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Elevation View

Top View

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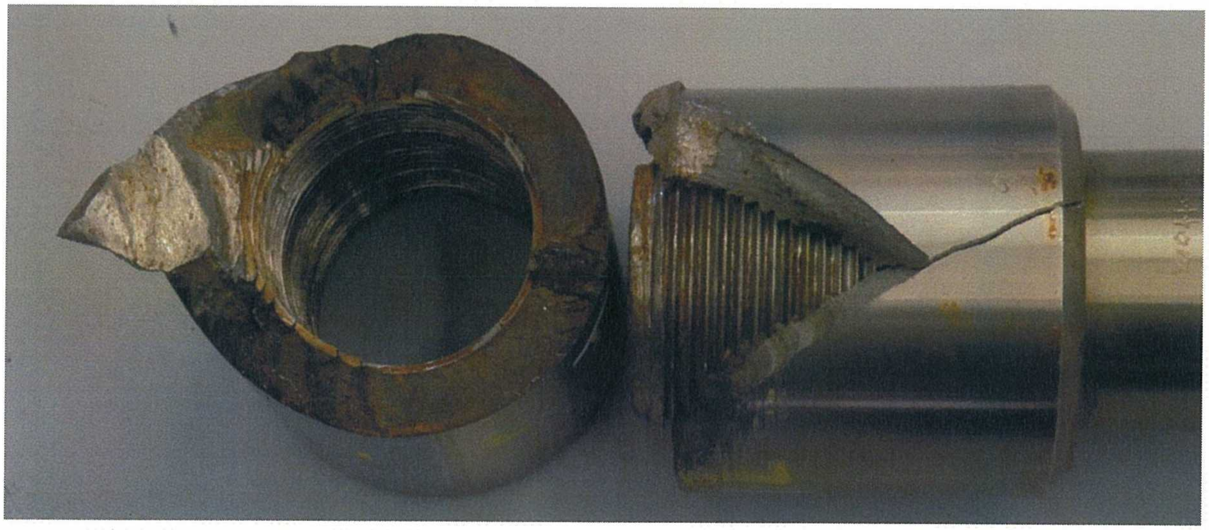
Figure 0-1: As-Received 09-P7C-7F



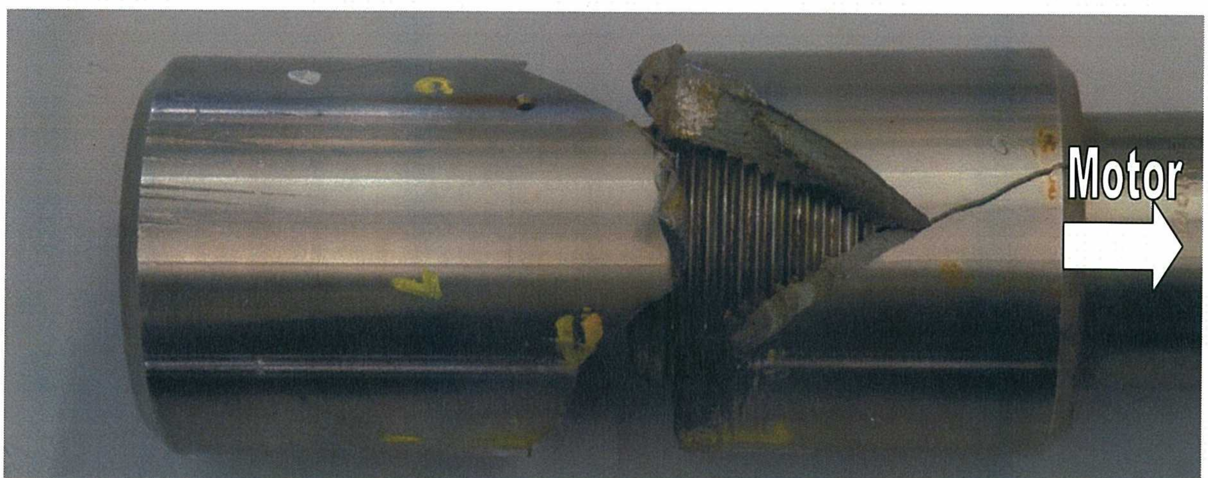


Figure 0-2: As-Received 11-P7C-6F

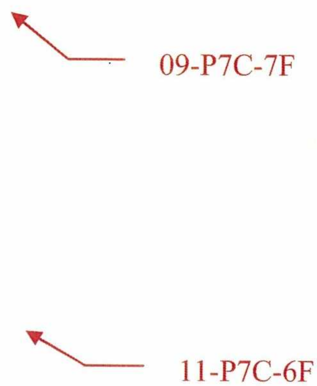
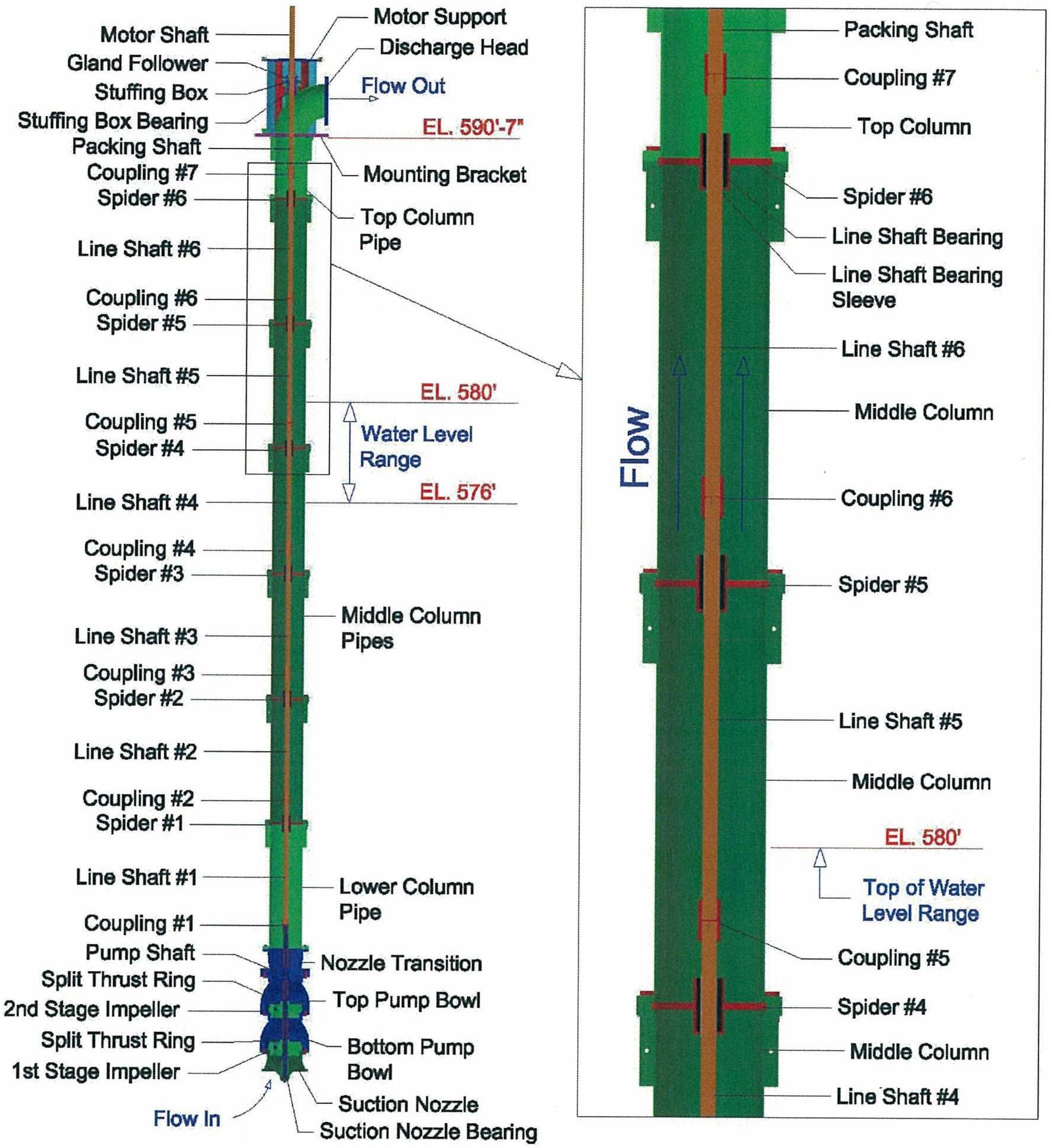


Figure 0-3: SWS Pumps Shaft Assembly [3b]



Note: Spider refers to intermediate shaft guidance bushing.

Figure 0-4: PLP SWS Pump Rendering

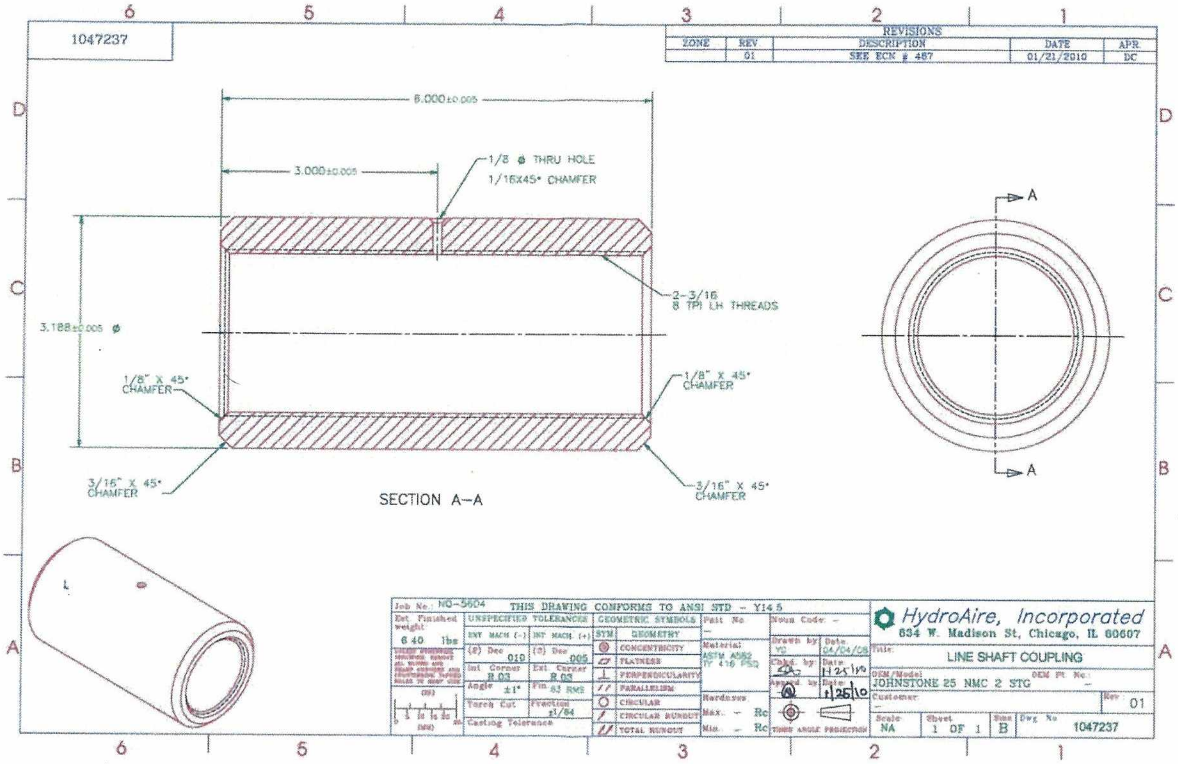


Figure 0-5: Coupling Drawing [19]

INPUTS/ASSUMPTIONS

The following inputs and assumptions are utilized for this report. Inputs and assumptions requiring verification are identified as such.

Inputs

1. Specified hardness for the couplings is in the range of 28 to 32 HRC [4].
2. Hydraulic forces on the pump coupling are taken to be 8kips per [14].
3. Service water basin elevation ranges from 576 ft to 580 ft for the period from January, 2009 to August, 2011. For the same period, the water temperature ranged from a minimum of 32°F to a maximum of 76°F (see data in Attachment A)
4. The SWS pumps are vertical turbine pumps that take suction from the bottom and discharges through the column and out the discharge head. Therefore line shafts, couplings and components below the stuffing box will be exposed to the service water when the pumps are on. Based on the service water basin elevation, couplings 1 through 4 are constantly submerged, whereas coupling 5 through 7 are subjected to cycles of wet and dry depending on whether the pumps are on or off. Also depending on water elevation, coupling 5 can be submerged when the pump is not on. Refer to Figure 0-4 for illustration of pump with water flow and relationship to basin water elevation variations.
5. The convention used in this report to reference couplings is as follows:

   YY-Pump-CN with Optional F

   Where:

   YY= two digit year in which the coupling was extracted from the pump.

   Pump = P7A, P7B or P7C

   CN = Coupling Number

   Optional F = Identifies a coupling that has failed.

   For example: 09-P7C-7F is the failed coupling extracted from Pump 7C in 2009.

Assumptions

1. There are no assumptions utilized in this report.

TESTING AND EXAMINATION

The submitted components, including the 09-P7C-7F and 11-P7C-6F couplings, were examined and tested in accordance with LPI Procedure F11358-P-001 [5] and the test matrix presented in Table 0-1. The result of the testing and examination is discussed in the following sections.

Visual and Stereomicroscopic Examination

11-P7C Intact Couplings

In all seven (7) intact couplings (#1 through 5, 7 and 8), disassembled from pump P7C following failure of 11-P7C-6F, were shipped to LPI for examination. Each coupling was engraved on each end with the shaft numbers that connected to the coupling. A representative example of an intact coupling is shown in Figure 0-1. The outer diameter of each intact coupling exhibited wrenching marks, which likely occurred during removal of the couplings. Evidence of previous hardness tests performed was present on both the outer diameter and ends of many couplings.

Each coupling exhibited a single alignment hole at its center, 0.125 in. in diameter. The coupling ends were chamfered at 45° on both outer (0.187 in.) and inner diameters (0.125 in.). The inner diameter of each coupling was fully threaded.

Visual examination of all intact couplings did not reveal significant signs of corrosion or degradation on the exterior. The 1/8" diameter shaft alignment holes on the intact couplings did not show any signs of corrosion deposits.

Coupling dimensions taken at points shown in Figure 0-2, are provided in Table 0-1.

Coupling 11-P7C-6F

The fracture surface of the impeller end of coupling 11-P7C-6F was sectioned for analysis, as shown in Figure 0-3. The fracture surface was located near the center of the coupling. Approximately half of the fracture surface was flat and aligned perpendicular to the coupling axis. The flat fracture surfaces occur in two regions that each display an elliptical shape emanating from the thread root at the inner diameter and extend to the outer diameter, as shown in Figure 0-3. The elliptical features reveal that cracks initiated at the thread root and propagated from the inner to the outer diameter of the coupling. Visually, the two elliptical crack patterns are indicative of stress corrosion cracking (SCC). The remaining portion of the fracture surface consisted of slanted fracture, indicating an overload event. The overload event occurred after the flat fractures propagated through the wall thickness. Thread roots exhibited red/brown corrosion products, as shown in Figure 0-4. Corrosion deposits are visually apparent on the facture surfaces, threads and at the 1/8" alignment hole of coupling 11-P7C-6F. The corrosion deposit streak at the bottom of the 1/8" diameter shaft alignment hole is indicative of the coupling undergoing a wet and dry cycle with the pump on and off (Figure 0-4).

The pointed tips of the fracture surfaces of the motor end and impeller end of fractured coupling 11-P7C-6F each exhibited signs of mechanical damage.

Coupling 09-P7C-7F

The fractured coupling 09-P7C-7F measured between 2.058 and 3.425 in. in length. Visual examination of the 09-P7C-7F coupling failure surface revealed similar patterns as the 11-P7C-6F failure surface with a smooth surface initiated at the thread root of the coupling. Dark spots indicative of corrosion deposits were also evident on the failure surface.

2011 Shafts

Two shafts (shaft #5 and 6) from pump P-7C were shipped to LPI for visual examination. The end of shaft 5 and 6 that touch each other inside of failed coupling 11-P7C-6F were visually examined to characterize the nature of the galling at the end of the shaft. The pointed tips of the fracture surfaces of the motor end and impeller end of fractured coupling 11-P7C-6F each exhibited signs of mechanical damage. The ends of shaft Nos. 5 and 6 also exhibited mechanical damage, as shown in Figure 0-5. This damage was most likely caused after the initial failure by repeated contact between the fractured couplings and the shaft ends.

Dimensional Examination

Coupling 11-P7C-6F was received in two halves that each exhibited a circumferential fracture surface. The bottom half (impeller end) of 11-P7C-6F measured between 3.030 and 4.290 in. in length. The top half (motor end) of the same coupling measured between 1.200 and 3.148 in. in length. The length and diameter of all intact coupling were measured and the results are summarized in Table 0-1. The outside dimensions are within the specified dimensions and tolerances of HydroAire drawing 1047237 [19].

To evaluate the concentric threading of each coupling, the wall thickness (from the outer diameter to the thread crest) was measured around the diameter on each coupling end, as shown in Figure 0-2. Table 0-2 gives the measured wall thicknesses. Coupling 11-P7C-4 exhibited the highest eccentricity (0.007 in.), occurring at its motor end. Couplings 11-P7C-5 and 11-P7C-6F were sectioned prior to dimensional analysis and subsequently some wall thickness measurements were not available

Magnetic Particle Examination (MT)

Coupling 11-P7C-6F

Visible cracks in coupling 11-P7C-6F readily highlighted the un-opened fracture surfaces upon MT examination as shown in Figure 0-6.

Intact Coupling

Couplings 11-P7C-5 and 11-P7C-7 were split in half in the longitudinal direction to examine for cracks or other discontinuities by fluorescent magnetic particle testing (MT). MT did not reveal any indications on coupling 11-P7C-5. MT revealed an indication, observed as a well-defined bright fluorescent line, at the thread root near the shaft alignment hole of coupling 11-P7C-7 as presented in Figure 0-7. The MT indication in coupling 11-P7C-7 is approximately 0.86” in length around the inner circumference along the thread root.

Metallurgical and Scanning Electron Microscopy

A longitudinal specimen cut through the 11-P7C-7 indication observed by MT was prepared by mounting in plastic, ground and polished for metallographic examination. Figure 0-8 shows, in the as-polished condition, a branching crack initiating from a pit in the thread root. The branching network of cracks is a typical feature of stress corrosion cracking (SCC).

Next, the specimen was suitably etched to reveal micro-structural details. The microstructure in the vicinity of the branched crack, as shown in Figure 0-9, reveals the intergranular nature of the network of cracks, which is characteristic of intergranular SCC (IGSCC). The general microstructure of the 11-P7C-7, as shown in Figure 0-9, was observed to be tempered martensite. This material can be susceptible to SCC.

The fracture surface of the 11-P7C-6F and 09-P7C-7F were examined in a scanning electron microscope (SEM). The threaded side of the fracture was cleaned in an ultrasonic bath containing an acetone/methanol mixture. The cleaned section was examined in a SEM at 20 kV accelerating potential. SEM examination revealed the fracture surface morphology to exhibit a rock-candy appearance, characteristic of intergranular stress corrosion cracking (IGSCC) as shown in Figure 0-10. This is typical for a quench and tempered steel, such as a 400 series martensitic steel.

Tensile Test

Tensile specimens were prepared for couplings 11-P7C-5, 11-P7C-6F and 11-P7C-7. The results of the tensile test on the specimens are documented in LPI Form "LPI-13.1-Rev-3-Att-A-Tensile Test and included in Attachment B. The tensile test results are summarized in the Table 0-3. The yield and tensile stresses are consistent with ASTM A582 Type 416 stainless steel [6].

Composition of Base Metal

The composition of the base metal for the 09-P7C-7F, 11-P7C-5, 11-P7C-6F and 11-P7C-7 were evaluated by chemical analysis and the results are provided in Table 0-4. The composition of all tested couplings is consistent with the chemical requirements of ASTM A582 Type 416 stainless steel [6].

Composition of Surface Deposit

Deposits on the 11-P7C-6F and 09-P7C-7F fracture surfaces were analyzed by energy dispersive x-ray spectroscopy (EDS) in the SEM prior to cleaning. As shown in Figure 0-11, the spectrum contained large peaks for iron, chromium, manganese, and silicon from the base material of the coupling. Note the high chromium level in the spectrum shown in Figure 0-11. The high level is attributed to a local concentration of chromium carbine in the EDS sampling volume. An additional EDS spectrum, taken over a larger area of the fracture surface, is provided in Figure 0-12. Also exhibited was a large peak for oxygen and smaller peak of chlorine and sulfur, indicating that corrosion products consisted of oxides, chlorides and sulfides. The presence of chlorine from the environment is known to be a primary cause of SCC in stainless steel.

Hardness Surveys

Surface Hardness

Surface hardness survey was performed in accordance with the requirements of ASTM E18-07 [7] on couplings 1 through 7 extracted from SWS P-7C following the 2011 event and coupling 09-P7C-7F. Results of the hardness survey were documented in form LPI-13.1-Rev-3-Att-A-Hardness Survey". The completed survey forms are presented in Attachment C. Surface hardness was measured on the top and bottom ends of each coupling, unless noted otherwise. Results of Rockwell C hardness (HRC) measurements are summarized in Table 0-5.

The required hardness for an intermediate tempered 416 stainless steel meeting specification ASTM Standard A582 is between 24 HRC and 32 HRC (248 HB and 302 HB). Based on the surface hardness results in Table 0-5, five couplings (11-P7C-4, 11-P7C-6F, 11-P7C-7, 11-P7C-8, and 09-P7C-7F) exhibit surface hardness above specification, and one coupling (11-P7C-3) exhibits surface hardness at the upper limit of the specification.

Thru-wall Hardness

Through thickness hardness was measured near the center of each coupling from the outer diameter (OD) to the inner diameter (ID) of couplings 11-P7C-5, 11-P7C-6F, and 11-P7C-7 at two diametrically opposite locations. Results of the through wall Rockwell C hardness measurements are presented in Table 0-6.

Charpy V-Notch (CVN) Impact Testing

Charpy V-Notch (CVN) impact test specimens with radial notches facing the inner diameter were machined from couplings 11-P7C-5, 11-P7C-6F, 11-P7C-7 and 09-P7C-7F. Impact testing was performed on the coupling material in accordance with ASTM Standard E23 [9] over a temperature range of 32°F to 152°F. Results of impact testing are given in Table 0-7. A plot of the CVN data is provided in Figure 0-13.

No requirements for CVN impact test absorbed energy are specified in ASTM Standard A582. Nevertheless, the impact tests reveal low absorbed energy that indicates the coupling material to be notch sensitive under dynamic loading conditions. The low facture toughness of the couplings makes them susceptible to stress corrosion cracking (SCC) under the right environment and subject to tensile stress that would not otherwise fracture the material. 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 582 Type 416 stainless steel, is a martensitic steel that is susceptible to SCC at low toughness.

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Table 0-1: Measurement of Coupling Outside Dimensions

Coupling	Length (in.)	OD (in.)
11-P7C-1	6.000	3.186
11-P7C-2	6.002	3.190
11-P7C-3	5.998	3.187
11-P7C-4	5.995	3.189
11-P7C-5	6.000	3.187
11-P7C-6F	(a)	3.186
11-P7C-7	5.997	3.187
11-P7C-8	5.998	3.187
09-P7C-7F	(b)	3.187

Notes: (a) coupling No. 6 was fractured near the center of the length and measurements of fractured pieces are described in the text, (b) only one half of the fractured coupling No. 09-P7C-7F was sent to LPI and the measurements of this piece of coupling are described in the text.

Table 0-2: Measurement of Coupling Wall Thickness

Coupling	Wall thickness (Motor End)				Wall Thickness (Impeller End)			
	t_1	t_2	t_3	t_4	t_1	t_2	t_3	t_4
11-P7C-1	0.566	0.566	0.565	0.567	0.568	0.566	0.565	0.566
11-P7C-2	0.567	0.568	0.567	0.569	0.566	0.565	0.567	0.567
11-P7C-3	0.567	0.567	0.568	0.567	0.571	0.566	0.570	0.569
11-P7C-4	0.574	0.567	0.569	0.569	0.568	0.569	0.571	0.569
11-P7C-5	0.571	0.570	0.570	N/A	0.568	0.570	0.572	N/A
11-P7C-6F (a)	N/A	N/A	N/A	N/A	N/A	0.568	0.569	N/A
11-P7C-7	0.572	0.571	0.569	0.568	0.568	0.570	0.569	0.570
11-P7C-8	0.563	0.566	0.567	0.567	0.567	0.566	0.564	0.566
09-P7C-7F (b)	N/A	N/A	N/A	N/A	0.569	0.569	0.568	0.567

Notes: (a) the top portion of fractured coupling No. 6 was not removed from shaft, (b) only the bottom half of fractured coupling 09-P7C-7F was available.

Table 0-3: Tensile Test Results

Coupling	Specimen Identification	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)
11-P7C-5	5-1	134	148	17.9
	5-2	131	147	16.2
11-P7C-6F	6-1	139	155	16.7
	6-2	142	155	15.7
11-P7C-7	7-1	138	151	13.3
	7-2	137	152	15.5

Table 0-4: Metal Composition of Couplings (Wt. %)

Element	Coupling No.				ASTM A582 TP 416 [6]
	11-P7C-5	11-P7C-6F	11-P7C-7	09-P7C-7F	
C	0.10	0.12	0.11	0.12	0.15 max
Cr	12.93	12.90	12.92	12.38	12.00 – 14.00
Cu	0.16	0.16	0.16	0.12	ns
Mn	1.09	0.85	068	1.13	1.25 max
Mo	0.03	0.03	0.03	0.05	0.60 max
Ni	0.14	0.14	0.14	0.19	ns
P	0.007	0.015	0.020	0.41	0.060 max
S	0.51	0.36	0.34	0.32	0.15 min
Si	0.23	0.23	0.25	0.46	1.00 max

ns – not specified

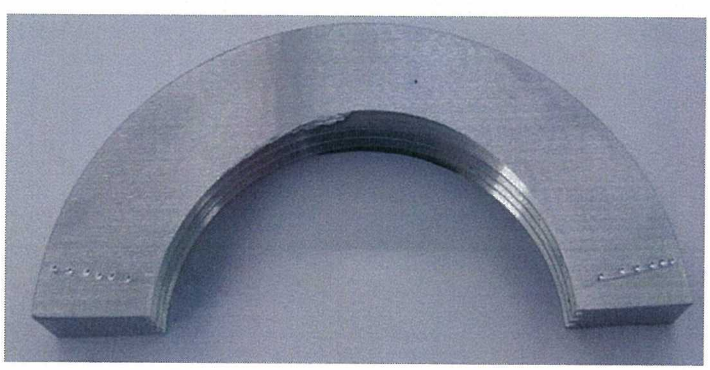
Table 0-5: Surface Hardness Survey of Couplings

Coupling	End	Average (HRC)	Measurements (HRC)
11-P7C-3	top	27.9	26.5, 28.0, 26.0, 28.6, 29.8, 28.2
	bottom	31.3	32.1, 31.5, 32.0, 29.9, 31.0, 31.0
11-P7C-4	top	31.5	30.0, 33.6, 29.4, 31.5, 30.6, 33.8
	bottom	30.8	29.7, 28.1, 30.8, 31.8, 32.1, 32.1
11-P7C-5	top	29.7	31.1, 29.6, 29.6, 30.0, 29.0, 29.0, 29.1, 30.0
	bottom	29.6	28.9, 29.5, 29.4, 29.0, 29.9, 30.9, 30.5, 27.9, 30.2
11-P7C-6F	top	–	(a)
	bottom	33.3	33.1, 33.0, 33.1, 33.0, 33.1, 33.5, 33.6, 33.6
11-P7C-7	top	32.2	31.5, 31.9, 32.0, 32.2, 32.6, 32.2, 32.2, 32.6
	bottom	30.6	30.6, 31.1, 31.3, 28.7, 30.0, 31.4, 31.0, 31.0
11-P7C-8	top	32.2	32.0, 31.8, 31.4, 32.0, 33.0, 32.7
	bottom	–	(b)
09-P7C-7F	top	32.1	33.7, 33.1, 32.8, 32.0, 30.2, 31.8, 31.2
	bottom	–	(c)

Notes: (a) top side of coupling No. 6 was kept in its as-received position on shaft No. 6, (b) deposits on the bottom of coupling No. 8 were kept intact and prevented hardness testing of the underlying base metal, (c) no bottom section of coupling 09-P7C-7F was received.

Table 0-6: Through Thickness Hardness of Couplings

Coupling	Location	Measurements from OD to ID (HRC)
11-P7C-5	1	27.2, 28.0, 28.0, 27.7, 28.0, 27.1
	2	31.5, 30.9, 30.4, 30.2, 30.2, 30.7
11-P7C-6F	1	31.5, 32.7, 32.0, 32.1, 32.2, 32.0
	2	31.5, 32.2, 31.9, 32.1, 31.5
11-P7C-7	1	31.2, 32.0, 31.7, 31.9, 31.3, 31.8
	2	32.0, 32.0, 32.0, 31.9, 32.6, 32.0



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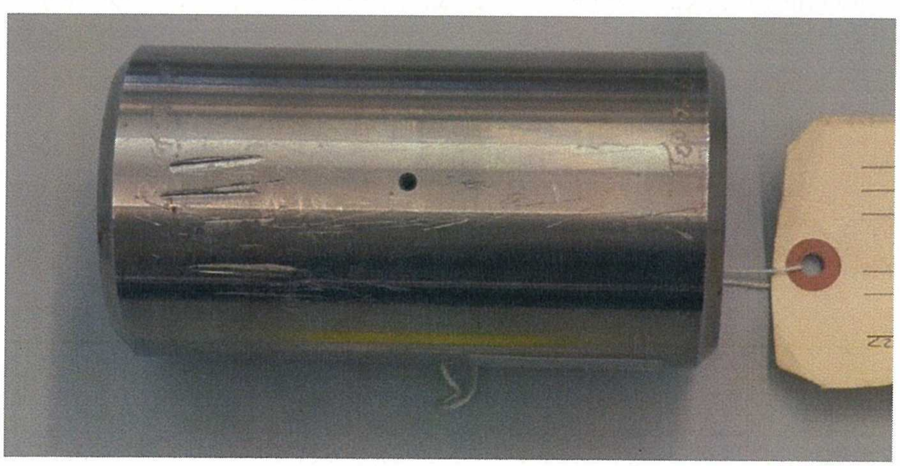
Sample through thickness hardness test specimen.

Table 0-7: CVN Impact Test Results

Coupling	Specimen Identification	Test Temperature (°F)	Absorbed Energy (ft-lb)	Lateral Expansion (in.)	Percent Shear (%)
11-P7C-5	5-C2	32	9	0.005	<10
	5-C4	32	9	0.006	<10
	5-C1	70	10	0.007	10
	5-C6	70	10	0.007	10
	5-C8	70	10	0.007	10
	5-C3	100	11	0.007	20
	5-C5	100	10	0.006	20
	5-C7	150	15	0.011	50
11-P7C-6F	6-C2	32	6	0.003	<10
	6-C4	32	8	0.006	<10
	6-C1	70	9	0.005	10
	6-C5	70	10	0.006	10
	6-C3	100	11	0.007	10
	6-C6	150	14	0.008	50
11-P7C-7	7-C2	32	10	0.003	<10
	7-C1	75	8	0.008	10
	7-C3	100	11	0.008	10
09-P7C-7F	709-C3	32	4	0.004	<10
	709-C4	32	3	0.004	<10
	709-C1	75	5	0.005	<10
	709-C2	75	6	0.002	<10
	709-C5	100	6	0.003	<10
	709-C6	152	6	0.006	<10



Coupling No. 7 in as-received form. Shaft numbers engraved on the ends. Coupling exhibited wrenching marks on outer diameter.

Figure 0-1: As-Received 11-P7C-7

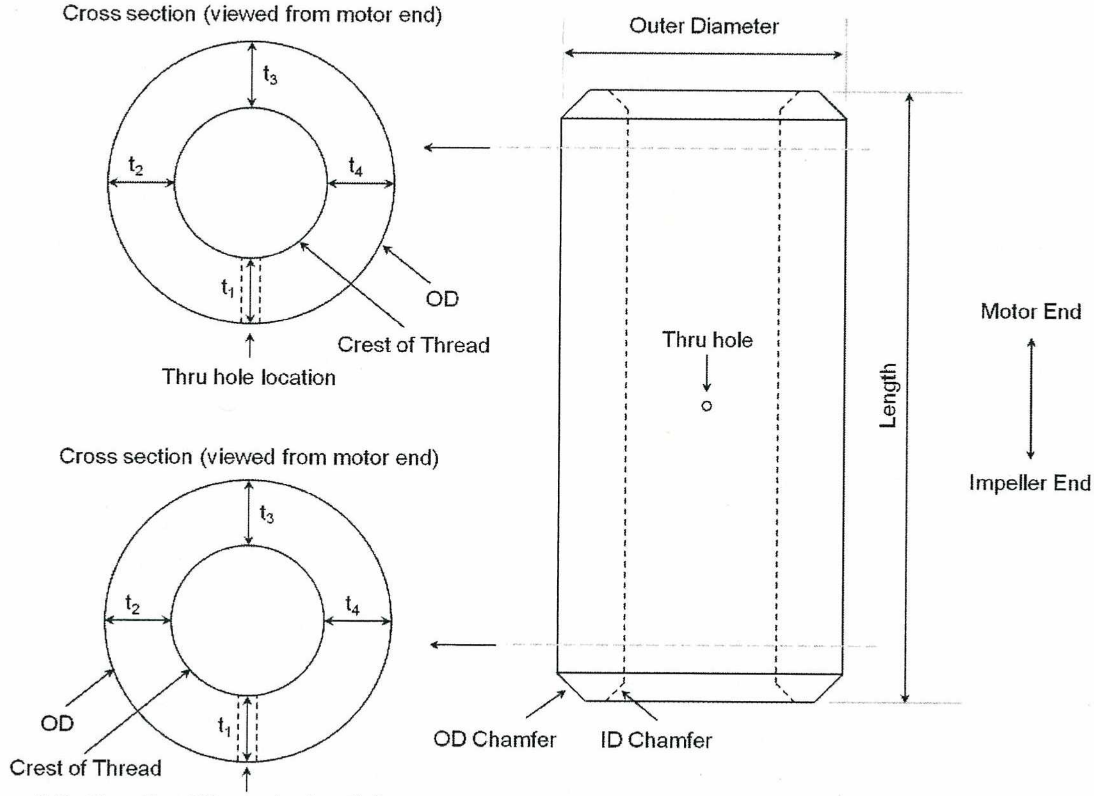
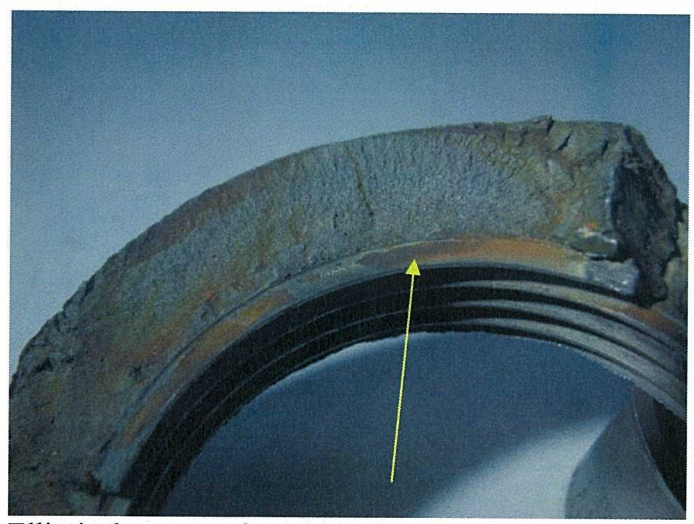


Figure 0-2: Coupling Dimensioning Scheme

Fracture surface was removed from the bulk of the coupling for analysis.



Elliptical pattern of crack on flat fracture surface, relative to coupling axis. Also, red/brown corrosion

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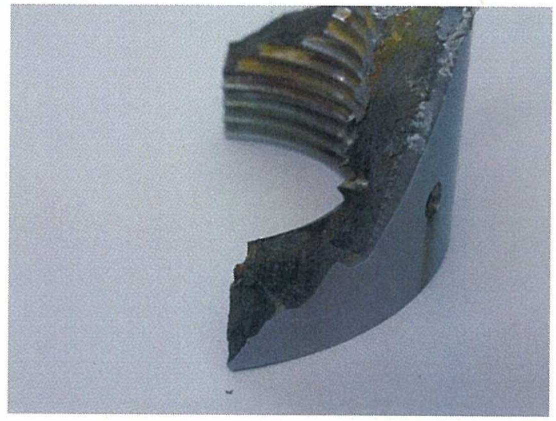
Fractured end exhibited mechanical damage (arrow). product found on the insides of coupling threads (arrow)

Figure 0-3: Visual of Fracture Surface on Coupling 11-P7C-6F



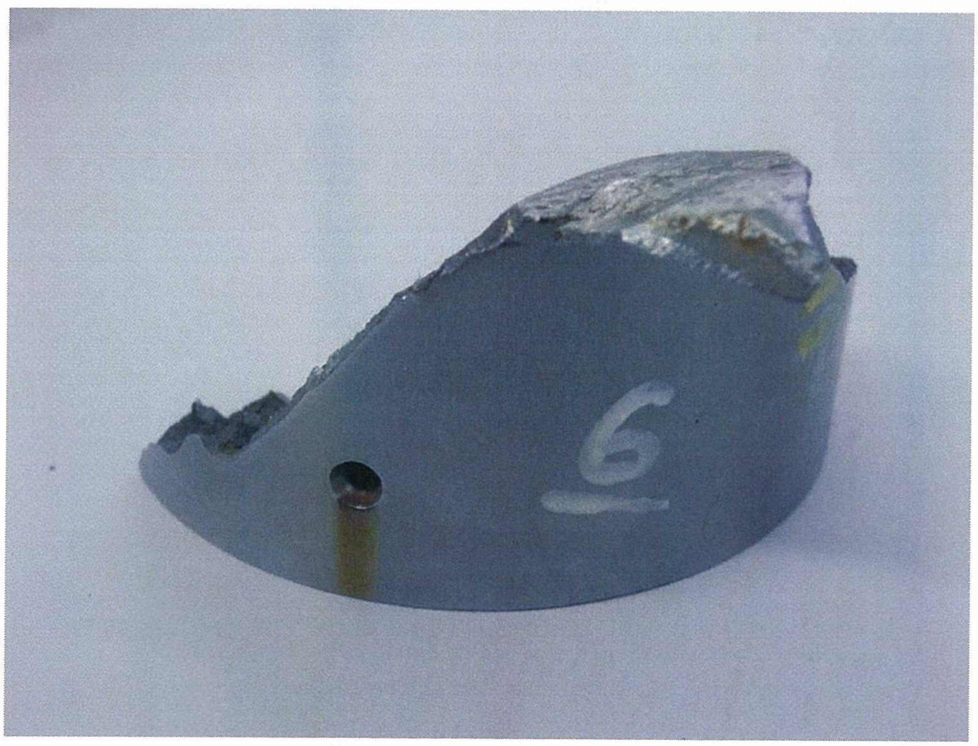


Figure 0-4: 11-P7C-6F showing Corrosion Deposit

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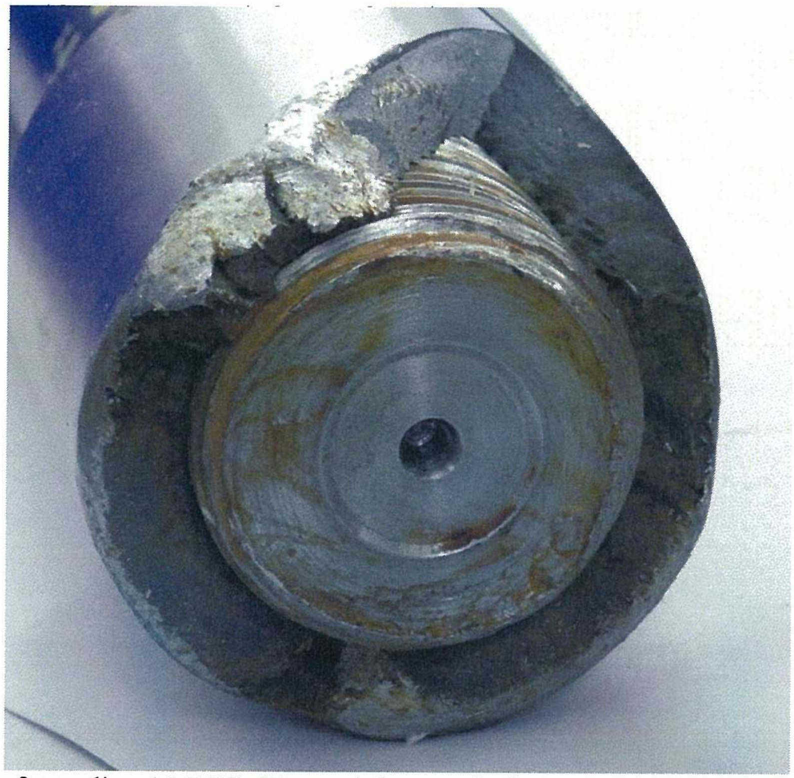
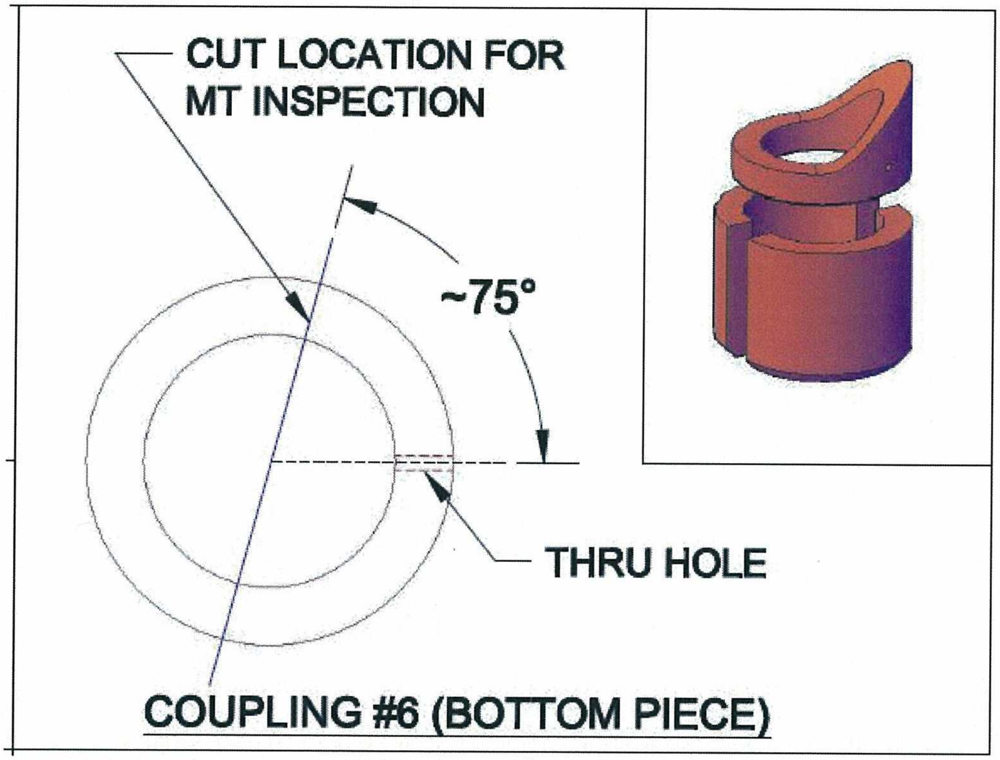
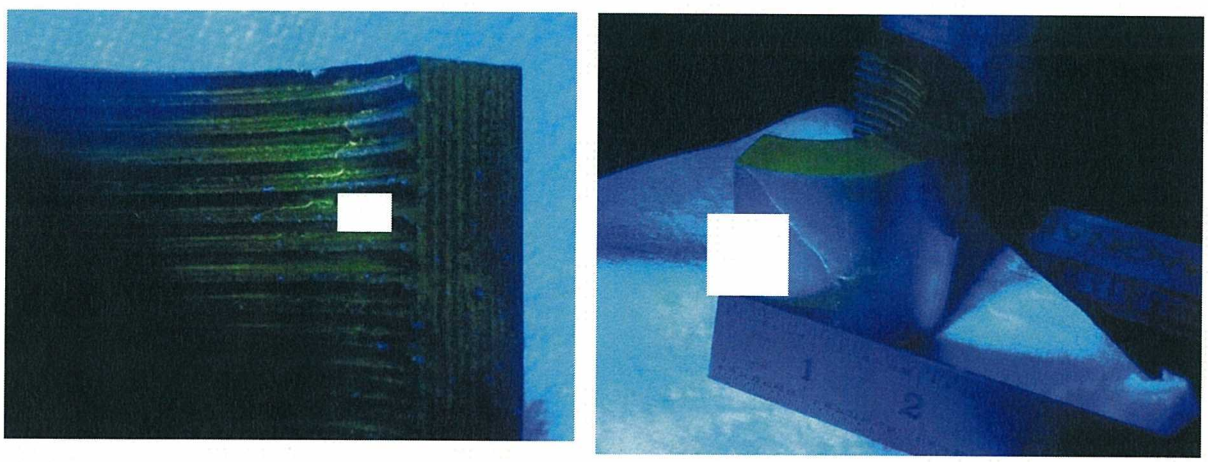


Half of coupling 11-P7C-6F remaining on shaft No. 6 exhibited damage on its fracture surface from contact with the mating coupling half and shaft 5, which occurred after fracture event.

End of shaft No. 5 exhibited gouging damage post 11-P7C-6F final failure.

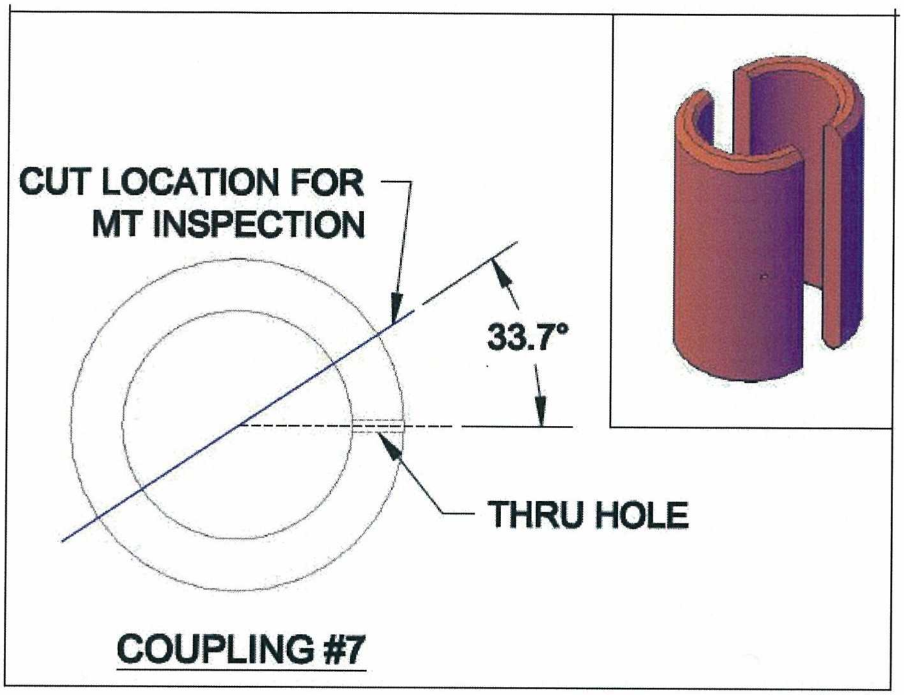
Figure 0-5: Ends of Shaft 5 and 6 Coupled by 11-P7C-6F

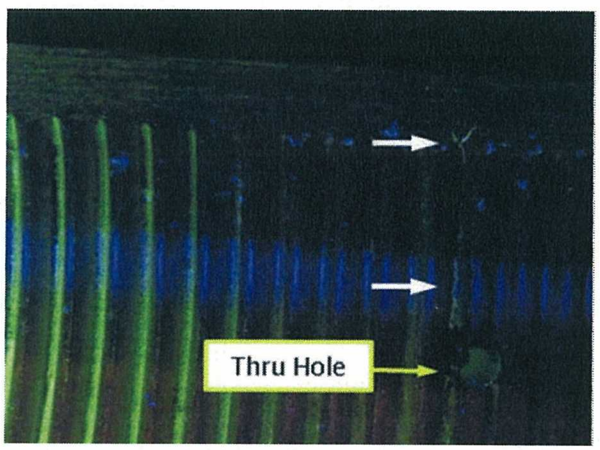


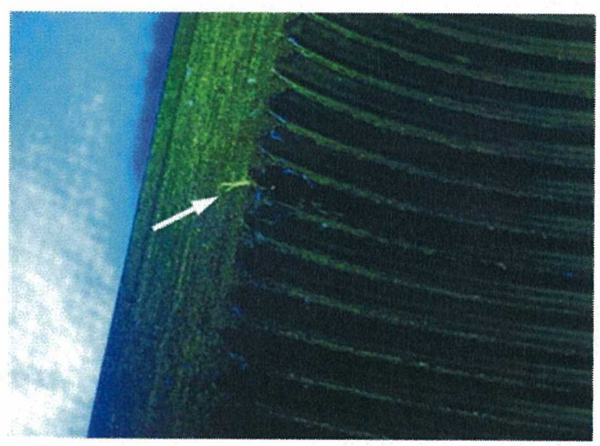


After fracture surface was sectioned, a remaining portion of coupling 11-P7C-6F was MT inspected. Arrows show location of indications.

Figure 0-6: MT Highlighting Un-Opened Fracture on Coupling 11-P7C-6F

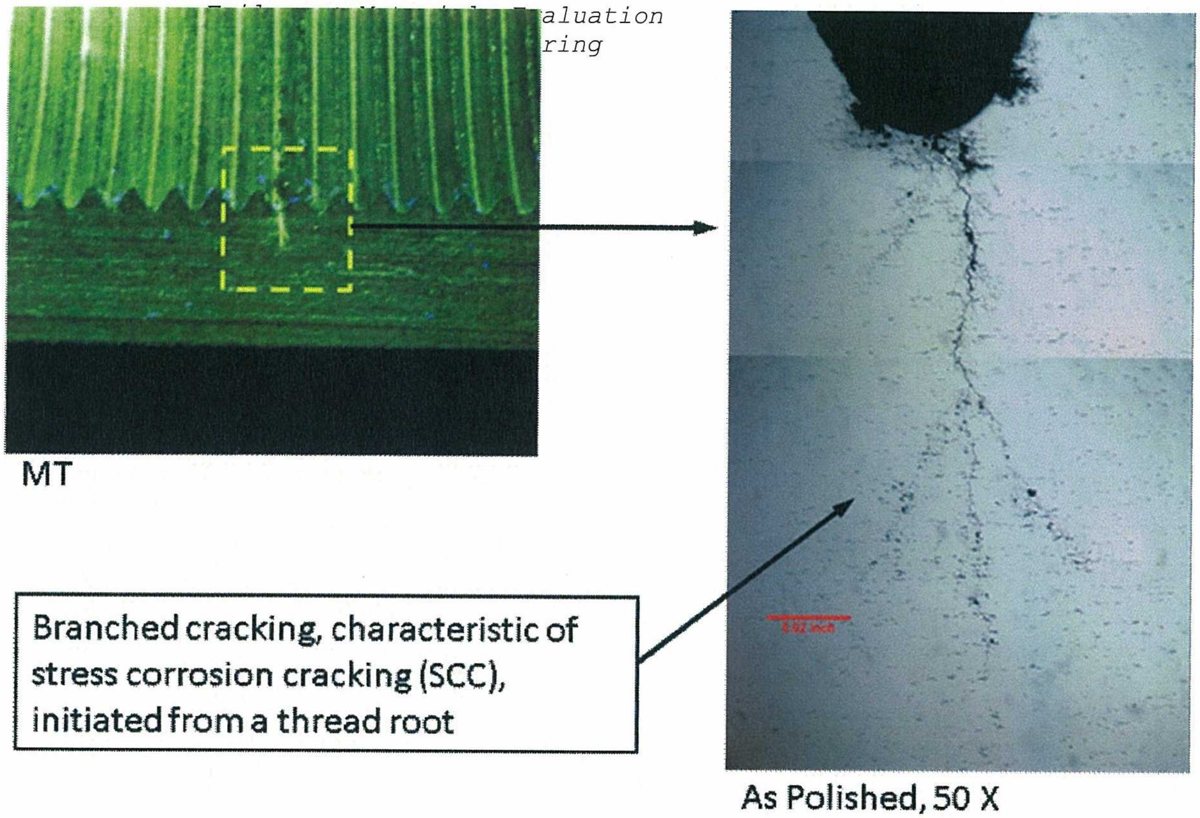






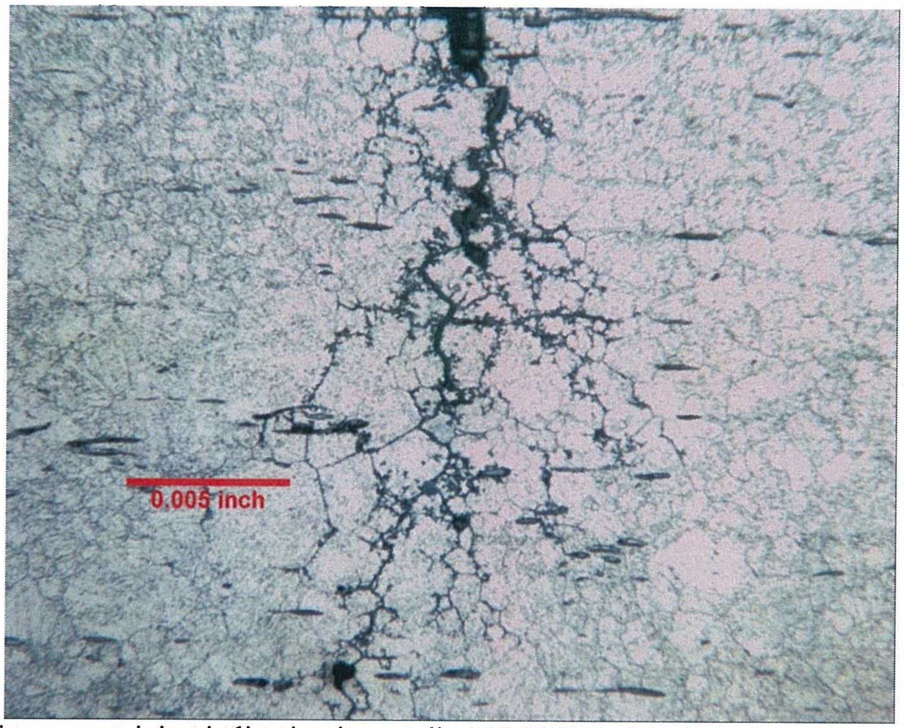
Top sketch show the cut line for coupling 11-P7C-7. Fluorescent MT examination of this coupling reveals an indication, shown by a well-defined fluorescent line, initiating from a thread root and propagating in the radial direction. The left and right images show the same indication on the two sections of this coupling after cutting in half longitudinally. Arrows show location of the indication.

Figure 0-7: MT Highlighting Crack on Coupling 11-P7C-7



Branched cracking of the indication found in 11-P7C-7. Specimen in the as-polished condition and viewed at 50x.

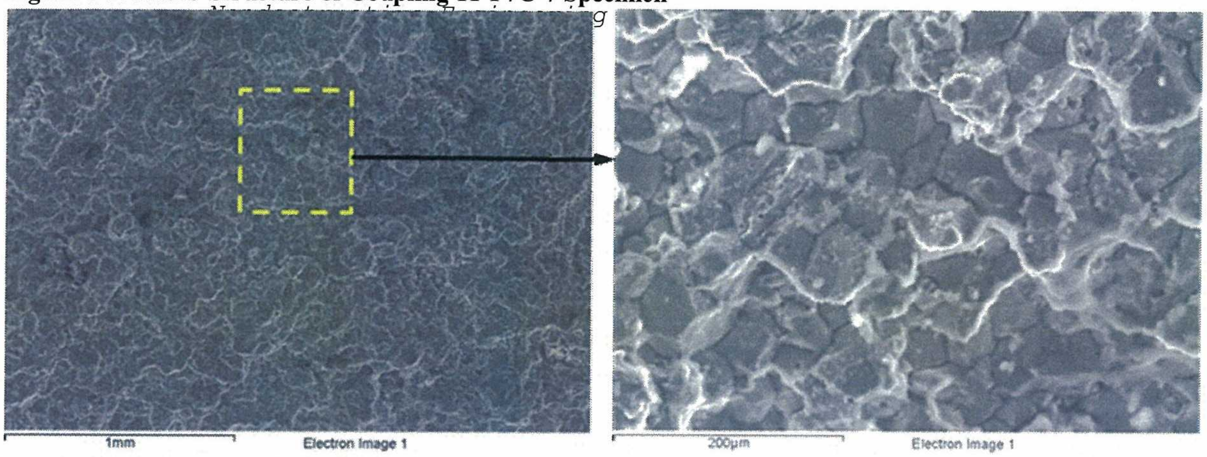
Figure 0-8: As-Polished of Coupling 11-P7C-7 Specimen



Etched specimen containing indication in coupling 11-P7C-7, showing microstructural features that reveal the intergranular nature of the branched cracking. Viewed at 200x.

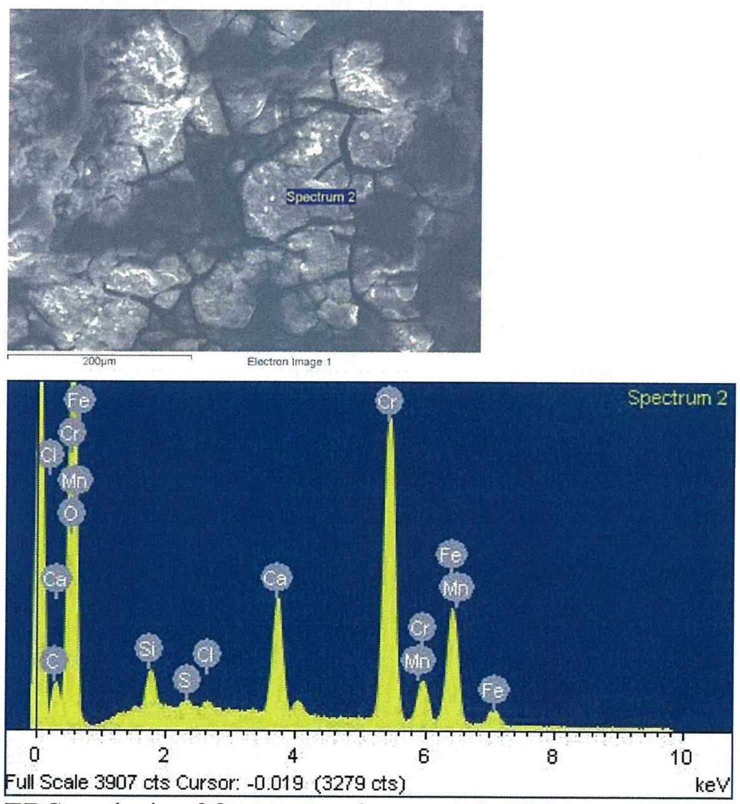
General microstructure of coupling 11-P7C-7 is tempered martensite. Specimen etched and viewed at 400x.

Figure 0-9: Micro-Structure of Coupling 11-P7C-7 Specimen



Fracture surface morphology exhibited a rock-candy appearance, characteristic of intergranular stress corrosion cracking. This is typical of a quench and tempered steel, such as a 400 series martensitic steel.

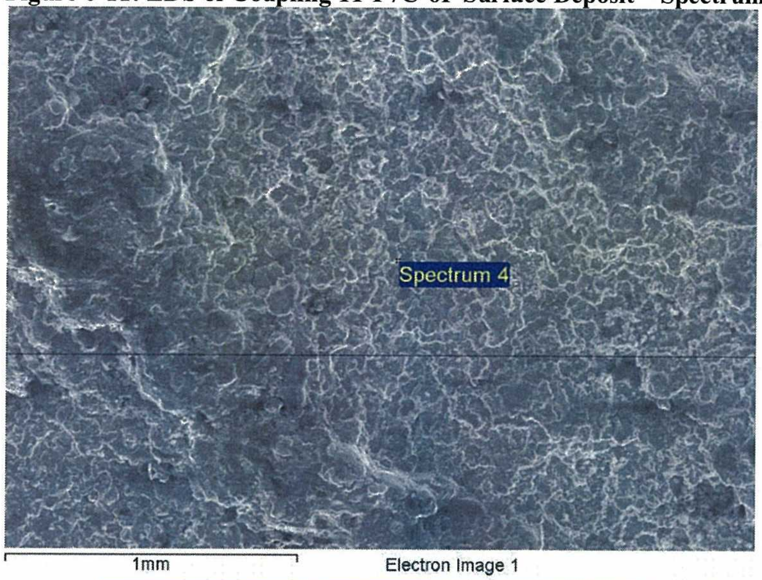
Figure 0-10: SEM of Coupling 11-P7C-6F Surface



Element	Weight%
O	40.1
Si	1.7
S	0.3
Cl	0.3
Ca	5.9
Cr	29.5
Mn	0.4
Fe	Bal.

EDS analysis of fracture surface revealed the presence of corrosive agents (chlorides, oxides and sulfides), consistent with stress corrosion cracking. Note the high chromium level in the spectrum. The high amount could be attributed to a local concentration of chromium carbine in the EDS sampling volume.

Figure 0-11: EDS of Coupling 11-P7C-6F Surface Deposit – Spectrum 2



Element	Weight %
O	7.5
Si	0.9
S	0.3
Cl	0.3
K	0.2
Ca	0.4
Cr	14.6
Mn	1.6
Fe	Bal.

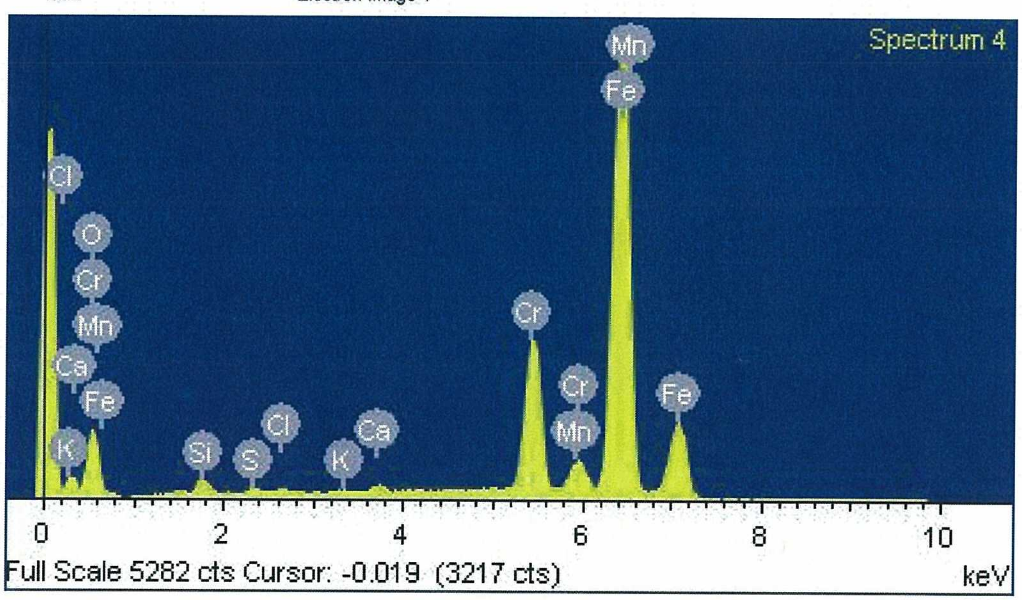


Figure 0-12: EDS of Coupling 11-P7C-6F Surface Deposit – Spectrum 4

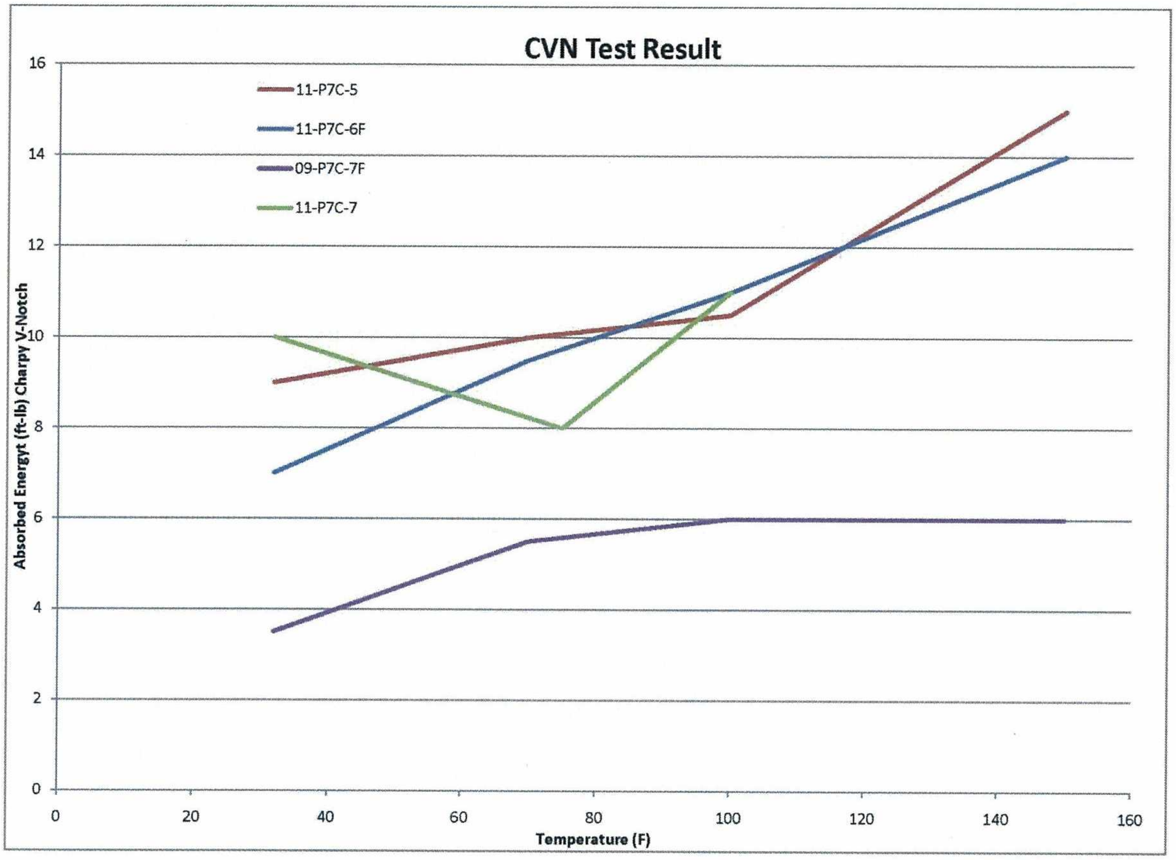


Figure 0-13: Charpy Test Result