations taken from the seals discussed above.

The analytical review performed using fracture mechanics has shown that:

1. The majority of "partially through-wall" cracks, if they exist in the expansion seals are categorized as non-propagating and will not grow over the life of the diesels.

2. For any "partially through-wall" cracks that border on being through-wall, a leak may develop, but will be small and will not undergo any noticeable growth over the life of the diesels. Any undetected through-wall cracks will react the same and will not undergo any noticeable growth over the life of the diesels.

3. Corrosion pits, although not specifically analyzed, are bounded by the crack analysis. Consequently it can be concluded that pits will not develop into fatigue cracks during service.

A copy of the analysis is included in Appendix 2, "Effects of Corrosion Pits and Cracks on Bellows Seal Performance."

OVERALL CONCLUSIONS

UNIT 2

The failure of the expansion seals due to MIC was a result of the same factors that resulted in the poor condition of the Unit 2 jacket water cooling system components. The replacement of the deficient piping and expansion seals in conjunction with the acid cleaning and MIC Control processes have adequately resolved the corrosion effects.

The replacement of the leaking expansion seals will be performed before the unit becomes operational. The pressure test that was performed provides assurance that no grossly MIC affected areas remain in the Unit 2 diesels.

Analytically, it is not expected that there will be any further growth of already initiated pitting. If there is a failure, it will be of a very small size, thus allowing the oil sample program to trend any failures in the seals. Since the jacket water is appropriately treated, MIC and stress corrosion cracking are arrested and will have no further degrading effects on the seals. No further action will therefore be required on the Unit 2 diesel generators.

UNIT 1

Based on the improved material condition of the Unit 1 engines and the favorable inspections, it is unlikely that MIC has occurred on the Unit 1 diesel generators. The stress and material analysis done for Unit 2 has shown that even if MIC has occurred, it is unlikely that new leaks will develop. If they do, they will be small and growth will be limited. If any leakage occurs, it will be detectable in oil samples in advance of a level damaging to the machine. Therefore, HL&P considers the condition of Unit 1 to be satisfactory with no further augmented inspection or pressure tests needed.

s/WGW/b

Appendix 1

Standy Diesel Generators Storage
and
Shipment History

APPENDIX 1

STANDBY DIESEL GENERATORS STORAGE AND SHIPMENT HISTORY

Unit No.	TPNS	Motor Sr. No.	Date Fab.	Factory Refurb.	Date To Site	Date Rec'd	Date Installed	On Site J. W. Flush
1	3Q151MDG0134	7195	10/79	NA	8/83	9/83	4/84	7/86 - 1/87
1	3Q151MDG0234	7196	11/79	NA	11/81	12/81	2/84	6/86 - 3/87
1	3Q151MDG0334	7197	12/79	NA	3/82	4/82	3/84	8/86 - 11/86
2	3Q152MDG0134	7192	3/79	7/83	4/84	5/84	4/86	Pending
2	3Q152MDG0234	7193	4/79	9/83	5/84	5/84	4/86	12/87
2	3Q152MDG0334	7194	5/79	8/83	10/84	11/84	4/86	1/88 - 2/88

Storage of diesel engines prior to shipment to site as follows:

Motor serial number 7192 stored at point of fabrication.
Motor serial number 7193 stored at point of fabrication.
Motor serial number 7194 stored at point of fabrication.
Motor serial number 7195 stored at point of fabrication.
Motor serial number 7196 shipped to New York for testing and storage.
Motor serial number 7197 stored at point of fabrication.

Storage at point of fabrication outdoors on rail cars.

When received onsite, each diesel was stored in an enclosure in accordance with ANSI N45.2.2 Level B Storage requirements,(warm dry air) until they were installed in the buildings.

s/WGW/b

Appendix 2

Effects of Corrosion Pits and Cracks
on
Bellows Seal Performance

Bechtel National, Inc.
Engineers—Constructors

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San Francisco, California
Mail Address: P.O Box 3965, San Francisco, CA 94119

STP File No. M10.05.02.02

To: R. L. Randels

File No. YC-048-01

Subject: Effects of Corrosion Pits and Cracks on Bellows Seal Performance
Bechtel Job 14926-001, STP PAC 01C

Date: April 4, 1988

From: Y. Chung

Of: R&D/Materials & Quality Services

At: 50/15/B5 Ext. 8-1489

Copies: R. A. Manley/F. C. Breismeister
T. T. Phillips
R. W. Straiton
R. A. White
DCC 0241177

Reference: Letter from Y. Chung to R. L. Randels, March 1, 1988 (BLN 8802-04)

The letter referenced above transmitted a laboratory report, "Failure Analysis of Diesel Cylinder Liner Expansion Bellows." These bellows are used as expansion seals in emergency diesel generators. The report contains the results of examination of two 16-inch Type 321 stainless steel bellows by Bechtel's M&QS. It concluded that the bellows failed (leaked) due to pitting corrosion and stress corrosion cracking, which was influenced by iron bacteria (Gallionella). This is commonly referred to as MIC (microbiologically influenced corrosion).

Figure 1 shows a sectional view of the bellows seal (item 10), which is secured to both the cylinder block and the liner by flanges. One of the two bellows examined by M&QS is shown in Figure 2. The design data (by Flexonics) for these bellows are presented in Appendix A. Basically, it is a single-ply-single-expansion bellows with three convolutions. The nominal wall thickness is 0.02 inch. Most of its life is spent as standby, during which the bellows are pressurized with 120°F water to 10 psig. During operation, the pressure and temperature rise to 20 psig and 170°F, respectively.

One of the two bellows examined revealed corrosion pits and cracks, creating one hole about 1/2 inch in diameter and another about 1/4 inch in diameter, in and near the longitudinal seam weld. See Figure 5(a) of the failure analysis report. Except for this failure area, most cracks and pits in other areas were small, 1/16 inch or less in the convolution. One exception was a 1/4-inch long crack which straddled a through-wall corrosion pit. See Figure 7(a) of the failure analysis report.

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From: Y. Chung
Subject: Effects of Corrosion Pits and Cracks on Bellows Seal Performance
Bechtel Job 14926-001

The bellows seals in the diesel engine generators were hydrotested at 35 psig subsequent to the discovery of the above bellows failure. Several leaked in Train A, 2 in Train C, none in Train B. It is possible that some of the bellows seals that passed the hydrotest may contain corrosion pits and cracks because of MIC. Some of these pits and cracks may have penetrated the bellows wall by 50 percent or more, yet without leading to a hydrotest failure. This is because pressure boundaries with local wall thicknesses below the design minimum, for example, at the bottom of a small corrosion pit or at the tip of a small crack, can still withstand the design or test pressure. Unless a wall thinning occurs generally in a large area (e.g., 1/2 inch in diameter, or more in this case), the wall will not rupture during a hydrotest. For example, it has been shown that small pits or cracks with depths more than 80 percent through the wall will not leak or rupture during hydrostatic tests.(1)

It may be hypothesized, therefore, that the corrosion pits or cracks which have not caused leaks during a hydrotest can still cause leaks during service if they grow due to corrosion or metal fatigue. We have been asked to evaluate the effects of corrosion pits and cracks, should they exist in some of the bellows seals. We will consider potential bellows seal failures from two aspects: (1) metal fatigue, and (2) MIC.

(1) Bellows Failure Due to Metal Fatigue

Fatigue cracks occur in metal components when they are subjected to cyclic stresses (or strains). The peak stress values are much less than the tensile strength of the material in a high cycle fatigue. The bellows seal would experience a small number of relatively large stress amplitudes because of startups and shutdowns and a large number of low stress amplitudes due to vibration during operation. Figure 3 illustrates schematically the type of stress cycles that a bellows may experience. Figure 3(a) is a case where the bellows was extended by a small amount during installation in the cylinder block; the bellows can be compressed during installation. Figure 3(b) shows idealized fatigue cycles and the definitions of stress terms.

In fatigue, it is the stress range ($\Delta\sigma = \sigma_{max} - \sigma_{min}$) and associated number of cycles which governs the material life. The stress range would be the same regardless whether the bellows are extended or compressed during installation. In the bellows elements, fatigue cracks will occur, if at all, in the circumferential direction, along the convolution, rather than in the axial direction. This is because, as shown in Appendix A, the stresses in the circumferential direction are much lower than those in the meridional (axial) direction. The stress ranges due to startups and shutdowns predominate over those due to vibration.

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(1) Machine Design, April 6, 1978, pp. 192-105. (A 2-inch OD tube with a 2.2 inch long x 0.012 inch wide slot, penetrating 83.2% of a 0.316 inch thick wall, passed a 6800 psi test.)

The process of fatigue cracking consists of three stages:

- crack initiation
- crack propagation
- final fracture (or perforation of the wall in the case of bellows)

These separate stages cannot be accounted for by the classical fatigue analysis of metal components using the traditional S-N curves and Goodman diagrams. This approach relies primarily on statistical failure date of laboratory test specimens for fatigue life prediction. Since the correlation between the specimen data and the performance of actual components is poor, the S-N curve approach has not worked well in fatigue life prediction. It has been useful, however, in providing conservative estimates of the so-called fatigue strength of a material for design purposes so that fatigue failures can be avoided altogether.

In recent years, significant progress has been made in developing a more accurate analytical tool for predicting a fatigue life. Much of this work has been based on fracture mechanics. Unlike the traditional method, fracture mechanics accounts for the three stages of fatigue mentioned above (albeit incompletely as yet in some aspects). It allows for existing flaws (e.g., pits or cracks) to be evaluated quantitatively by calculating crack growth rates for given stress cycles. A basic premise of fracture mechanics is that a single parameter K (stress intensity factor) can describe the stress distribution at the crack tip. Two important aspects of fatigue cracking in fracture mechanics have been recognized, as follows.

- A threshold stress intensity factor range ($\Delta K_{threshold}$) exists below which a crack is nonpropagating regardless of the number of stress cycles imposed. This is conservatively estimated at $\Delta K = 3 \text{ ksi}\sqrt{\text{in}}$ for austenitic stainless steels.

- The rate of fatigue crack growth da/dN can be expressed in terms of a stress intensity factor range ΔK. This is commonly expressed, in simplified terms, as follows,

$$da/dN = C(\Delta K)^n, \text{ where C and n are material constants}$$

Figure 4(a) is a schematic relationship between da/dN and ΔK and Figure 4(b) a data plot of fatigue cracking for A533 steel at ambient temperature, shown here as an illustration. In general, in Region B, the crack growth follows a power-law behavior. The ASME Section XI Task Group for Piping Flaw Evaluation recommends the following equation for fatigue crack evaluation of flaws in austenitic stainless steel piping.(2) This equation will give conservative (high) estimates of fatigue crack growth rate as the code requirements are conservative.

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(2) Journal of Pressure Vessel Technology, vol. 108, August 1986, pp. 352-366.

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$da/dN = C\,E\,S\,(\Delta K)^n$

where da/dN = change in crack depth, a, per fatigue cycle, in/cycle
C, n = material constant, $n = 3.3$, $C = 2 \times 10^{-19}$ (in/cycle)/$(\text{psi}\sqrt{\text{in}})^n$
S = R ratio correction factor = $[1.0 - 0.5R^2]^{-4}$
R = K_{min}/K_{max}
E = environmental factor (equal to 1.0, 2.0, and 10.0 for air, PWR, and BWR environments, respectively)
ΔK = $K_{max} - K_{min}$, $(\text{psi}\sqrt{\text{in}})$, and
K_{min}, K_{max} = minimum and maximum values, respectively, of applied stress intensity facctor

The stress intensity factor K is related to stress σ or the stress intensity factor range ΔK to stress range $\Delta\sigma$, as follows.

$\Delta K = \Delta\sigma\sqrt{\pi a}\cdot F(a/t,\ a/c,\ b/c,\ \phi)$

where F = shape factor
t, b, c, ϕ = see Figure 5, a surface crack in a finite plate
a = crack depth (or one-half the crack length in a through-wall crack)

It can be seen that the shape factor F is influenced by many factors. Numerical values for F are readily available in the literature for a/t up to about 50 percent; for example, graphically from Figures A-3300-1, A-3300-3, and A3300-5 in ASME Code Section XI. When a crack penetrates the wall by more than 50 percent, however, the shape factor is influenced greatly by the behavior of the remaining ligament, which may behave in a nonlinear manner. Therefore, it is difficult to define ΔK at the tip of a crack which may be on the verge of breaking through the wall.

In ductile and tough materials like the bellows material (Type 321 SS), K is higher at $\phi = 90$ degrees (Figure 5) than at other angles. Thus, the aspect ratio (depth/length) of a crack tends to be high as compared with the cracks in less ductile and tough materials like carbon steel. This means that fatigue cracks in bellows seal would tend to be short (say, less than 0.1 inch in length) when they just break through the wall, leading to leak. (This does not apply to stress corrosion cracks.) Therefore, even if fatigue cracks develop at the bottom of a pit or at the bottom of a small stress corrosion crack due to stress cycles from startups and shutdowns, it will be a short crack which may "weep." No massive leaks are possible. Furthermore, it is unlikely that any of the presumed corrosion pits or stress corrosion cracks not detected by hydrotests will ever develop into fatigue cracks. This is because the following fracture mechanics calculations indicate that ΔK is either below $\Delta K_{threshold}$ or the crack growth rates are so low as to be negligible.

Table 1 shows a summary of ΔK and da/dN calculations for assumed cracks of different sizes. Sample calculations of ΔK and da/dN are presented in Appendix B. According to these results, ΔK for cracks with a depth less than 50 percent of the wall thickness for stress ranges between standby and operation are well below $\Delta K_{threshold}$ (about 3 ksi$\sqrt{in}$). Therefore, surface cracks even 1/2 inch or more in length with a depth less than 50 percent of the wall thickness will not grow no matter what the number of stress cycle is. Because of the difficulty in calculating ΔK for the cracks with a depth more than 50 percent of the wall thickness, we calculated ΔK and da/dN for through-wall cracks for comparison purposes. ΔK for a 1/8-inch long through-wall crack is only 2.6 ksi$\sqrt{in}$; thus, it will not propagate. Even a 1/2 inch long through-wall crack will grow less than 1 microinch (10^{-6} inch) per stress cycle or less than 1 mil in 1000 stress cycles.* It would seem reasonable to expect that 1/4-inch long crack with most of the wall thickness penetrated would have a crack growth rate lower than 1 mil in 1,000 stress cycles. Even with the longest crack (1/4-inch long with a corrosion pit in the middle) in the bellows seal that contained the most serious corrosion failures, the above calculations indicate that the stress cycles due to startups and shutdowns are not likely to cause the existing flaws (cracks or pits) to grow. When compared with the stress ranges (5800 psi) due to startups and shutdowns, the stresses due to vibration are so low(3) that they may be ignored from fatigue consideration.

Corrosion pits are not as sharp as cracks. As the above calculations show that even cracks will not grow due to fatigue, no corrosion pits in the bellows seal will develop fatigue cracks during service.

<u>(2) MIC Control</u>

The water for the bellows seal has been treated with a high dose of hydrogen peroxide as biocide. This is complemented by adding triazole, sodium borate and sodium nitrite, and the water pH adjusted to 10 to 10.3 using sodium hydroxide. The high dose hydrogen peroxide treatment has been shown to be effective in eradicating bacteria. Even if they survive under some protected crevices, MIC becomes inactive in high pH environments. Therefore, recurrence of MIC in the bellows during standby and operation is not expected.

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*The emergency diesel generators may be started up and shut down once a month. Thus, 1000 stress cycles is conservative for a 40-year life.

(3) The vibrational stresses are estimated to be 100 psi (Telecon between R. Randels of Bechtel and R. Miklos of Cooper, 3/28/88).

There is an extensive amount of literature reporting that high pH reduces the tendency of austenitic stainless steels to chloride stress corrosion crack. For example, Theus and Staehle(4) show an increase in time to failure at 200°C as the pH increases from 1 to 13. Sedriks(5) gives the most definitive data. Figure 6 (attached) shows the effect of pH, chloride ion content and temperature on both stress corrosion cracking and pitting. Uhlig and Revic,(6) in addition to mentioning the beneficial effects of alkalinity, also state that eliminating oxygen and addition of certain inhibitors, e.g., nitrates, reduces stress corrosion cracking of austenitic stainless steels. Theus and Staehle(4) also show the beneficial effects of reducing oxygen.

Since nitrite is added as an oxygen scavenger, it will have two beneficial effects. First, it will reduce the tendency for stress corrosion cracking by reducing the oxygen content. Second, it will create nitrate as the deaeration mechanism is nitrite reacting with oxygen to form nitrate. The nitrate formed is also an inhibitor of stress corrosion cracking.(7)

Conclusions

1) Fracture mechanics calculations on fatigue crack growth in stainless steel bellows seals indicate that leaks due to fatigue cracking from existing corrosion pits or cracks are unlikely. Most of the cracks (if they exist) that passed a hydrotest will be dormant during service (i.e., they will not grow to cause a leak). It is possible, however, leaks may develop from cracks or pits which just barely made the test. Any leaks from these flaws will be small.

2) It is possible to control the MIC which caused the bellows seal failure. Recurrence of MIC leading to leaks is unlikely in high pH water environments in which the bellows are subjected to during standby and operation.

Y. Chung
Y. Chung

YC:gf

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(4) G. J. Theus and R. W. Staehle, Review of Stress Corrosion Cracking and Hydrogen Embrittlement in the Austenitic Fe-Cr-N Alloys, Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys, NACE (1977).

(5) A. J. Sedriks, Corrosion of Stainless Steels, John Wiley & Sons (1979).

(6) H. H. Uhlig and R. W. Revic, Corrosion and Corrosion Control, third edition, John Wiley & Sons (1985).

(7) H. Hirano, et al., The Effect of Dissolved Oxygen and NO$_3$ Anions on the Stress Corrosion Cracking of Type 304 Stainless Steel in Water at 290°C, Corrosion (1983), 313.

TABLE 1

A Summary of Stress Intensity Factor Range ΔK and Crack Growth Raten da/dN Calculations for Assumed Cracks

Crack Type	Crack Size Length (ℓ) (inch)	Depth (a) (inch)	Stress Intensity Factor Range ΔK $ksi\sqrt{in}$	Crack Growth Rate (inch)
Partially through-wall	0.06	0.01	0.8	Nonpropagating
	0.125	0.01	1.0	
	0.25	0.01	1.3	
Through-wall	0.125	0.02	2.6	Nonpropagating
	0.25	0.02	3.6	0.2×10^{-6}
	0.50	0.02	5.1	$0.7 \times 10^{-}$
	0.75	0.02	6.3	1.4×10^{-6}
	1.00	0.02	7.3	2.2×10^{-6}

Appendix A Bellows Design Data and Stress Calculations

d = outside diameter of cylindrical tangent, 16.625 inch (from Flexonics)
t = wall thickness 0.020 inch
w = convolution height 0.675 inch (from Flexonics)
n = number of plies 1
q = bellows pitch 0.50 inch (from Flexonics)
P = internal pressure $P_s = 10$ psig (standby), $P_o = 20$ psig (operating)
$d_p = d + w$, mean diameter of bellows, 17.30 inch
$t_p = t(d/d_p)^{1/2}$, thickness corrected for thinning 0.0196 inch

$q/2w$ = correction factor for Graphs Fig. C18, 19 & 20 = 0.37
$q/(2.2)(d_p t_p)^{1/2}$ " = 0.39

C_p = factor from graph Fig. C18 (from Std of the EJMA) = 0.74
C_f = " Fig. C19 = 1.52
C_d = " Fig. C20 = 1.53

$\Delta\sigma_3$ = bellows meridional membrane stress range due to internal pressures

$= \Delta P w/2nt_p = (10)(0.675)/(2)(1)(0.0196) = 170$ psi

$\Delta\sigma_4$ = bellows meridional bending stress range due to internal pressures

$= (\Delta P/2n)(w/t_p)^2 \cdot C_p$

$= (10/2)(0.675/0.0196)^2(0.74) = 4390$ psi

$\Delta\sigma_5$ = bellows meridional membrane stress range due to deflections (Δe)

$= (E_b\ t_p^{\ 2} \Delta e)/2w^3 C_f$ E_b= modulus of elasticity for the bellows

$= (27.9 \times 10^6)(0.0196)^2(9.4 \times 10^{-4})/(2)(0.675)^3\ (1.52) = 10$ psi

$\Delta e = (2.250 - 2.156) \times 10^{-2} = 9.4 \times 10^{-4}$ (from Flexonics)

$\Delta\sigma_6$ = bellows meridional bending stress range due to deflections (Δe)

$= (5E_b t_p \Delta e)/(3w^2 C_d)$

$= (5)(27.9 \times 10^6)(0.0196)(9.4 \times 10^{-4})/(3)(0.675)^2(1.53) = 1230$ psi

$\Delta\sigma_m = \Delta\sigma_3 + \Delta\sigma_5 = 170 + 10 = 180$ psi (sum of membrane stress ranges)

$\Delta\sigma_b = \Delta\sigma_4 + \Delta\sigma_6 = 4390 + 1230 = 5620$ psi (sum of bending stress ranges)

As compared with the above stress ranges, the stress range in the circumferential direction is much lower, as follows.

$\Delta\sigma_2$ = bellows circumferential membrane stress range due to internal pressure

$= (Pd_p/2nt_p)\{1/(0.571 + 2w/q)\}$

$= (10)(17.30)/(2)(1)(0.0196) \cdot (1)/(0.571 + 2.703) = 1350$ psi

Appendix B Fracture Mechanics Calculations

1. Stress Intensity Factor Range ΔK

1.1 Surface Crack

From ASME Section XI, A-3000

$$\Delta K = \Delta\sigma_m M_m \sqrt{\pi a/Q} + \Delta\sigma_b M_b \sqrt{\pi a/Q}$$

where $\Delta\sigma_m$, $\Delta\sigma_b$ = membrane and bending stress ranges, psi
a = flaw depth surface crack
Q = from Fig. A-3300-1
M_m = from Fig. A-3300-3
M_b = from Fig. A-3300-5

ℓ	a	a/ℓ	a/t	M_m	M_b	ΔK ksi$\sqrt{in}$
0.06	0.01	0.167	0.5	1.40	0.65	0.7
0.125	0.01	0.08	0.5	1.85	0.97	1.0
0.25	0.01	0.04	0.5	2.5	1.42	1.4

1.2 Through Wall Crack

$$\Delta K = \Delta\sigma\sqrt{\pi a}$$

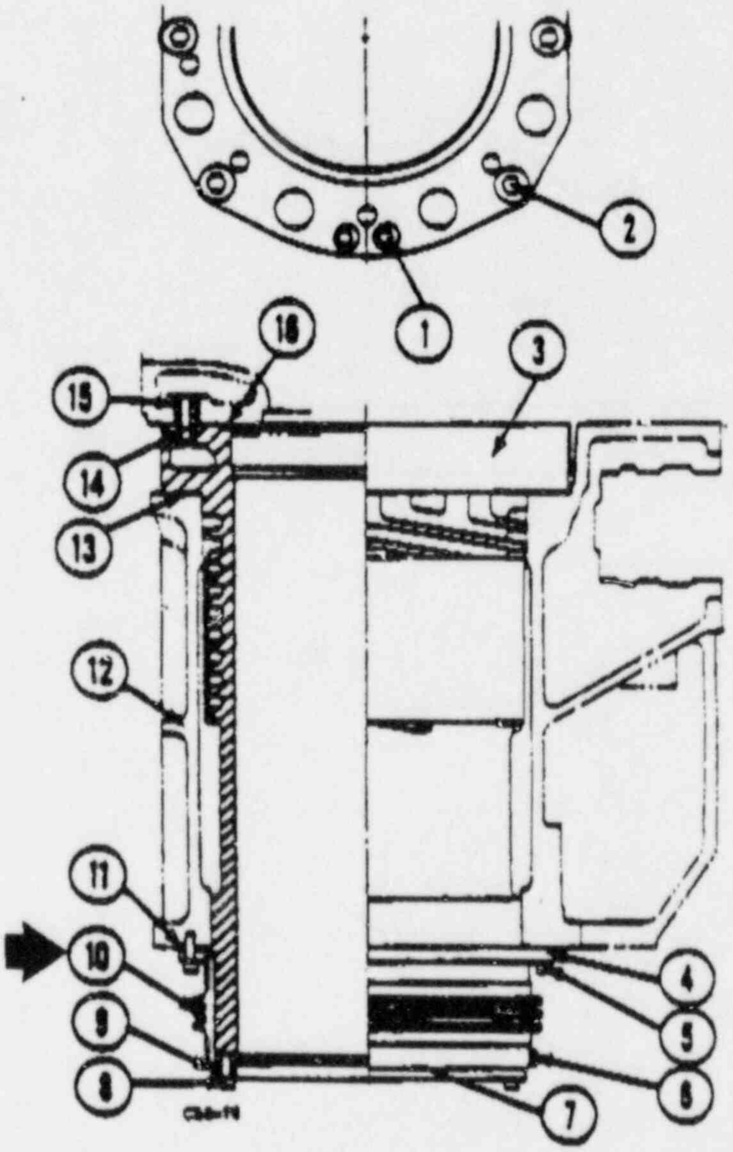
$$\Delta\sigma = \Delta\sigma_m + \Delta\sigma_b = 5800 \text{ psi}$$

2. Fatigue Crack Growth Rate

$$da/dN = C \cdot E \cdot S \cdot (\Delta K)^n$$

$C = 2 \times 10^{-19}$
$n = 3.3$
$E = 2$
$S = 1$

ℓ	a	ΔK	da/dN (inch/cycle)
0.25	0.125	3.6	0.2×10^{-6}
0.50	0.25	5.1	0.7
0.75	0.375	6.3	1.4
1.00	0.50	7.3	2.2



1. Screws, 3/4-10 (4)
2. Screws, 1-8 (6)
3. Cylinder Liner
4. Split Flange
5. Screw and Washer (12)
6. Drain Plug
7. Gasket
8. Screws (8)
9. Flange
10. Expansion Seal
11. Gasket
12. Cylinder Block
13. "Plastic" Gasket
14. Water Connection
15. O-ring Seal
16. Fire Gasket

Figure 1 A sectional view of the emergency diesel engine cylinder block. Item 10 (arrow) is the bellows expansion seal.

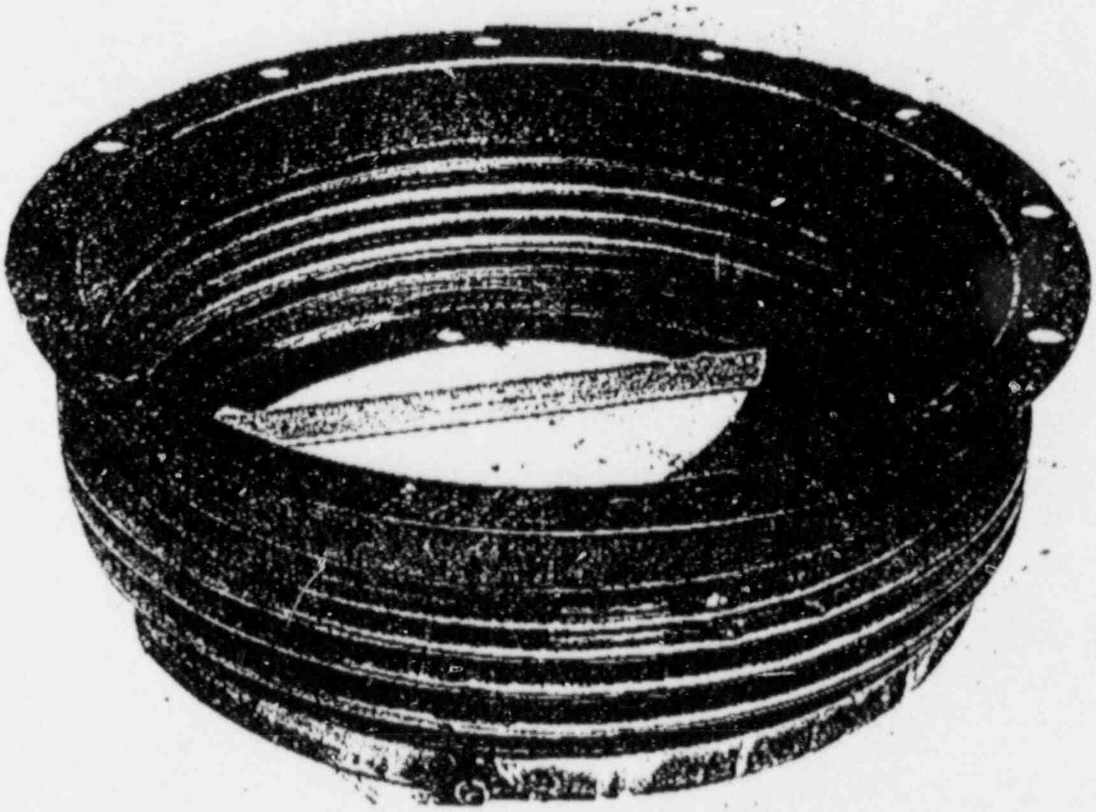
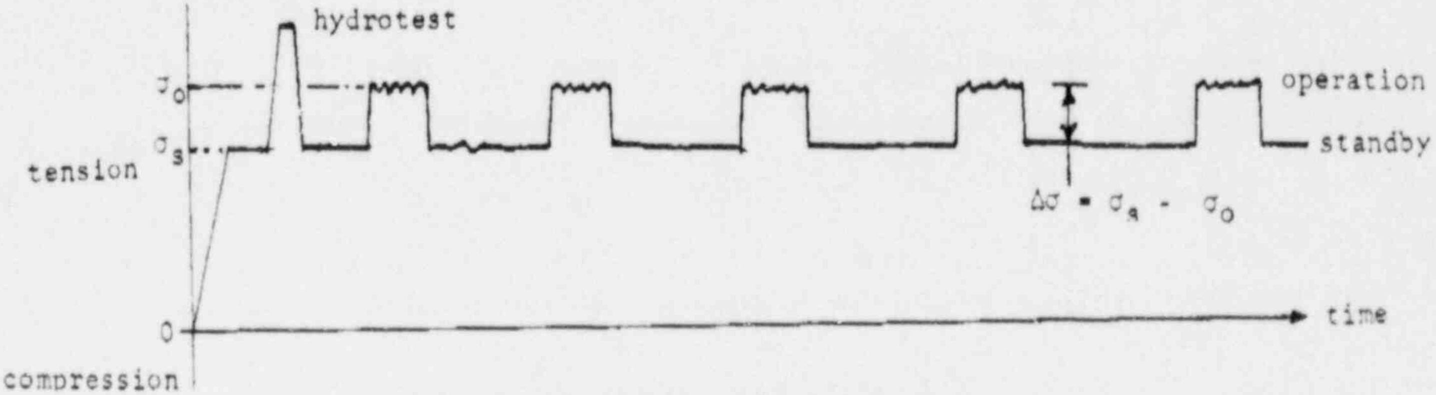
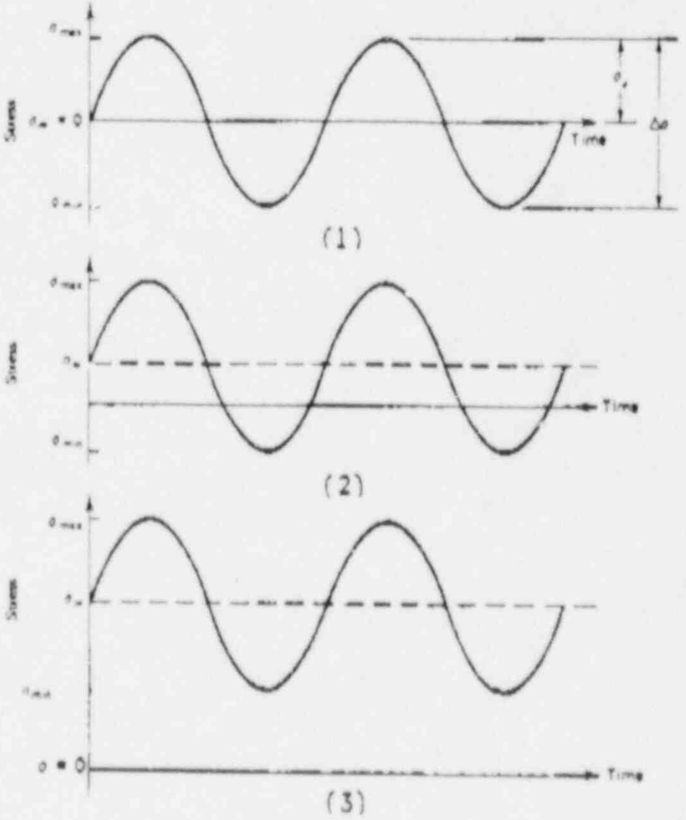


Figure 2 One of the bellows seals examined by M&QS



(a) Bellow seal stress cycle spectrum



σ_{max} = maximum stress in the cycle

σ_m = mean stress = $\frac{\sigma_{max} + \sigma_{min}}{2}$

σ_{min} = minimum stress in the cycle

σ_a = alternating stress amplitude = $\frac{\sigma_{max} - \sigma_{min}}{2}$

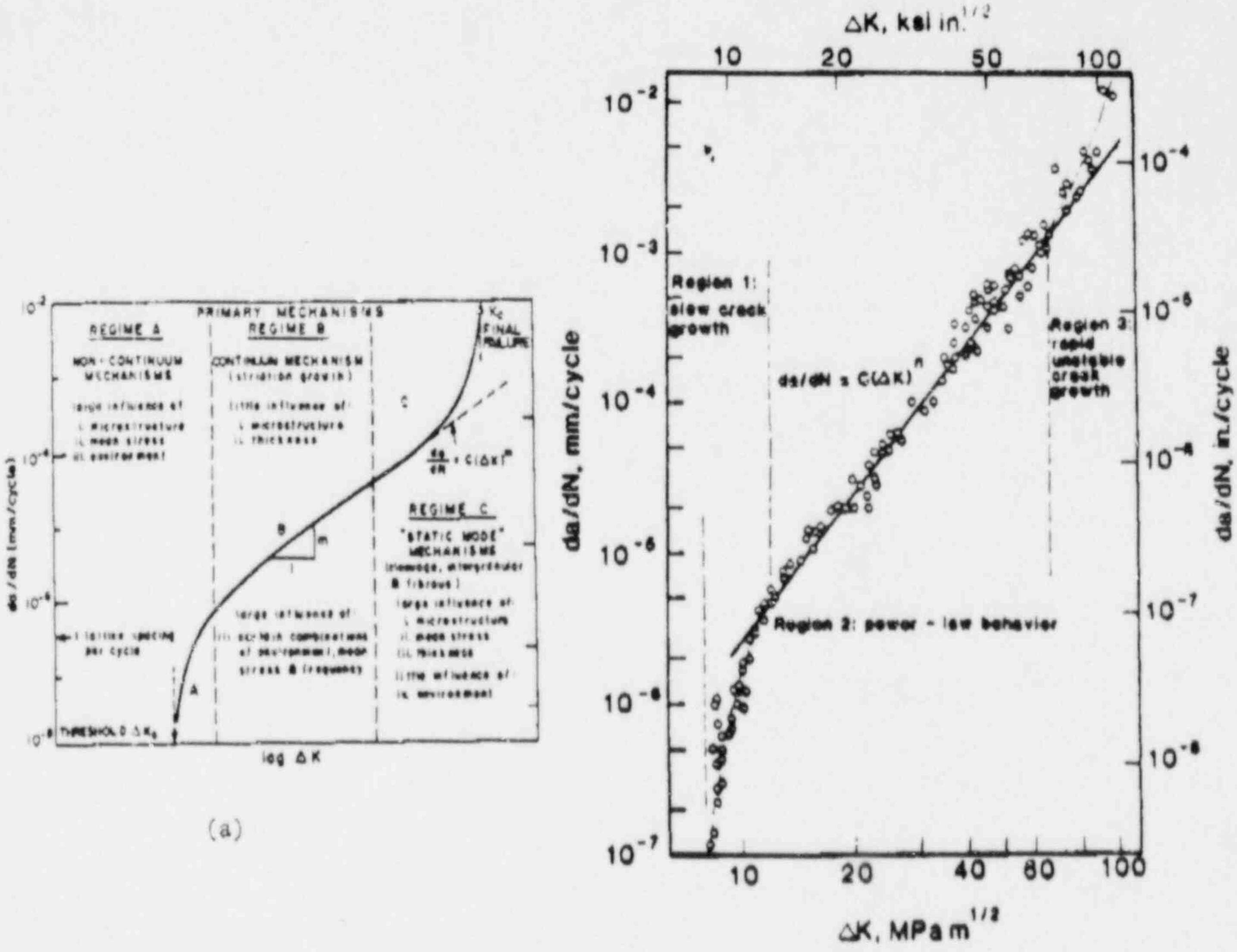
$\Delta\sigma$ = range of stress = $\sigma_{max} - \sigma_{min}$

R = stress ratio = $\frac{\sigma_{min}}{\sigma_{max}}$

A = amplitude ratio = $\frac{\sigma_a}{\sigma_m} = \frac{1 - R}{1 + R}$

(b) Idealized fatigue stress cycles

Figure 3 A simplified stress cycles for the bellows seal as compared with idealized fatigue cycles and defintions.



(a)

(b)

Figure 4 (a) Schematic relationship between fatigue crack growth rate da/dN and stress intensity factor range ΔK.

(b) A plot of fatigue crack data for A533 steel at ambient temperature

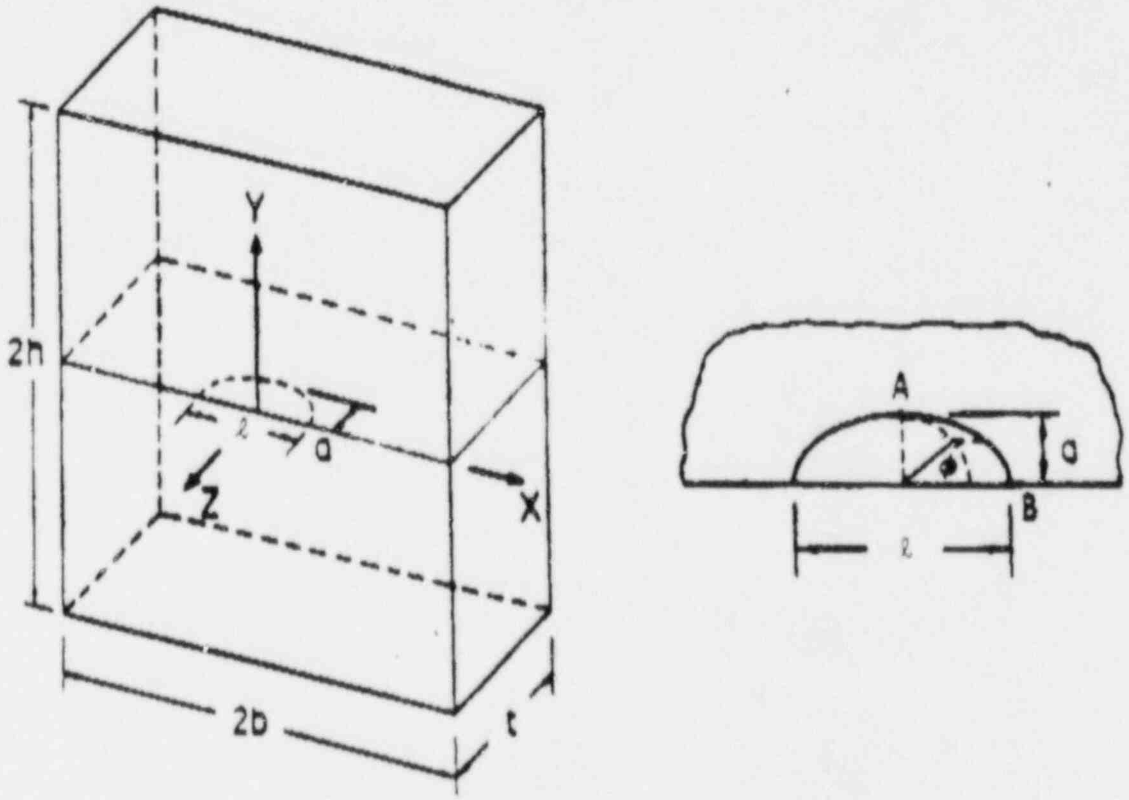


Figure 5 A surface crack in a finite plate

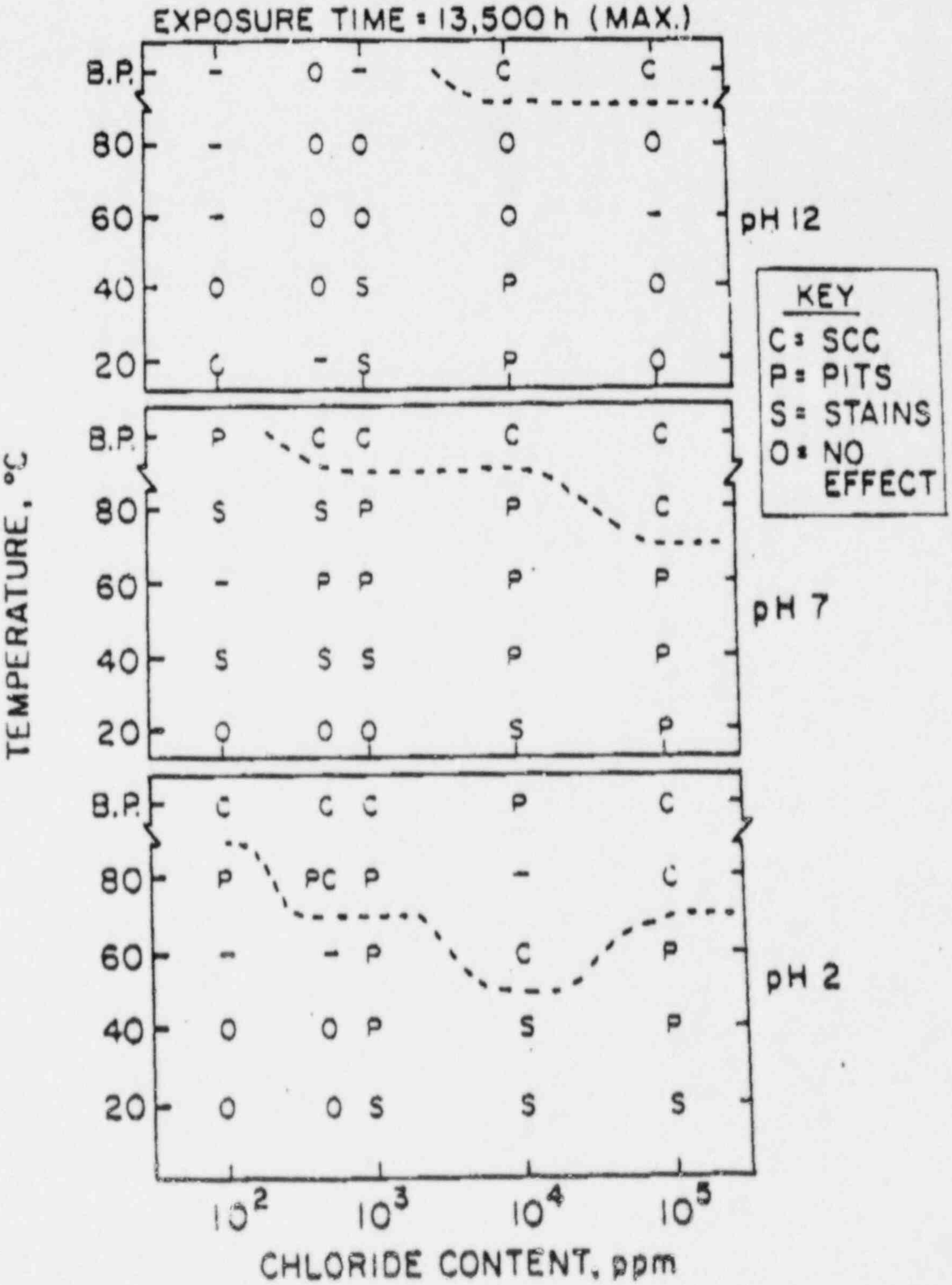


Figure 6 Effect of pH on the chloride content and temperature required to produce cracking of Type 304 stainless steel in sodium chloride solution. (After Truman)

Appendix 3

Diesel Cylinder Liner Expansion Seal Bellows Failure

Bechtel National, Inc.
Engineers—Constructors

Fifty Beale Street
San Francisco, California
Mail Address: P.O. Box 3965, San Francisco, CA 94119

To: **R. L. Randels**

File No. M10.05.02.02

Subject: Diesel Cylinder Liner
Expansion Seal Bellows Failure
Bechtel Job 14926-001, STP

Date: March 1, 1988

From: Y. Chung

Of: R&D/Materials & Quality Services

At: 50/15/B5 Ext. 8-1489

Copies: R. A. Manley/F. C. Breismeister
T. T. Phillips
R. W. Straiton
R. A. White
BLN 8802
DCC 0138177

Reference: Memorandum from T. T. Phillips to R. A. White, 2/12/88

A copy of our report on the failure analysis of expansion bellows from diesel cylinder liner expansion seals is enclosed. The results of our investigation show that the Type 321 stainless steel bellows failed due to pitting corrosion and cracking which was influenced by bacteria.

Y. Chung

Y. Chung

YC:gf

Enclosure

NAME	COPY
UIIM	
UIM	
PE	
MECH	3-25-88
I&C	
ELECT	
LIC	
PE	
PESG	
CIVIL	
PIPING	
A&R	
CODES	
PE	
ADMIN	
DEPT SVC	
SMTS	
WELDING	
[illegible]	
[illegible]	
OTHER	

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MAR 25 1988

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