EVALUATION

Metallurgical analysis of the 11-P7C-6F coupling, documented in Section 3.0, identified the failure mechanism to be intergranular stress corrosion cracking (IGSCC). Stress corrosion cracking is defined as a failure of a material subjected to tensile stress in a corrosive environment in which the material is susceptible. Each of the three criteria 1) susceptible material, 2) corrosive environment and 3) tensile stress; considered to be necessary for SCC to occur is discussed in the following subsection.

Susceptible Material

The coupling material was specified to be ASTM A582 Type 416 SS with hardness in the Rockwell C range of 28 to 32 (HRC). ASTM A582 Type 416 SS is a martensitic stainless steel that has excellent machining characteristics and has generally low corrosion resistance due to its relatively high sulfur content.

Based on heat traces provided in Attachment A for the couplings currently installed in P-7A, P-7B and P-7C and the couplings extracted from P-7C post 2011 failure event, the couplings were hardened by quenching from approximately 1870°F using nitrogen and then air cooled. Tempering to achieve the desired hardness of 28 to 32HRC was performed at temperatures ranging from 1025°F to 1090°F. In some cases, a second temper was required to achieve the desired hardness. Plots of the SWS pump coupling heat treatment (hardening and tempering) are provided in Figure 0-1 and Figure 0-2.

The tempering temperature of the material can have an adverse effect on the toughness and corrosion resistance of the material. Based on tempering curves for the batch of couplings installed in P-7A, P-7B and P-7C (Figure 0-2), the tempering temperatures are in the range to be avoided between 400°C and 580°C (752°F to 1076°F) for 416SS. These tempering temperatures can lead to low toughness and susceptibility of the material to SCC. In fact, low impact toughness values (indicated by the CVN) are seen in the couplings that have failed with most CVN values in the single digits at the temperature range of the service water (refer to Table 0-7).

Corrosive Environment

The Service Water System (SWS) takes cooling water from Lake Michigan via pumps P-7A, P-7B and P-7C for the removal of waste and decay heat. For the period between January 2009 to August of 2011, service water basin level ranged from elevation 576' to 580'. For the same period, the water temperature ranged from a minimum of 32°F to a maximum of 76°F. Chlorination occurs on a daily basis and consists of the addition of sodium hypochlorate (i.e. bleach) upstream of the traveling screens to control microbial species in the SWS. A water sample was taken by the Palisades chemistry department on 8/19/11 downstream of YS-0134 in the Chemistry cold lab prior and post chlorination of the Service Water System. The chemistry water sample data is presented below.

	Pre Chlorination	**Post Chlorination**
Date/Time	8/19/2011 14:10	8/19/2011 18:48
Chlorination in Progress	No	Yes
Temperature	22.8 C	22.5 C
PH	8.30	8.21
Dissolved Oxygen	9 ppm	10 ppm
Chloride Concentration	9.72 ppm	10.2 ppm

This data indicates there is sufficient chlorine and dissolved oxygen in the service water for SCC of 416 SS to occur, even when chlorination is not in progress. Also due to the intermittent nature of the pump service the couplings above the normal water basin will experience wet /dry cycles that will leave a higher chlorine concentration on the couplings as the coupling dries out with pump stopped. Visual examination of the failed coupling shows corrosion products staining the area below the vent hole and are present on the fracture surface and on the internal threads.

Tensile Stress

The fracture surface revealed that the 11-P7C-6F failed due to stress corrosion cracking from the inner diameter at the thread root to the outer diameter from two initiation sites traversing the thickness in an elliptical manner. To support this failure mechanism, an evaluation of the coupling stresses was performed to determine the tensile stress in the coupling.

The function of the couplings is to couple the various segments of shafts (i.e. line shafts, packing shaft and motor shaft) together in order to transmit the motor torque to the impeller approximately 40 feet below. The design of the couplings enables the shaft ends to bear against each other that could lead to both tensile stresses and shear stresses across the coupling. To determine the stresses across the couplings, a finite element analysis (FEA) model of the coupling was created in ANSYS [12]. ANSYS is a multipurpose finite element analysis software program and is verified and validated in accordance with LPI Procedure 4.1 [15], as documented within [16].

FEA Model Description

A half FEA model of an intact coupling was developed using ANSYS and consists of the steel body, alignment hole and threads. The model was constructed of the eight-node brick element, SOLID45 (see Figure 0-5). The symmetric boundary condition, $U_z=0$ and $U_\theta=0$, is applied on the inner surface as shown in Figure 0-6.

ASTM A582 Type 416 stainless steel material property for the coupling FEA model is as follows:

Young's modulus: 29.2×10^6 psi

Poisson's ratio: 0.3

Coupling threads are 2-3/16, 8 TPI (see Figure 0-5) which is not a common thread form. Specific thread properties are not available in the Machinery's Handbook [13]. Therefore, internal thread properties of the coupling is taken to be the average internal diameter of 2-1/4, 8 TPI and 2-1/16, 8 TPI in the Machinery's Handbook [13].

Loading Condition

Loading on the coupling model consists of the weight of components below the coupling, hydraulic thrust and motor torque. These loads are extracted from HydroAire calculation NQ5940 [14] as follows:

Two motor torque loading scenarios (MTS) are considered for transmittal of the motor torque across the coupling; 1) motor torque is transmitted across the coupling by shaft to coupling purely by thread friction (MTS1; see Figure 0-3) and 2) motor torque is transmitted across the coupling by bearing of the shaft ends against each other within the coupling (MTS2; Figure 0-4). To simulate uneven shaft alignment within the coupling, a bending moment is also considered as a load. These loads are combined as follows for evaluation of the couplings.

Load Combination 1 (LC1) = Weight + Thrust + MTS1

For this load combination, component weight and hydraulic thrust is combined with the motor torque loading scenario 1 (MTS1) in which motor torque is transmitted across the coupling purely by friction. Axial thrust, F=8780lb, is evenly distribute on the nodes on the inner surfaces of each thread (see Figure 0-7). Torque, T=18694 in-lb [14], is first converted into circumferential force, F by T= F*R where R is the coupling friction radius and then evenly applied on the same nodes that the axial thrust load is applied.

Load Combination 2 (LC2) = Weight + Thrust + MTS2

For this load combination, the weight and axial thrust is applied in the same manner as in LC1. Bearing of the shafts within the coupling will induce tensile stress across the coupling. The tensile force of 42 kips is evenly distributed to the first three threads from the contact plane of the two shafts (see Figure 0-8). Typically with threaded connections, the first few threads near the plane of induced load carry the majority of this load [17]. For this assessment, the first three threads were considered to carry the load.

Load Combination 3 (LC3) = Weight + Thrust + MTS2 + Moment

For this load combination, loads are applied in the same manner as LC2 with the addition of a moment on the coupling to account for misalignment or other postulated scenarios that can induce bending across the coupling. A bending moment equivalent to 20% of the stress induced by MTS2 of approximately 4,962 in-lb (see below) was also applied to the coupling. This moment was converted into axial force, Fz, and applied on the nodes on the end cross-section based on the nodes' y direction distance from center (see Figure 0-9).

$OD := 3.187 \cdot in$	Out diameter of coupling
$ID := \frac{(2.125 + 2.25) \cdot in}{2}$	Internal diameter of coupling
$Sp := \frac{\pi \cdot (OD^2 - ID^2)}{4}$	Area of cross-section of coupling
$Fp := 42335 \cdot lb$	Clamping force
$\sigma := \frac{Fp}{Sp}$	
$Ip := \left(\frac{\pi}{64}\right) \cdot (OD^4 - ID^4)$	Area moment of inertia of coupling
$Mom := 0.2\sigma \cdot \frac{Ip}{\frac{OD}{2}}$	
$Mom = 4.962 \times 10^3 \, in \cdot lb$	Moment can result in 20% stress result from clamping force

FEA Results

1) LC1: In this case, the circumferential stress, axial stress and first principal stress are relatively low due to the even distribution of loads on the coupling (see Figure 0-10). Axial tensile stresses at the thread root are on the order of 3.5 to 5 ksi. This result indicates that if the motor torque is transmitted across the coupling purely by thread frictional resistance, then the coupling tensile stresses are relatively low.

2) LC2: This load combination results in high stress concentrations at the thread root of the coupling at the contact plane of the two shafts. Axial tensile stresses at the thread root are over 10 times greater than LC1 with stresses on the order of 50 to 60 ksi.

3) LC3: This load combination does not significantly increase stresses at the thread root of the coupling from LC2. The additional bending moment on the coupling produces additional stresses on the outside diameter of the coupling however does not appreciably increase stresses at the thread root where SCC initiation and propagation is postulated.

Average tensile stresses at the first thread root for each load combination is summarized in the matrix below.

Load Combination	Average Tensile Stress (psi)
LC1: No Bearing	3790
LC2: Shaft Bearing	58250
LC3: Bearing Shaft and Bending	58220

The stress tabulation above indicates that the failure was not a single overload event since the average yield and tensile strength are approximately 136 ksi and 151 ksi (see Section 0), respectively. The typical stress intensity required to initiate a crack at a notch due to SCC is on the order of $15\ to\ 20\ ksi\sqrt{in}$ dependant upon material and environment. Clearly from the FEA, sufficient tensile stress is present to facilitate crack initiation for the load combination involving shaft end bearing.

Crack Propagation

Given the tensile stresses for the three load combinations evaluated in Section 4.3 above, a crack propagation evaluation is performed in this section to estimate the amount of time to propagate a crack through coupling 11-P7C-7.

WORK IN PROGRESS

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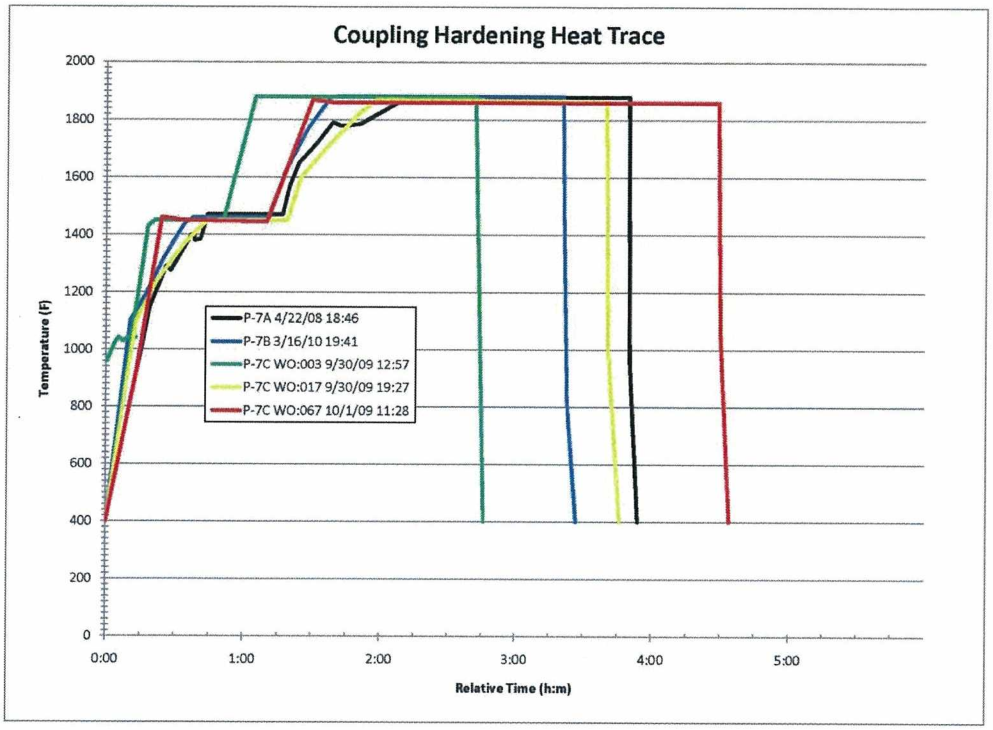


Figure 0-1: Hardening Heat Traces

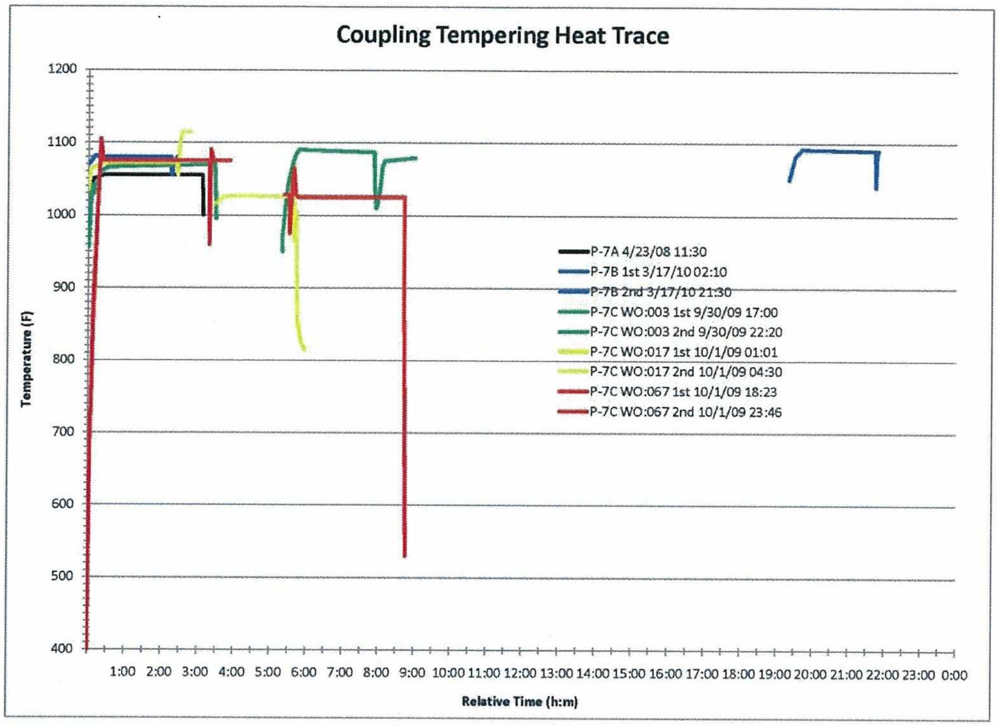


Figure 0-2: Tempering Heat Traces

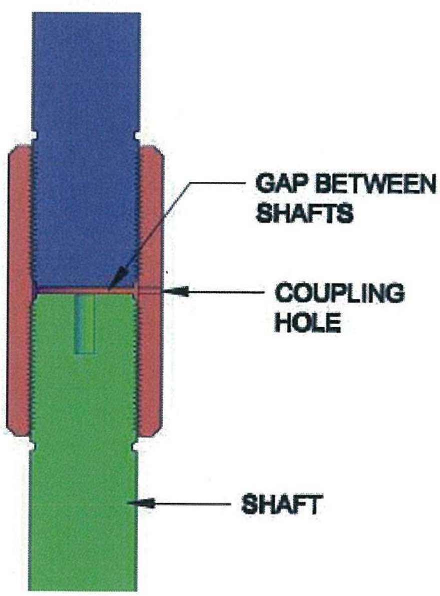


Figure 0-3: MTS1: Shaft Not Bearing

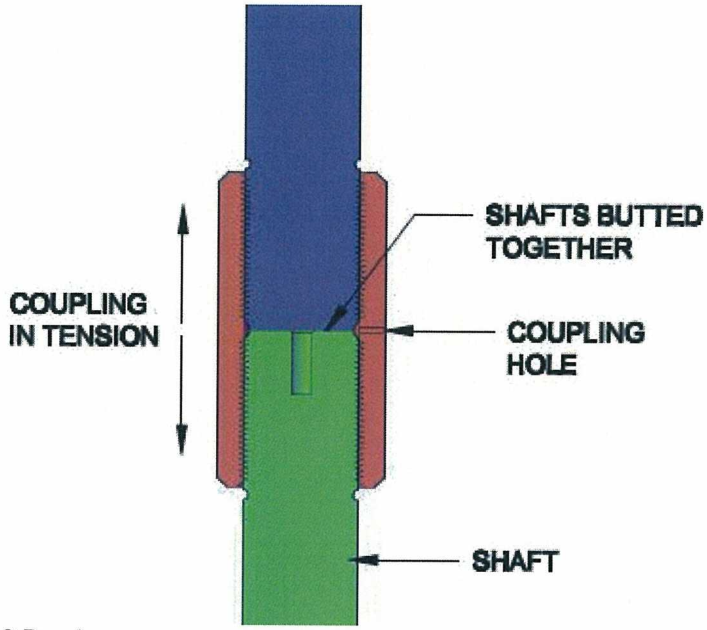


Figure 0-4: MTS1: Shaft Bearing

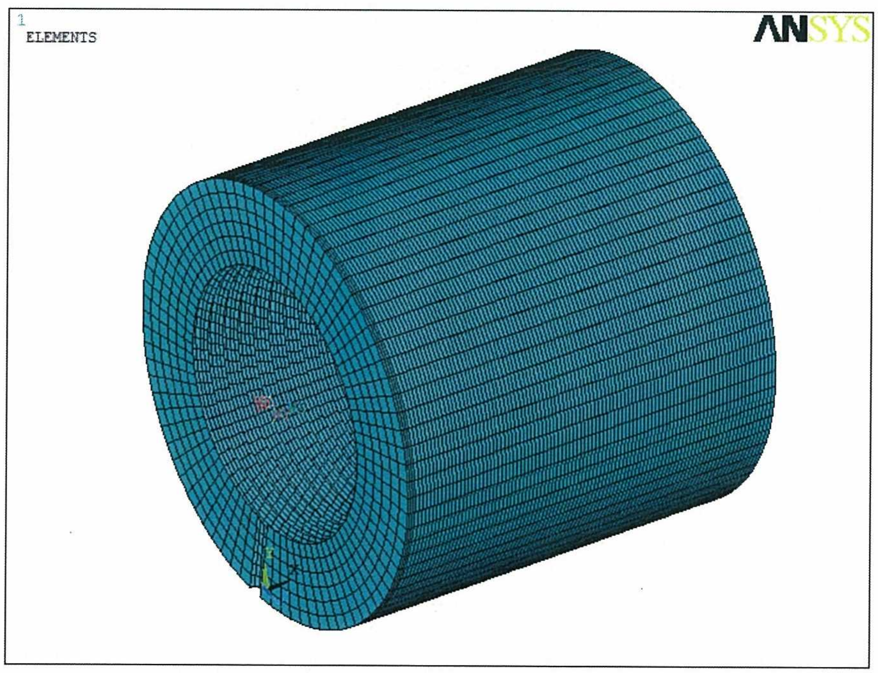
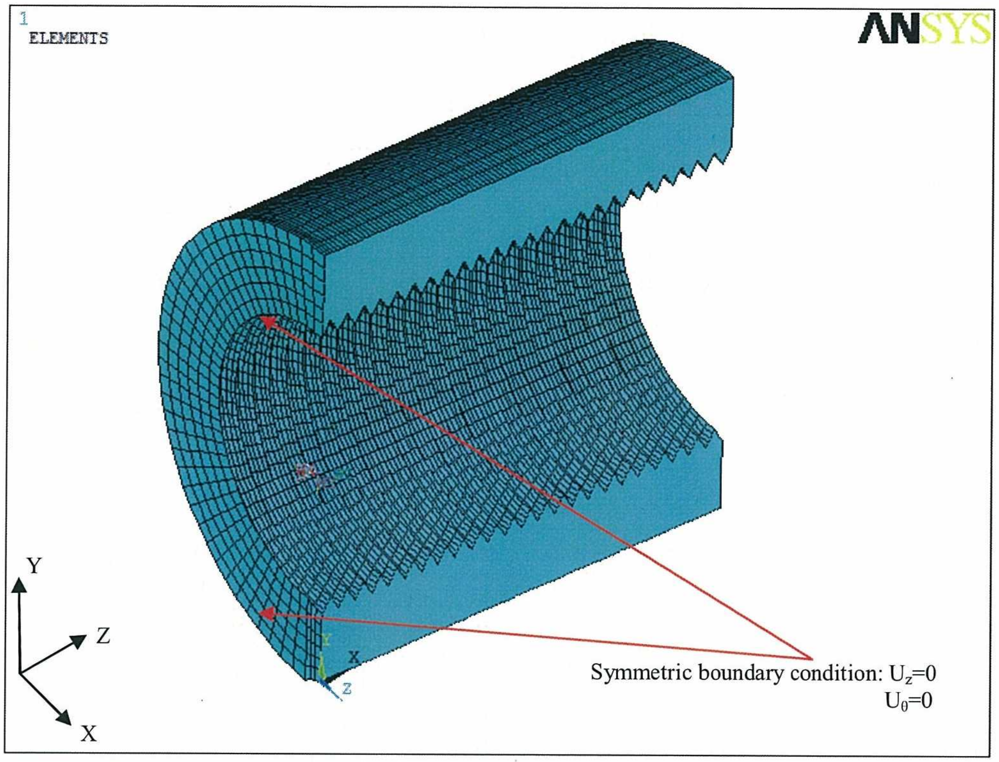


Figure 0-5: Half FEA model of coupling



Local coordinate system numbered 11 is cylindrical coordinate system

Figure 0-6: Cross-section of half FEA coupling model

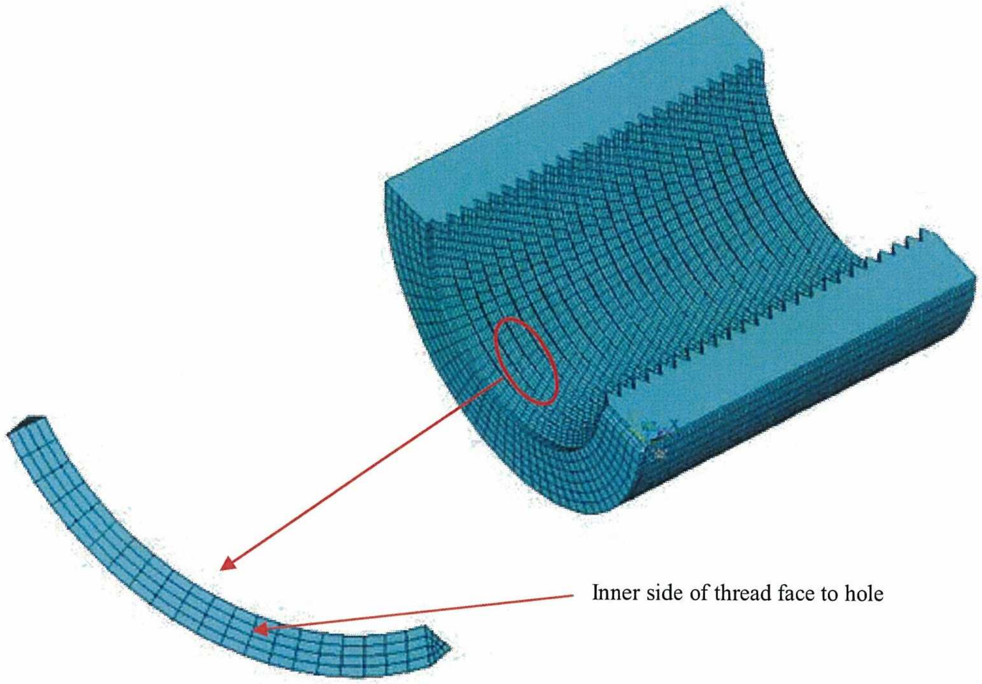


Figure 0-7: Load application Sketch of loading condition in no bearing case

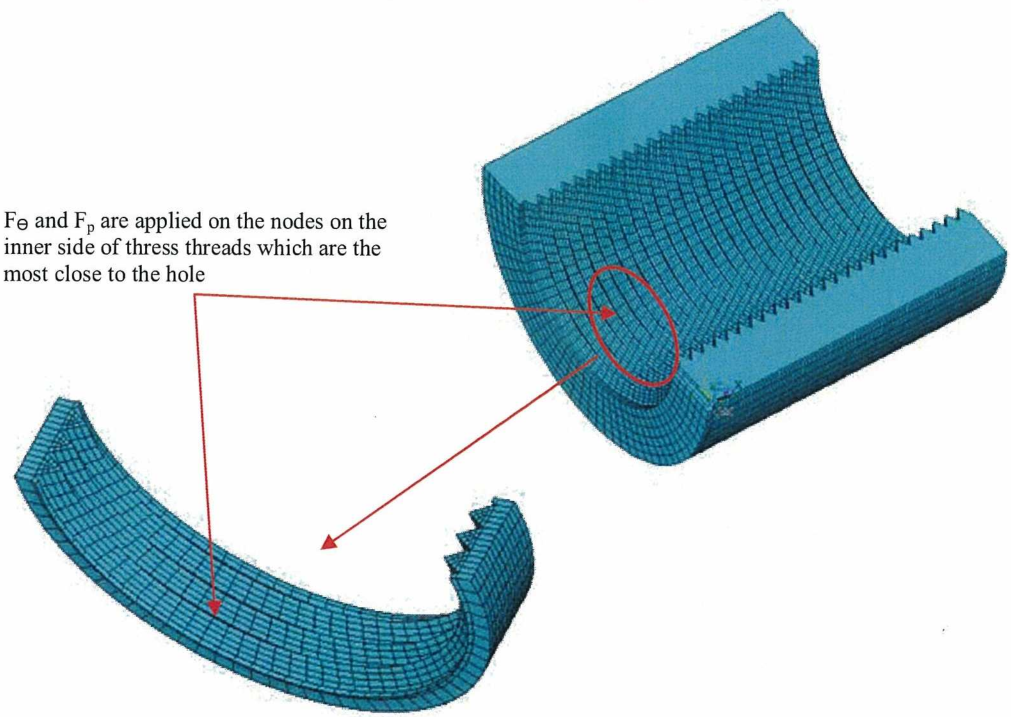


Figure 0-8: Sketch of loading condition in shafts bearing case

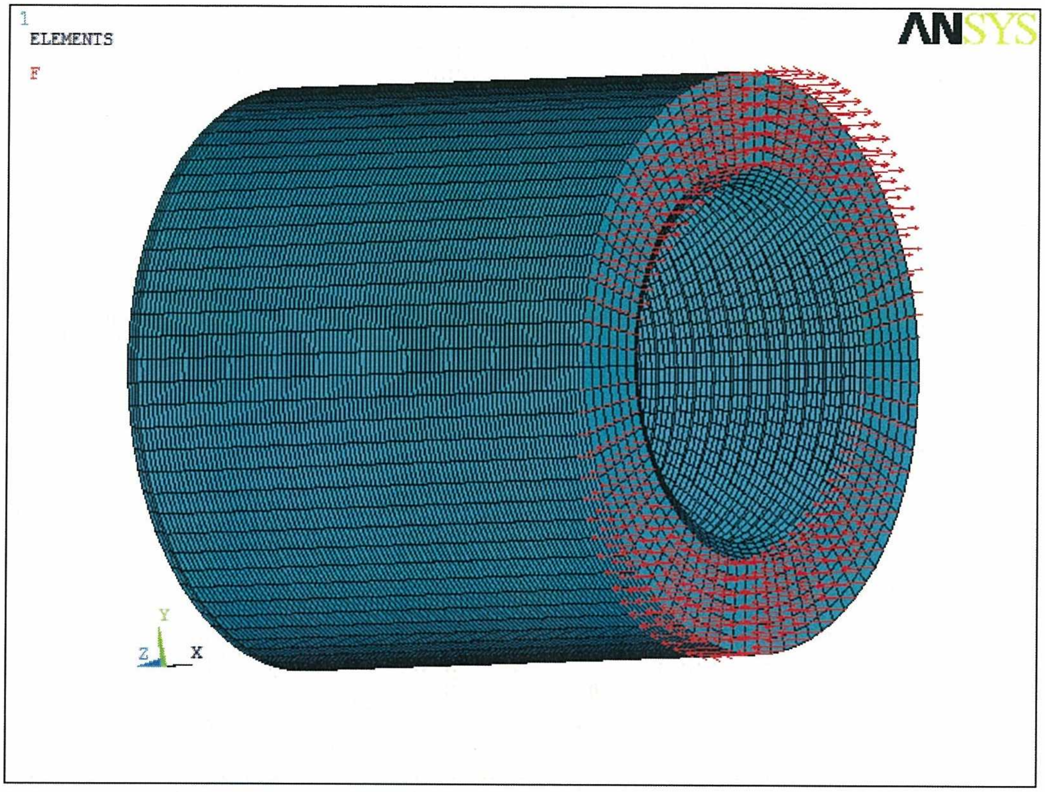


Figure 0-9: Sketch of axial force result from bending moment

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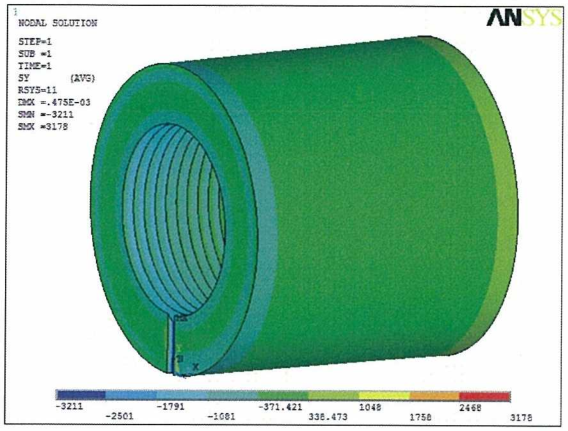
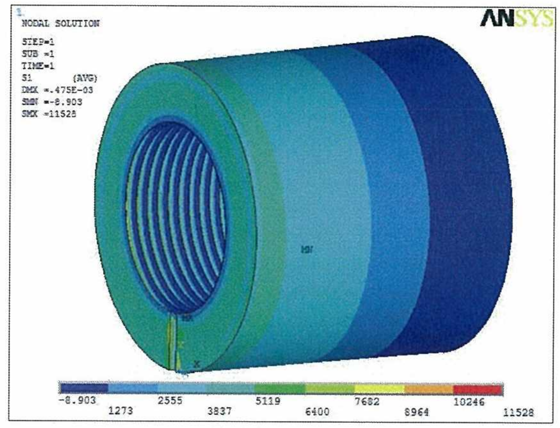
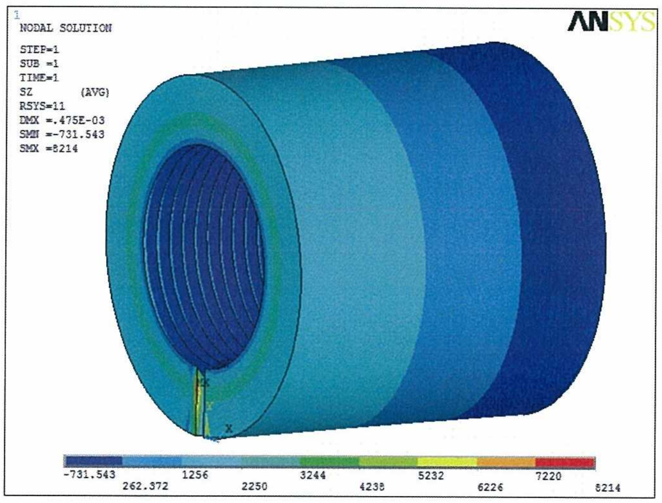
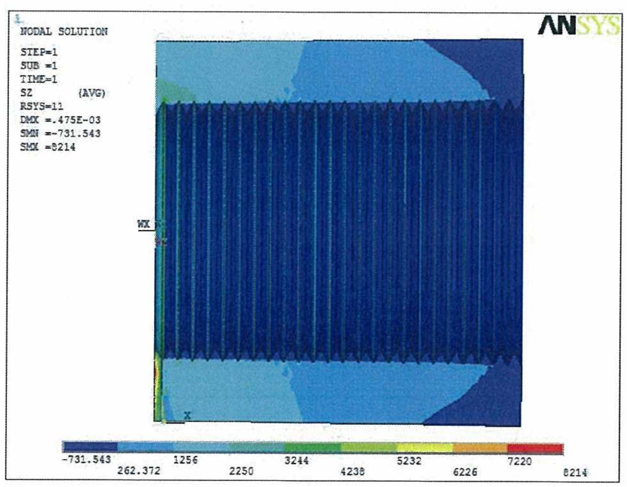


Circumferential Stress



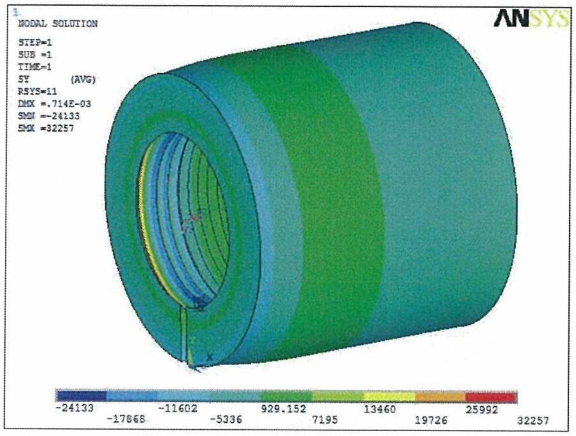
1st Principal Stress



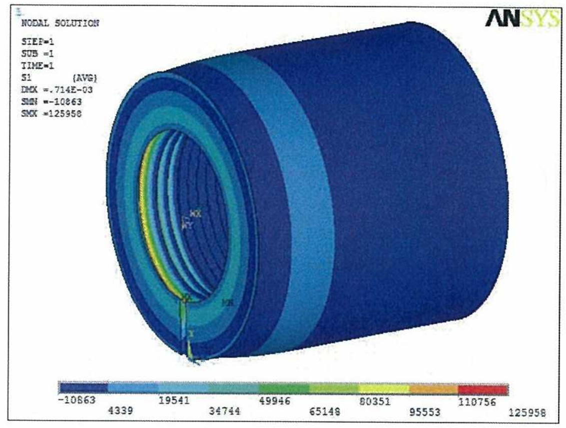


Axial Stress

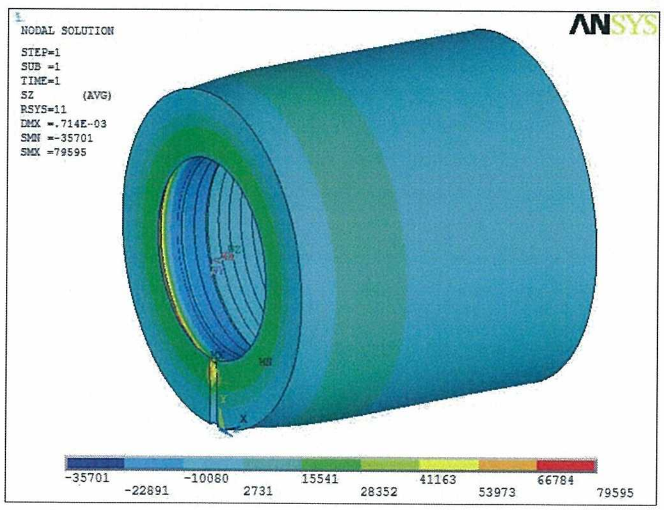
Figure 0-10: Resultant stresses for LC1



Circumferential Stress



1st Principal Stress



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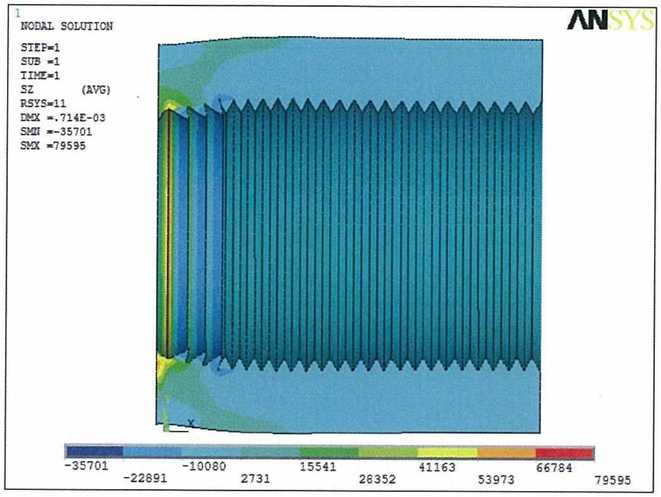
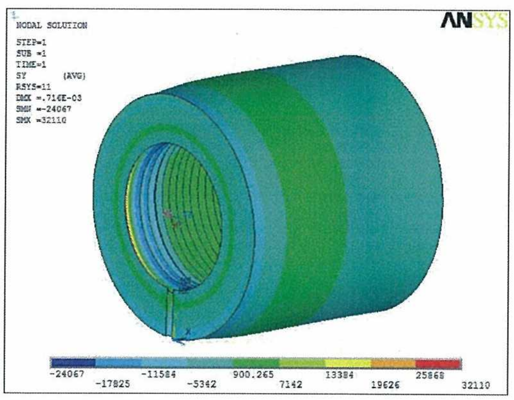
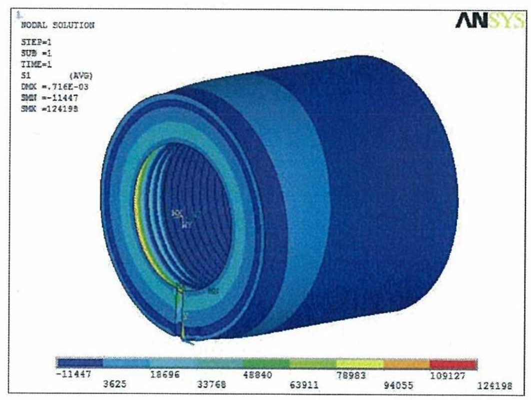


Axial Stress

Figure 0-11: Resultant stresses for LC2



Circumferential Stress



1st Principal Stress

Axial Stress

Figure 0-12: Resultant stresses for LC3

SUMMARY/RECOMMENDATION

Palisades SWS pump P-7C coupling #6 (identified herein as 11-P7C-6F) failed in August, 2011. The failure is determined, based on metallurgical evaluation, to be the result of intergranular stress corrosion cracking (IGSCC). The 2009 failure of the #7 coupling (identified herein as 09-P7C-7F) on the same pump (P-7C) was determined in [18] to also be a result of IGSCC. LPI's independent examination of the 2009 failed coupling 09-P7C-7F concurs with the failure mode as documented in [18].

For SCC to occur three criteria to promote SCC must exist; 1) susceptible material, 2) corrosive environment and 3) tensile stress. The specified coupling material, ASTM A582 Type 416 stainless steel, is a martensitic steel that is susceptible to SCC at low toughness. Charpy V-Notch (CVN) testing of the 2011 failed coupling (11-P7C-6F) resulted in toughness values in the range of 6 to 10 ft-lbs impact energy for test temperatures of 32 and 70F. CVN testing of the 09-P7C-7F coupling resulted in impact toughness values in the range of 3 to 6 ft-lb for test temperatures of 32°F and 75°F, respectively. These low impact toughness values make the couplings susceptible to SCC in the presence of chlorides and sufficient tensile stress to initiate and propagate a crack.

The couplings are subjected to tensile stresses during normal operation by the weight of the components below the coupling and hydrodynamic forces due to pump operation. In addition, the design of the couplings results in the shaft ends bearing against each other that likely led to sufficient tensile stresses (with a maximum value near the center where the two shafts bear against each other) in the coupling to initiate and propagate a crack.

The majority of the pump couplings below the packing (couplings #1 through #4) are submerged below the water level in the intake structure at normal basin levels. Couplings #5 through #7, above normal basin water levels see intermittent cycles of wet and dry depending on whether the pump is operating. When the SW pumps are on, all couplings below the stuffing box are wet and when they are off, couplings #5[2], #6 and #7 begin to dry. Chemistry samples of the service water indicate that there are low levels of chlorine in the raw water of Lake Michigan on the order of 9 ppm. Chlorination of the service water increases the chlorine level slightly to approximately 10 ppm. Even these relatively low levels of chlorine combined with a high humidity oxygen rich environment (as is the case for the couplings #5, #6 and #7 when the pump is off) can lead to a local

[2] Unless the service water basin level is above coupling #5. In which case, coupling #5 would be submerged in water.

breakdown of the passivation layer. SCC can nucleate at these locally damaged sites, develop and propagate under sufficient tensile stress to form highly branched network of fine cracks, as can be seen in Figure 0-8 and Figure 0-9.

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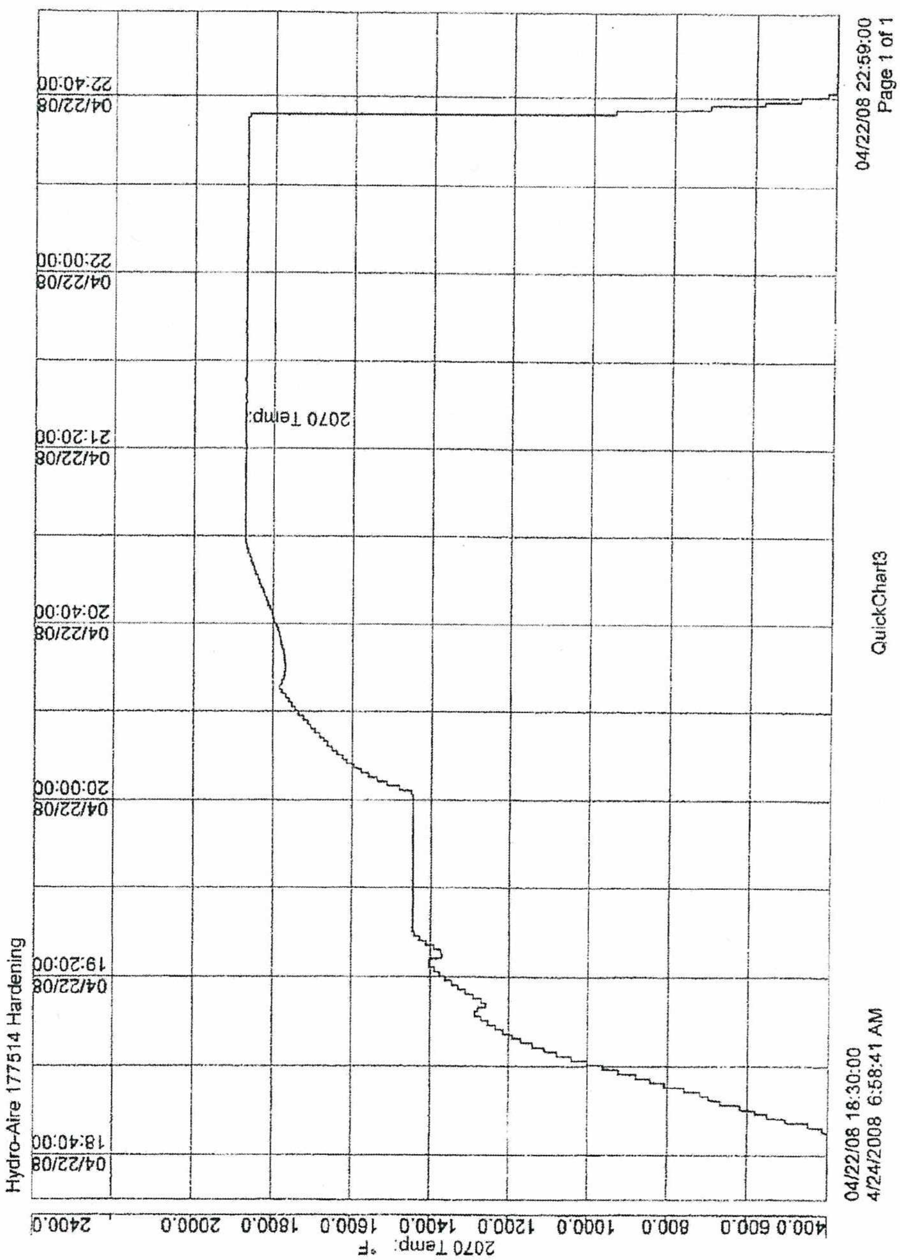
Attachment A

Misc. Inputs

Entergy - Palisades Nuclear Job# N.Q. 5604 P.O. 00019919 Model: 25 NMC 2 Stg. Johnston Page 53 of 123



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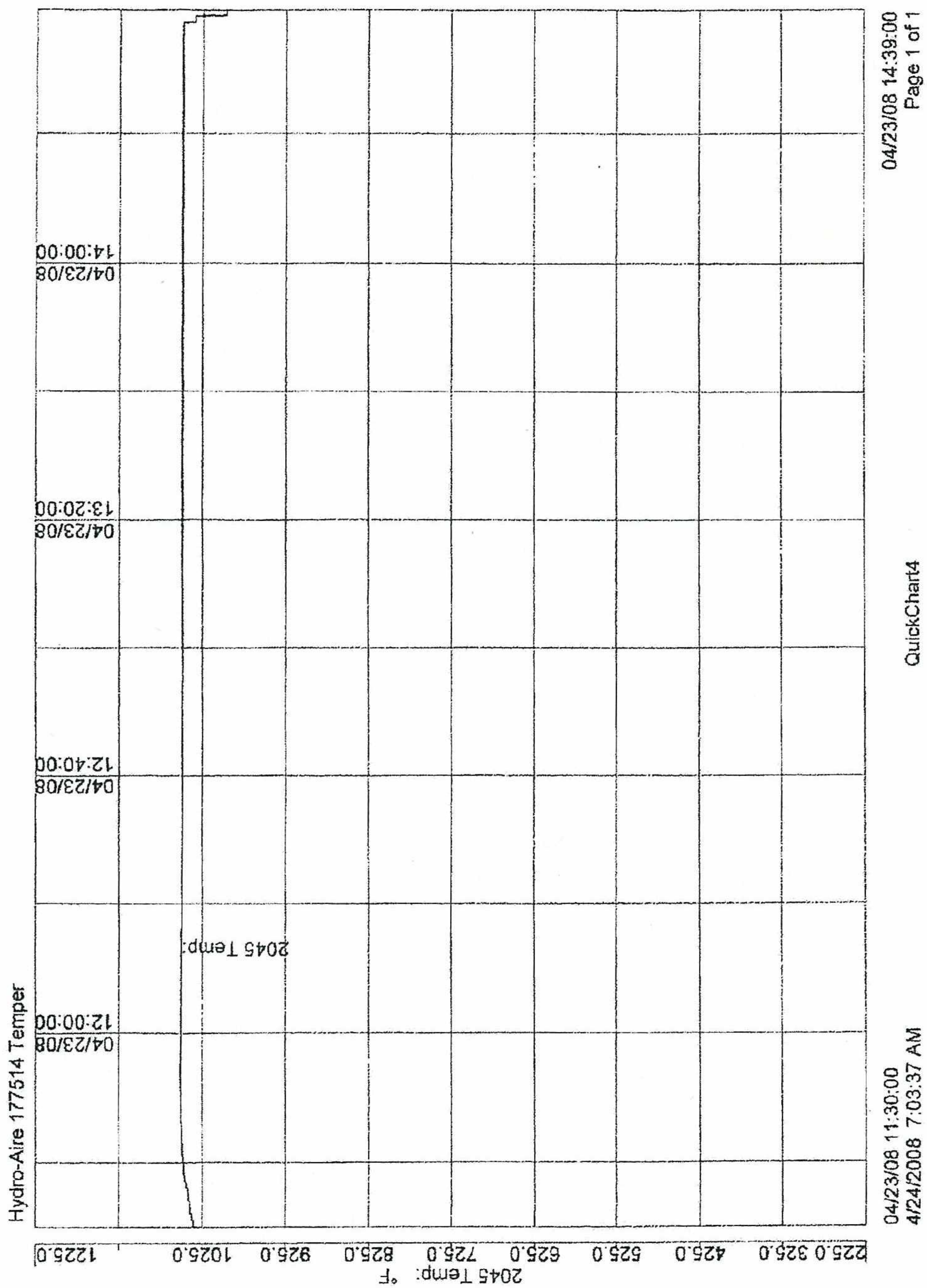

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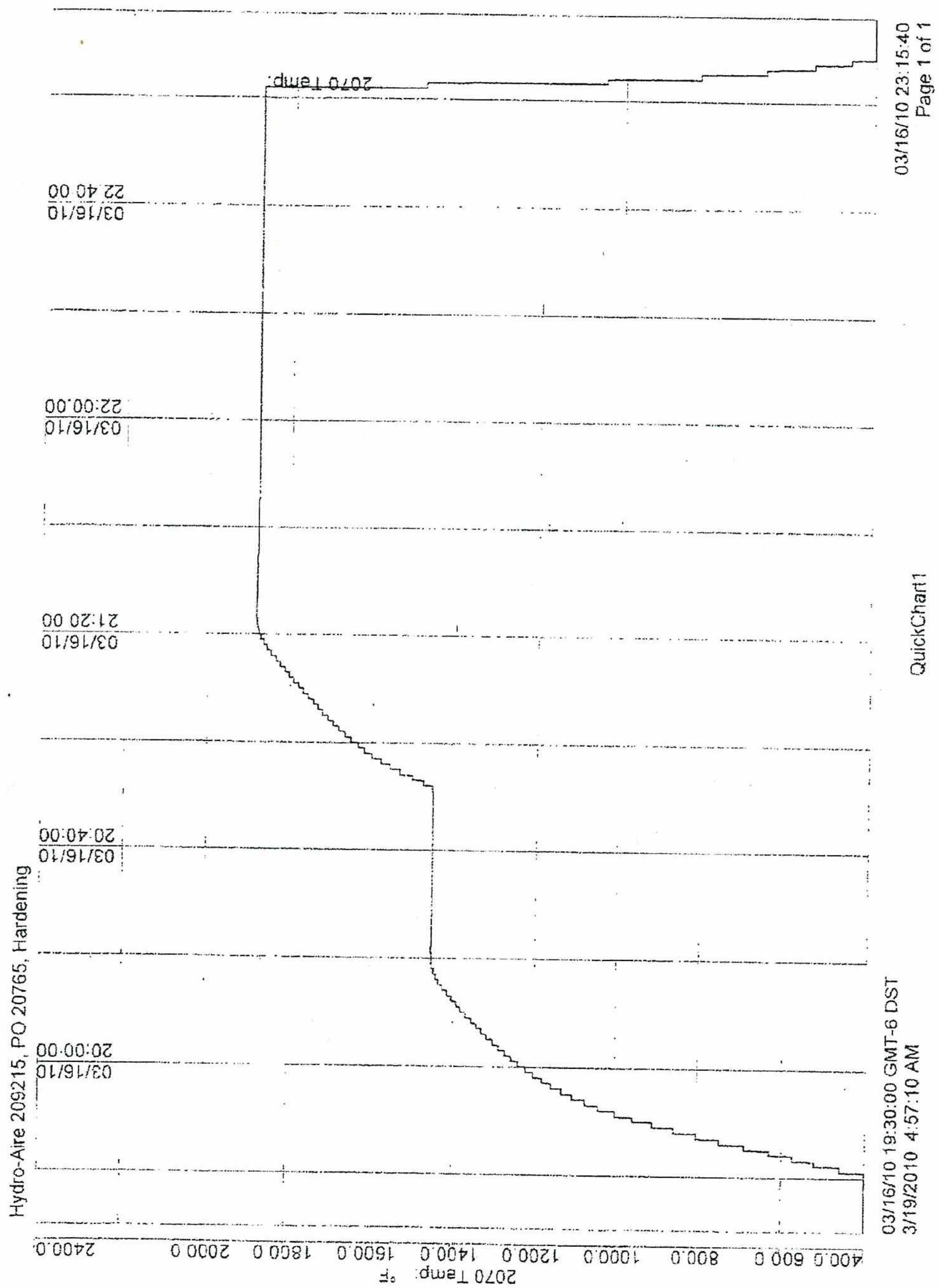

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Attachment B

Tensile Test Data

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Attachment C

Hardness Survey Data

Attachment V: LPI Report

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