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Nondestructive Engineering

METALLURGICAL AND FAILURE ANALYSIS OF SWS PUMP P-7C COUPLING #6

Report No. F11358-R-001
Revision 1

December, 2011

Prepared For

ENTERGY NUCLEAR OPERATIONS, INC.
PALISADES NUCLEAR PLANT

Boston Area Office, 36 Main Street, Amesbury, MA 01913
Tel: 978-517-3100   Fax: 978-517-3110   www.luciuspitkin.com

New York, NY   Boston, MA   Richland, WA

"Ensuring the integrity of today's structures for tomorrow's world" ™

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DOCUMENT RECORD

Document Type:	☐ Calculation ☒ Report ☐ Procedure
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Revision	Approval Date	Preparer	Checker	Design Verification	Approver[4]
0	10/17/11	S. Yim Ryan Chen (Section 4.3)	John Mills, Ph.D B. Elaidi (Section 4.3)	P. Bruck	P. Bruck
1	12/5/11	[signature] S. Yim	[signature] John Mills, Ph.D	[signature] P. Streeter	[signature] P. Bruck

[4] The Approver of this document attests that all project examinations, inspections, tests and analysis (as applicable) have been conducted using approved LPI Procedures and are in conformance to the contract/purchase order. Individual tests and inspections as documented in the attachments were performed and reviewed by various LPI personnel, not reflected in the document record.

Page	2	of	230	**Total Pages**	Include any Title Sheet and Attachments in page count

	DESIGN VERIFICATION CHECKLIST					
	Document No(s)[1]:	F11358-R-001			Rev.:	1
	Review Method:	X	Design Review		Alternate Calculation	Test

	Criteria	DV[2]
1	Were the inputs correctly selected and incorporated into design?	[initials]
2	Are assumptions necessary to perform the design activity adequately described and reasonable? Where necessary, are the assumptions identified for subsequent re-verifications when the detailed design activities are completed? If applicable, has an as built verification been performed and reconciled?	[initials]
3	Are the appropriate quality and quality assurance requirements specified?	[initials]
4	Are the applicable codes, standards and regulatory requirements including issue and addenda properly identified and are their requirements for design met?	N/A
5	Have applicable construction and operating experience been considered, including operation procedures?	N/A
6	Have the design interface requirements been satisfied?	[initials]
7	Was an appropriate design method used?	[initials]
8	Is the output reasonable compared to inputs?	[initials]
9	Are the specified parts, equipment, and processes suitable for the required application?	N/A
10	Are the specified materials compatible with each other and the design environmental conditions to which the material will be exposed?	N/A
11	Have adequate maintenance features and requirements been specified?	N/A
12	Are accessibility and other design provisions adequate for performance of needed maintenance and repair?	N/A
13	Has adequate accessibility been provided to perform the in-service inspection expected to be required during the plant life?	N/A
14	Has the design properly considered radiation exposure to the public and plant personnel?	N/A
15	Are the acceptance criteria incorporated in the design documents sufficient to allow verification that design requirements have been satisfactorily accomplished?	[initials]
16	Have adequate pre-operational and subsequent periodic test requirements been appropriately specified?	N/A
17	Are adequate handling, storage, cleaning and shipping requirements specified?	N/A
18	Are adequate identification requirements specified?	N/A
19	Are requirements for record preparation review, approval, retention, etc., adequately specified?	N/A
20	Has an internal design review been performed for applicable design projects? Have comments from the Internal Design Review been appropriately considered/addressed?	N/A

(1) Include any drawings developed from reviewed documents, or include separate checklist sheet for drawings
(2) Design Verifier shall initial indicating review and mark N/A where not applicable

DV Completed By:	Printed Name: P. Streeter	Signature: [signature]	Date: 12/5/11

Page 1 **of** 1 **Total Pages** — Include DV Checklist and Comment Resolution sheets in page count

RECORD OF REVISION

Revision No.	Date	Description of Change	Reason
0	*	Original Issue	
1	*	Changes are denoted by a revision bar.	Incorporated comments provided in Attachment X

* See Document Record

DOCUMENT SOFTWARE RECORD

(Include Separate Sheet for Each Software Package Utilized)

1	**Computer Software Used** (Code/Version)	ANSYS Version 11.0	
2	**Software Supplier**	ANSYS, Inc.	
3	**Software Update Review**	☒ Error notices; describe: Reviewed error reports for elements used ☐ Other; describe:	
4	**Nuclear Safety Related Software**	☐ NO ☒ YES[1]	1. If YES: Hardware identification # used for execution: *Desktop Serial #: J2WTBM1* Basis for V & V: [17]
5	**Input Listing(s)**	☐ Input listing(s) attached: ☒ Not attached; identify <u>File</u>/Disc ID*: Coupling Pump Bearing & Bending.txt Coupling Pump Bearing.txt Coupling Pump No Bearing.txt *A CD with input listings and output data to be provided on project completion.	
6		☐ Output results attached: ☒ Not attached; identify <u>File</u>/Disc ID*: *A CD with input listings and output data to be provided on project completion.	
7	**Output Identifier(s)***	(see 6 above)	
	*e.g., run date/time; use for reference, as appropriate, within body of calculation		
8	**Comments**		
9	**Keywords****	SOLID45, Static	
	**For use in describing software features used <u>in this calculation</u>; use common terms based on software user manual.		
10	**Project Manager Name:**	S. Yim	
If computer software was used on project, complete form with required information. Update the LPI <u>Computer Software Use List</u> per LPI Procedure 13.1 requirements.			

DOCUMENT INSTRUMENT RECORD				
Instrument Used		Instrument Description	Serial No.	Calibration Due Date
1	☒	Tensile Testing Machine (120 kips)	Baldwin 37205	4/7/12
2	☒	Extensometer (1 in)	2620-824/1033	4/7/12
3	☒	Charpy Impact Tester	Satec Model SI-1K/1306	6/17/12
4	☒	Hardness Tester	Wilson 5YR/58	4/7/12
5	☒	Thermocouple	Omega 650 J/8320	7/12/12
6	☒	Caliper	Fowler 6"/7082002	6/21/12
7	☒	Magnetic Yoke	Magnaflux Y-6/43530	*Per use calibration*
8	☒	Caliper	Starrett 6"/09324754	6/24/12
9	☒	Caliper	Mitutoyo 12"/06535451	6/21/12
10	☒	Caliper	VME 6"/2-12005	6/21/12
11	☒	SEM/Oxford EDS	17218-118-01	*Per use calibration*
12	☐			
13	☐			
14	☐			
	Project Manager Name:	S. Yim		

For instrument(s) used on the project, identify instrument and include the instrument calibration due date. Update the LPI *Instrument Use List* per LPI Procedure 13.1 requirements.

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1.0 INTRODUCTION/BACKGROUND

Two failed Type 416 stainless steel (SS) couplings along with other intact couplings and shafts extracted from service of the Service Water System (SWS) pumps at Palisades Nuclear Plant (PLP) were submitted to **LPI** (Lucius Pitkin, Inc.) for material and failure assessment, as documented in the receipt inspections provided in Attachment B. One of the two failed couplings was from a failure event in September 2009 as documented in CR-PLP-2009-04519 [1][1] and the other was from a failure event in August 2011 as documented in CR-PLP-2011-03902 [2]. The failed couplings from the 2009 and 2011 failure events are herein referred to as "09-P7C-7F" and "11-P7C-6F", respectively (refer to coupling identification convention in Section 2.1). Photographs of couplings 09-P7C-7F[2] and 11-P7C-6F are presented in Figure 1-1 and Figure 1-2, respectively. The majority of intact couplings (22 in total) and two (2) shafts were from all three SWS pumps following the 2011 failure event and remaining couplings (3 in total) were extracted from pump P-7C following the 2009 event.

The SWS is comprised of three motor driven vertical multistage pumps, tagged P-7A, P-7B and P-7C, supplying water from Lake Michigan to three service water headers. All three SWS pumps are similar in design in that they are comprised of two stage stainless steel impellers coupled to the motor by six line shafts, a packing shaft and a motor shaft for a total height of over forty (40) feet from suction to discharge. Figure 1-3 shows the shaft and coupling arrangement for the SWS pumps and identifies the location of couplings 09-P7C-7F and 11-P7C-6F. As can be seen in Figure 1-3, 09-P7C-7F is coupling #7 and 11-P7C-6F is coupling #6 in the assembly. A rendering that identifies the pump components (excluding the motor) is provided in Figure 1-4.

P-7A and P-7C are Layne and Bowler Model 25RKHC pumps while P-7B is a Johnston Model 25NMC pump. Each pump is driven by a 350 horsepower (HP) motor providing a rated 8000 GPM at 140 ft total developed head (TDH), which is 50% of the service system capacity [1].

The specified material of all shaft couplings on the three SWS pumps, including 09-P7C-7F and 11-P7C-6F, was ASTM A582 Type 416 stainless steel (SS) [4]. The material specification for the shaft couplings on all three pumps was changed from carbon steel to 416 SS and specified with a Rockwell C hardness (HRC) value of 28 to 32 under engineering change EC-50000121762 [4] in December

[1] Numbers in brackets (e.g. [5]), indicate references listed in Section 6.0.
[2] Only the bottom half or impeller end of 09-P7C-7F was available for examination. The other half had been utilized in support of failure analysis in 2009.

2007. The couplings were also redesigned to incorporate an alignment hole that allows verification of proper shaft installation. The shaft couplings for P-7A were replaced on April 4, 2009 per Work Order (WO) 51637416 (see [2]). The shaft couplings for P-7C were replaced on June 12, 2009. The shaft couplings on P-7B were replaced during a rebuild of the pump and installed in June of 2010 [2]. A detailed drawing of the line shaft coupling is provided in Figure 1-5.

1.1 Scope and Purpose

The scope and purpose of this report is to provide results of the metallurgical examination and tests performed in accordance with LPI Procedure F11358-P-001 [5], and provide a probable root cause of the 2011 coupling failure. The scope of tests and examinations performed are provided in the Table 1-1 Test Matrix.

Table 1-1: Test Matrix

Test/Exam	Couplings			
	2011			2009
	P-7C	P-7B	P-7A	P-7C
Visual & Photographic	1 thru 8	4 thru 7	4 thru 7	
Surface Hardness	1 thru 8	4 thru 7	5 thru 7	7
Dimensional Exam	1 thru 8	4 thru 7	4 thru 7	
Comp Analysis of Surface Deposits	6 and 7			
MT Exam	4 thru 7	4 thru 7	4 thru 7	
Tensile Test	5 thru 7	5 thru 7	5 thru 7	
CVN Test	5 thru 7	5 thru 7	5 thru 7	7
Thru Thick Hardness	5 thru 7	5 thru 7	5 thru 7	7
Comp Analysis	5 thru 7	5 thru 7	5 thru 7	
Metallography	6 and 7	5 thru 7	6	
SEM	6			7

1.2 Evaluation Timeline

This section discusses the evaluation and testing timeline of the above scope. Coupling 11-P7C-6F failed on August 9th, 2011. Following the failure, LPI was contracted by Entergy's PLP to provide metallurgical and failure assessment of failed coupling 11-P7C-6F and provide on-site metallurgical support to the root cause evaluation (RCE) team. LPI received couplings 11-P7C-6F, -5, -7K, and shaft 5 and 6 from P-7C as documented in LPI receipt inspection dated 8/17/11. On 8/17/11 following visual examination of 11-P7C-7F, LPI provided a preliminary verbal assessment of the failure mechanism as being typical of stress corrosion cracking (SCC). Based on this preliminary observation, LPI recommended that in the short term PLP should consider replacing (at a minimum) couplings subjected to wet/dry cycles (i.e. couplings 5, 6, and 7) on pumps P-7A and P-7B with available spare couplings. For the long term, LPI advised that a permanent replacement material should be investigated for the service environment but suggested Nitronic 50 or AL-6XN as possible replacement material for the subject SWS pump couplings. The verbal assessment and recommendation were directed to the RCE team and the NRC's special inspection team (SIT).

On 8/18/11, LPI received coupling 09-P7C-6F and remaining couplings 11-P7C-1 through -4 and 11-P7C-8 for testing and evaluation. On 8/19/11, LPI issued two (2) preliminary interim reports, F11358-IR-002 which summarized the finite element analysis model of a typical coupling and F11358-IR-003, which summarized the VT and MT findings of couplings 11-P7C-5, -6F and -7K and hardness testing of 11-P7C-6F. On 8/23/11, Revision 0 of F11358-IR-003 was transmitted to PLP via LPI letter F11358-L-003. F11358-IR-003 summarized the VT, MT, and hardness values of couplings 11-P7C-5, -6F and -7K and Charpy results of couplings 11-P7C-5 and -6F. Based on these results, PLP implemented plans to replace the existing 416 SS couplings on P-7A and P-7B with 17-4PH recommended in [19].

On 8/24/11, the 416SS couplings on P-7A were replaced with 17-4PH couplings. LPI received extracted couplings 11-P7A-1 through -8 on 8/30/11, as documented in the receipt inspection in Attachment B. Preliminary LPI F11358-IR-004 was issued on 9/1/11 which summarized the VT, MT, hardness, tensile and CVN impact test results.

On 8/31/11, the 416SS couplings on P-7B were replaced with 17-4PH couplings. LPI received extracted couplings 11-P7B-4 through -7 on 9/2/11. Preliminary LPI F11358-IR-005 was issued on 9/12/11 which summarized the VT, MT, hardness, and tensile test results.

Elevation View

Top View

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

(Only the bottom half or impeller end of 09-P7C-7F was available. Scale in units of inches; typical throughout)

Figure 1-2: As-Received 11-P7C-6F

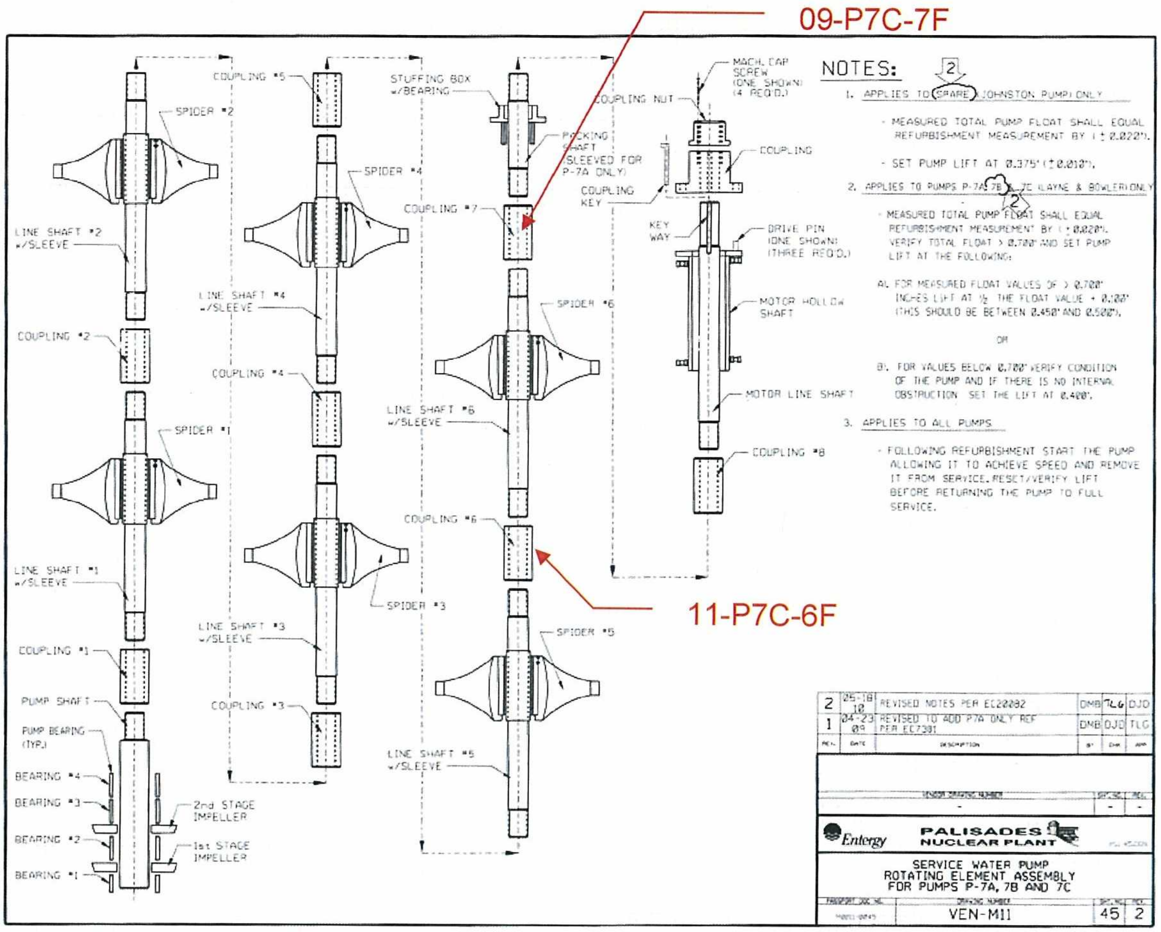
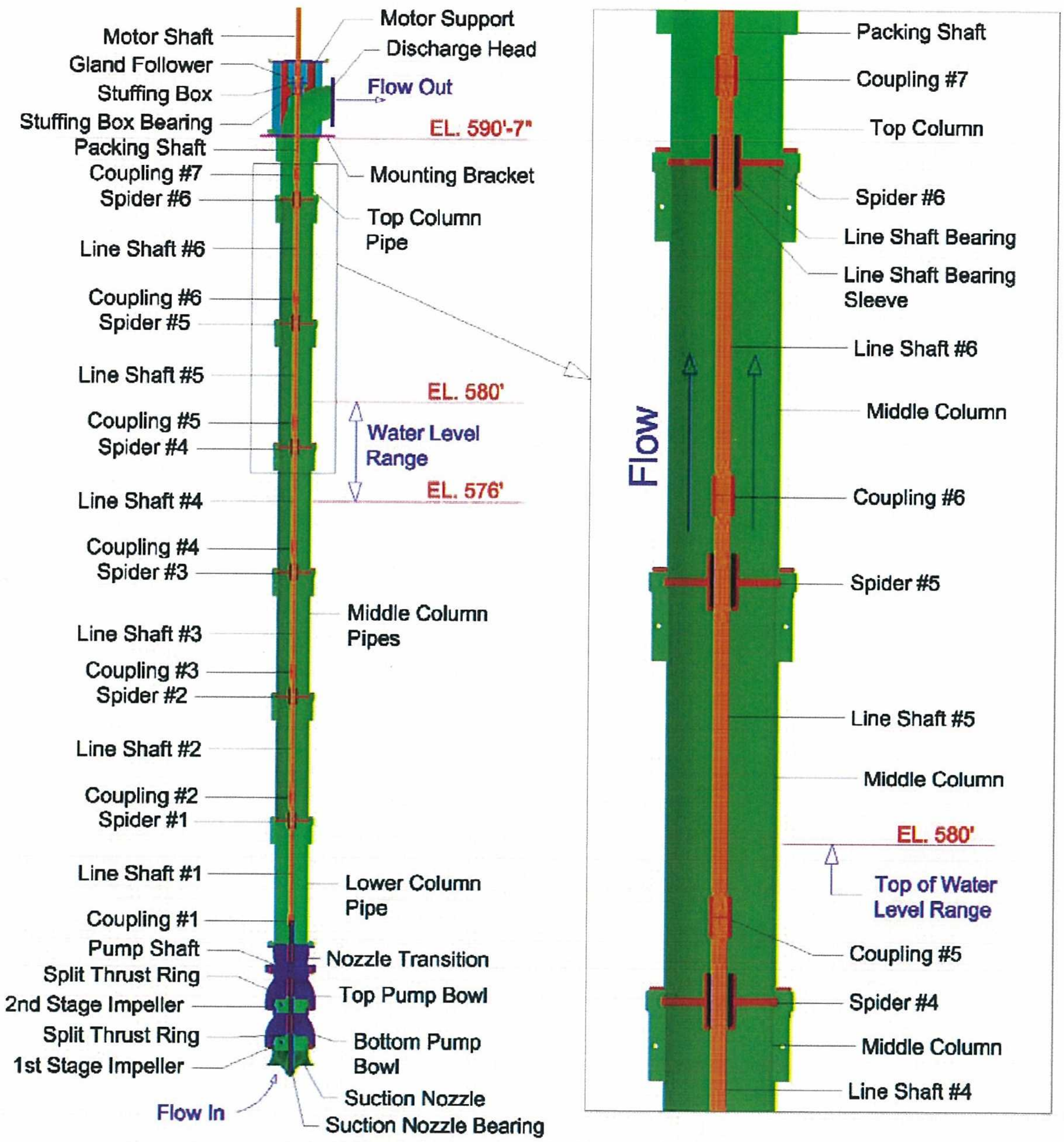


Figure 1-3: SWS Pumps Shaft Assembly [3b]



Note: Spider refers to intermediate shaft guidance bushing.

Figure 1-4: PLP SWS Pump Rendering

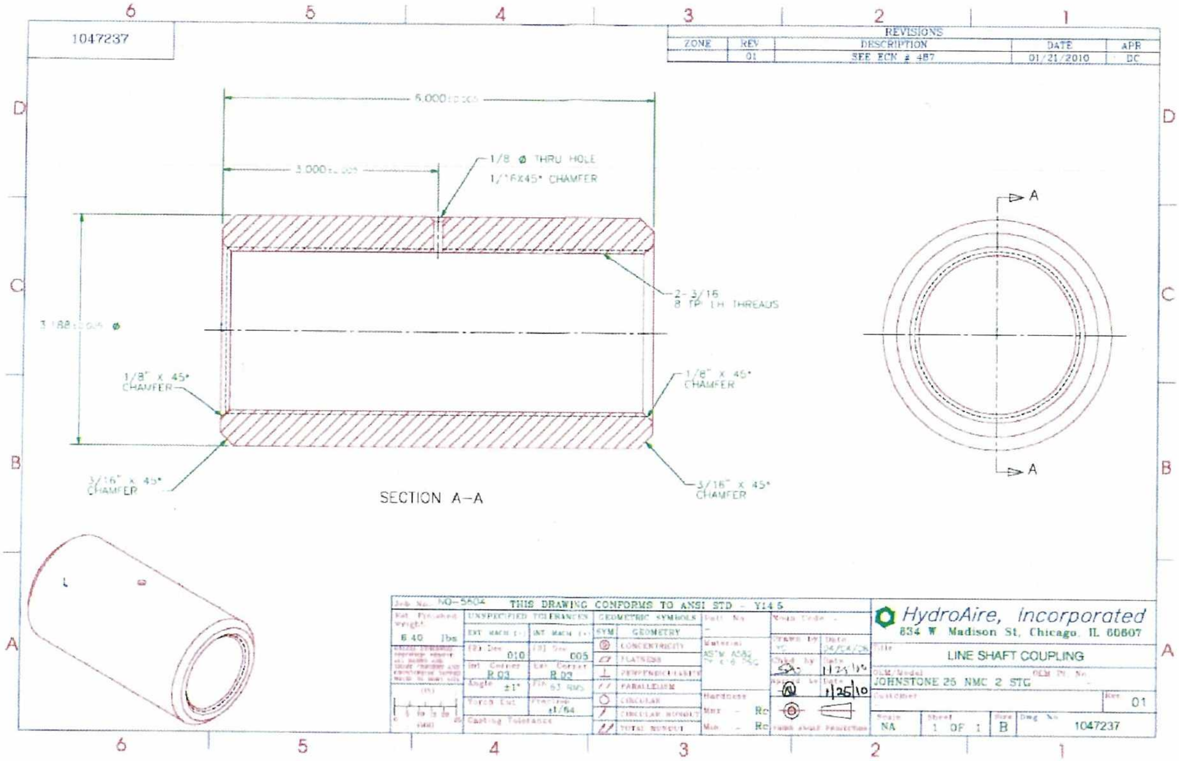


Figure 1-5: Coupling Drawing [20]

2.0 INPUTS/ASSUMPTIONS

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

2.1 Inputs

1. Specified hardness for the couplings is in the range of 28 to 32 HRC [4].
2. Coupling loads are taken from [15] with hydraulic thrust equal to 8000 lb, torque of 18,694 lb-in and preload of 42,335 lb.
3. Table 2-1 summarizes the SWS pump coupling service history at time of extraction.
4. Based on data provided by PLP and presented in Figure 2-3, the service water basin elevation ranged from 576 ft to 580 ft for the period from January 2009 to August 2011. For the same period, the water temperature ranged from 32°F to 76°F.
5. The SWS pumps are vertical turbine pumps that take suction from the bottom and discharges through the column and out the discharge header pipe. Therefore, line shafts, couplings and components below the stuffing box are exposed to service water when the pumps are on. Based on the service water basin elevation, couplings 1 through 4 are constantly submerged and couplings 5 through 7 are subjected to wet and dry cycles depending on pump state (i.e. on or off). Also depending on water elevation, coupling 5 may be submerged when the pump is off. Refer to Figure 1-4 for a sketch of the service water pump with illustration of water flow and relationship of couplings to basin water elevation variations.
6. The convention used in this report to reference couplings is as follows:

   YY-Pump-CN with Optional F or K

   Where:

   YY= two digit year when coupling was extracted from pump.

   Pump = P7A, P7B or P7C

   CN = Coupling Number

   Optional F = Identifies a coupling that has failed.

   Optional K = Identifies a coupling that exhibits a crack.

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

2.2 Assumptions

1. There are no assumptions utilized in this report.

Table 2-1:SWS Pump Coupling Life

Pump	Date Installed	Date Extracted	Installed Time (hrs)	Run Time (hrs)	Start/Stops	Notes
P-7A	4/4/09	8/28/11	21,024	16,259	148	1
P-7B	5/12/10	9/1/11	11,391	9,073	70	2
P-7C	6/12/09	9/29/09	2,616	2,414	13	3
P-7C	10/1/09	8/8/11	16,224	14,115	95	4

Notes:

1) Run hours and stops and starts based on total presented in Palisades response to NRC RFI 43 [6] plus average monthly hours from 4/10 to 9/10 times 6 months.
2) Information provided in Figure 2-1.
3) Information provided in Figure 2-2.
4) Run hours and stops and starts based on total presented in Palisades response to NRC RFI 43 [6].

Sontra Yim

From: DeBusscher, Derek [ddebuss@entergy.com]
Sent: Wednesday, September 28, 2011 8:02 AM
To: Sontra Yim
Cc: Forehand, James M
Subject: RE: Palisades comments on LPI report F11358-LR-001
Attachments: RFI 43 Response.doc

Sontra,

P-7B was put into service with the new couplings on 5/12/10 as stated by the WO 20082. From that date I calculated the approximate run time hours to be 9072.5 and the pump start/stops to be 70 since that time. Total installed hours are approximated 11,391 hrs.

I have attached the RFI that was reviewed. Note that the times only include up to 8/9/11. P-7B ran for 703 hrs during August (not 204), and had one additional start.

If there is any other information you need please let me know so we can get this minor issue hashed out as soon as possible.

Thanks.

Derek DeBusscher
BOP Systems Engineering
Palisades Nuclear Power Plant
269-764-2997
ddebuss@entergy.com

Figure 2-1: P-7B Run Time

Data Source: Palisades PI Datalink

Time Start:	6/12/09 0:00		*Update highlighted cells and click "Update Sheet" button.*	Update Sheet (must have PI add-in installed)
Time Stop:	10/1/09 0:00			
	Service Water Pump P-7C		**None**	**None**
Total Run Time:	**2414.44**	**hrs**		
1	6/12/09 12:22 6/12/09 12:23	Started Stopped		
2	6/12/09 15:03 6/12/09 15:33	Started Stopped		
3	6/12/09 15:34 6/19/09 3:44	Started Stopped		
4	6/19/09 16:17 7/17/09 10:52	Started Stopped		
5	7/17/09 11:42 7/17/09 12:02	Started Stopped		
6	7/17/09 13:22 7/23/09 5:03	Started Stopped		
7	7/23/09 9:04 8/8/09 21:38	Started Stopped		
8	8/8/09 21:39 8/13/09 3:55	Started Stopped		
9	8/13/09 3:56 8/28/09 10:40	Started Stopped		
10	8/28/09 10:41 9/2/09 13:06	Started Stopped		
11	9/9/09 11:15 9/22/09 20:32	Started Stopped		
12	9/22/09 23:38 9/29/09 7:34	Started Stopped		
13	9/29/09 7:35 9/29/09 9:11	Started Stopped		
14				

Figure 2-2: P-7C Run Time

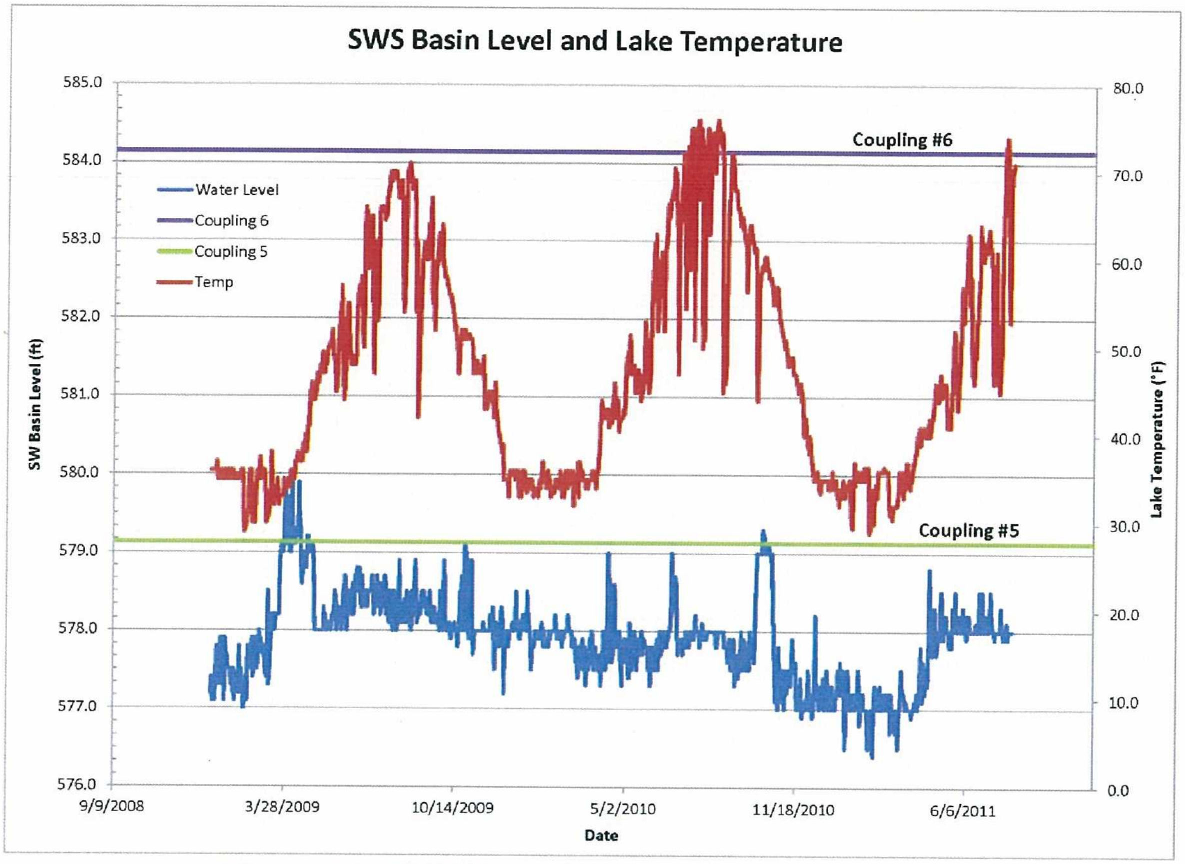


Figure 2-3: SWS Basin Level and Lake Temp Data

3.0 TESTING AND EXAMINATION

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

3.1 Visual and Stereomicroscopic Examination

3.1.1 P-7C Components

3.1.1.1 2011 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. Couplings were labeled to indicate the orientation of shafts that connected to the respective coupling. A representative example of an intact coupling is shown in Figure 3-1. The outer diameter of each intact coupling exhibited wrenching marks, which likely occurred during removal of the couplings. Indentations, which are evidence of previously performed hardness tests, were present on both the outer diameter and ends of many couplings with values written adjacent to the indentations of coupling 11-P7C-7 (see Figure 3-2).

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 is fully threaded.

Visual examination of received intact couplings did not reveal significant signs of corrosion or degradation on the exterior surfaces (unthread surfaces). Some corrosion deposits were noted near the 1/8" diameter alignment hole and at the ends of some intact couplings, however not to the degree exhibited on coupling 11-P7C-6F.

3.1.1.2 Coupling 11-P7C-6F

The fracture surface of 11-P7C-6F is located near the mid-length of the coupling. The fracture surface on the impeller end of coupling 11-P7C-6F was sectioned for analysis, as shown in Figure 3-5. Approximately half of the fracture surface exhibited a smooth "flat" appearance and was aligned perpendicular to the coupling axis. The flat fracture surfaces occur in two regions that both display an elliptical shape emanating from the thread root at the inner diameter and extending to the outer diameter, as shown in Figure 3-5. The elliptical features are typically associated with cracks that initiate at the thread root (and in this case propagated from the inner to the outer diameter of the coupling). 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.

The thread roots exhibited red/brown corrosion products, as shown in Figure 3-6. Corrosion deposits are visually apparent on the facture surfaces, threads and at the alignment hole of coupling 11-P7C-6F. The corrosion deposit streak at the bottom of the 1/8" diameter shaft alignment hole suggests that the coupling underwent wet and dry cycles (Figure 3-6).

The tips of fracture surfaces on both pieces of fractured coupling 11-P7C-6F exhibited signs of impact from mechanical contact, likely occurring post failure.

3.1.1.3 Coupling 09-P7C-7F

Fractured coupling 09-P7C-7F measured between 2.06" to 3.43" in length. Visual examination of coupling 09-P7C-7F revealed similar fracture surface characteristics to 11-P7C-6F. The fracture surface has a relatively flat region with an elliptical shape emanating from the thread root and extending to the outer diameter (see Figure 3-3). The elliptical feature reveals that the crack initiated at the thread root and propagated to the outer diameter. The remaining portion of the fracture surface was slanted, which indicates a subsequent overload of the remaining ligament. Corrosion deposits are also evident on the facture surface.

3.1.1.4 2011 Shafts

Two shafts (shaft #5 and 6) from pump P-7C were shipped to LPI for visual examination (see 8/17/11 receipt inspection in Attachment B). Visual examination of shaft #5 and #6 showed damage on the ends coupled by coupling 11-P7C-6F (see Figure 3-7). It is postulated that this damage was most likely caused after the initial failure of coupling 11-P7C-6F by repeated impact between the fractured coupling and the shaft ends. This postulate is supported by the blunted fracture surfaces exhibited on the 11-P7C-6F halves.

3.1.2 Couplings from P-7A

Visual inspection of as-received P-7A pump couplings 11-P7A-4 through -7 identified the threads to be well coated with Neolube. A photograph of the as-received coupling 11-P7A-7 is provided in Figure 3-8. No significant signs of corrosion or degradation on the exterior of couplings were observed. This was in contrast to observations of the P-7C couplings in the as-received condition, where lubricant was not observed to be as well coated on the threads. A comparison of this is shown in Figure 3-9.

Visual inspection of the as-split P-7A couplings revealed them to be well coated with Neolube. The mid section of the couplings contained little to no corrosion products, however some sand-like deposits were present within the middle two-to-three threads of the couplings. The split and cleaned couplings, in preparation for MT, did not reveal any visible indications, as shown in Figure 3-10 for 11-P7A-5.

3.1.3 Couplings from P-7B

A photograph of the as-received couplings 11-P7B-4 through 11-P7B-7 are shown in Figure 3-11. Visual examination of these intact couplings revealed wrench marks on the exterior of all couplings and the presence of Neolube on the interior threads of couplings 11-P7B-5 to -7. No significant signs of corrosion or degradation on the exterior of couplings were observed. The interior of 11-P7B-4 appeared to have been cleaned in the as-received condition.

Couplings 11-P7B-4 though 11-P7B-7 were split longitudinally for fluorescent magnetic particle inspection (MT). The as-split coupling 11-P7B-4 appeared to have been cleaned and exhibited a dye liquid penetrate residue on the threads (see Figure 3-12). The presence of the liquid penetrate on the thread surface is consistent with efforts by Palisades to examine this coupling for possible re-use due to procurement issues with the replacement couplings fabricated from 17-4PH material. As-split couplings 11-P7B-5 through 11-P7B-7 are shown in Figure 3-13 through Figure 3-15. Neolube is present on the threaded surfaces of coupling 11-P7B-5 to 11-P7B-7. However, an apparent band of corrosion product was observed at the center two-to-three threads of couplings 11-P7B-6 and 11-P7B-7. Coupling 11-P7B-5 also exhibited some corrosion at the center threads but not to the extent of couplings 11-P7B-6 and 11-P7B-7. A layer of sand-like material was also present over the corrosion products.

3.2 Dimensional Examination

A dimensional examination of couplings was performed and presented in Table 3-1. Measurements of wall thickness (from the outer diameter to the thread crown) of couplings to evaluate eccentricity are given in Table 3-2.

The dimensioning scheme is shown in Figure 3-4. All intact couplings (i.e. those that did not fail) were found to have outside dimensions within the specified dimensions and tolerances of HydroAire drawing 1047237 [20].

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 3.03" and 4.29" in length. The top half (motor end) of the same coupling measured between 1.200" and 3.148" in length.

3.3 Magnetic Particle Examination (MT)

Fluorescent magnetic particle testing (MT) was used to determine if intact couplings contained cracks or other discontinuities. MT was performed on all intact couplings exposed to wet and dry cycles (coupling Nos. 5, 6, and 7) and coupling #4 which is always submerged for all three service water pumps. Couplings were split longitudinally to facilitate access to the inner diameter threaded region for MT inspection. Result of the inspections is provided in Attachment D.

3.3.1 P-7C Couplings

3.3.1.1 Coupling 11-P7C-6F

Visible cracks in coupling 11-P7C-6F were readily observed upon MT examination, as shown in Figure 3-16. The nearly 45 degree MT indication is consistent with torsional loading of the coupling.

3.3.1.2 Intact Couplings 11-P7C-4, -5, and -7

MT did not reveal any indications on couplings 11-P7C-4 and 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-7K, as shown in Figure 3-17. The MT indication in coupling 11-P7C-7K is approximately 0.86" in length and located along a thread root. At the sectioned location, the indication is a quarter through the thickness.

3.3.2 P-7A Couplings

Following cleaning, couplings 11-P7A-4 through 11-P7A-7 were MT inspected. No indications of linear flaws were observed from the MT inspection of couplings 11-P7A-4 through 11-P7A-7.

3.3.3 P-7B Couplings

Following cleaning, couplings 11-P7B-4 through 11-P7B-7 were MT inspected. MT inspection of couplings 11-P7B-4 through 11-P7B-7, revealed indications at the center (location of corrosion products) of couplings 11-P7B-

5, 11-P7B-6 and 11-P7B-7. Figure 3-18 presents photographs highlighting the crack at the center of 11-P7B-7K revealed by MT. Two relatively small indications were also found at the motor end of coupling 11-P7B-5. No indication was found on coupling 11-P7B-4.

A summary of the as-found crack dimensions on MT inspected couplings is provided in Table 3-3.

3.4 Metallography

Longitudinal specimens were prepared from the coupling material, mounted in plastic, ground, polished, and etched for metallographic examination. General views of the microstructure for one coupling from each pump are shown in Figure 3-19. The microstructure shows prior austenite grain boundaries with colonies of commonly oriented martensite lath inside the grains. This structure is characteristic of a martensitic stainless steel.

Longitudinal specimens were prepared through cracks from fractured and cracked couplings, mounted in plastic, ground, polished, and etched for metallographic examination. Metallographic images are shown in both the as-polished and etched conditions, as shown in Figure 3-20. All cracks displayed a similar appearance of a branching network of cracks along the prior austenite grain boundaries, which is characteristic of intergranular stress corrosion cracking (IGSCC). This cracking mechanism is common for martensitic stainless steels exposed to chloride-containing aqueous and other corrosive environments.

From the metallographic images in Figure 3-20, it appears that IGSCC cracks originate from pits. The thread roots of coupling Nos. 4 to 7 for all pumps were visually examined by stereomicroscopy for pitting. It was observed that pitting occurred at the thread roots of couplings that exhibited cracks, as shown in Figure 3-21. Couplings without cracks exhibited some general corrosion, however contained no readily observable pitting. A representative image of a P-7A coupling showing general corrosion but no pitting at the thread root is presented in Figure 3-22.

3.5 Scanning Electron Microscopy

The fracture surface morphology and composition of the corrosion product were evaluated for the two fractured couplings, 09-P7C-7F and 11-P7C-6F.

The fracture surfaces of 11-P7C-6F and 09-P7C-7F were examined in a scanning electron microscope (SEM) to evaluate the crack initiation and propagation mechanism. Deposits on the fracture surfaces of couplings 11-P7C-6F and 09-P7C-7F were analyzed by energy dispersive x-ray spectroscopy (EDS) in the SEM. As shown in Figure 3-23, the spectrum contained large peaks for iron, chromium, manganese, and silicon from corrosion products of the base material. The high chromium level in the spectrum, shown in Figure 3-23, is likely attributed to a local concentration of chromium carbides in the X-ray sampling volume. An additional EDS spectrum, taken over a larger area of the fracture surface, is provided in Figure 3-24. Also exhibited was a large peak for oxygen and smaller peaks of chlorine and sulfur, indicating the presence of oxides, chlorides and sulfur species. Chlorides and sulfides from the environment are known to cause corrosion and SCC in martensitic stainless steels.

The fracture surface was cleaned in an ultrasonic bath containing an acetone/methanol mixture prior to examination 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 3-25. This cracking mechanism is common for martensitic stainless steels exposed to chloride-containing aqueous and other corrosive environments.

3.6 Physical and Mechanical Properties

3.6.1 Tensile Test

Tensile specimens were prepared from couplings as indicated in the Test Matrix (Table 1-1). The results of the tensile test on the specimens are included in Attachment F and summarized in Table 3-4. The tensile test results were in the approximate range for Type 416 stainless steel with an intermediate temper based on specified hardness values in ASTM A582 [7]. Yield strength values ranged from 108 to 142 ksi and the elongation ranged from 12.8 to 17.9 %.

3.6.2 Composition of Base Metal

The base metal compositions of all couplings within the Test Matrix (Table 1-1) were evaluated by chemical analysis and the results are provided in Table 3-5. The results indicate that the chemical composition of all tested couplings conform to the chemical requirements of ASTM A582 Type 416 stainless steel [7].

3.6.3 Hardness Surveys

Surface hardness surveys were performed in accordance with the requirements of ASTM E18-07 [8] with the results presented in Attachment E and summarized in Table 3-6. Unless otherwise noted, surface hardness was measured on the ends (motor and impeller ends) of each coupling.

Through thickness hardness of couplings extracted in 2011 were measured near the center of each coupling from the outer diameter (OD) to the inner diameter (ID) of tested couplings at two diametrically opposite locations. Hardness measurements on coupling 09-P7C-7F were taken at the mid-wall along the length of the coupling from the center to the end of the coupling. Results of the through thickness Rockwell C hardness measurements are presented in Table 3-7.

3.6.4 Charpy V-Notch (CVN) Impact Testing

Charpy V-Notch (CVN) impact test specimens with radial notches facing the inner diameter were machined and tested in accordance with ASTM Standard E23 [10] over a temperature range of 32°F to 152°F. Results of impact testing are given in Table 3-8.

Table 3-1: 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
11-P7A-4	6.000	3.187
11-P7A-5	5.999	3.189
11-P7A-6	6.000	3.188
11-P7A-7	6.000	3.188
11-P7B-4	5.995	3.189
11-P7B-5	5.996	3.189
11-P7B-6	6.001	3.188
11-P7B-7	6.000	3.188

Notes: (a) coupling 11-P7C-6F 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 09-P7C-7F was sent to LPI and the measurements of this piece of coupling are described in the text.

Table 3-2: 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
11-P7A-4	0.565	0.567	0.567	0.567	0.568	0.567	0.567	0.568
11-P7A-5	0.566	0.566	0.566	0.567	0.568	0.568	0.566	0.567
11-P7A-6	0.566	0.567	0.566	0.566	0.568	0.567	0.567	0.567
11-P7A-7	0.568	0.568	0.567	0.566	0.567	0.568	0.568	0.568
11-P7B-4	0.568	0.569	0.571	0.569	0.568	0.568	0.568	0.568
11-P7B-5	0.566	0.567	0.567	0.567	0.568	0.566	0.566	0.568
11-P7B-6	0.569	0.568	0.568	0.567	0.568	0.569	0.568	0.567
11-P7B-7	0.565	0.566	0.566	0.566	0.566	0.566	0.567	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 3-3: MT Detected Crack Dimensions

Coupling	Crack Location	Crack Length Along Thread Root (in.)	Crack Depth (in)
11-P7C-7K	Center	0.86	0.125
11-P7B-5K	Center	1.25	0.065
	Motor End	0.25 and 0.19 (a)	0.02
11-P7B-6K	Center	0.50	0.132
11-P7B-7K	Center	0.50	0.043

Note (a): These two indications were located close to each other and toward the motor end of the coupling. All other indications were found at the center of couplings.

Table 3-4: 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-7K	7-1	138	151	13.3
	7-2	137	152	15.5
11-P7A-5	A5-1	132	146	14.1
	A5-2	136	153	14.6
11-P7A-6	A6-1	112	126	16.2
	A6-2	108	123	16.1
11-P7A-7	A7-1	136	151	12.8
	A7-2	136	150	15.4
11-P7B-5K	5-1	118	136	17.9
	5-2	118	136	14.6
11-P7B-6K	6-1	131	144	14.2
	6-2	126	140	15.2
11-P7B-7K	7-1	114	129	17.3
	7-2	115	129	16.5

Table 3-5: Metal Composition of Couplings (Wt. %)

	Element								
Standard	**C**	**Cr**	**Cu**	**Mn**	**Mo**	**Ni**	**P**	**S**	**Si**
ASTM A582 TP 416 [7]	0.15 max	12.00 – 14.00	ns	1.25 max	0.60 max	ns	0.060 max	0.15 min	1.00 max
Couplings									
11-P7C-5	0.1	12.93	0.16	1.09	0.03	0.14	0.007	0.51	0.23
11-P7C-6F	0.12	12.9	0.16	0.85	0.03	0.14	0.015	0.36	0.23
11-P7C-7K	0.11	12.92	0.16	0.68	0.03	0.14	0.02	0.34	0.25
09-P7C-7F	0.12	12.38	0.12	1.13	0.05	0.19	0.041	0.32	0.46
11-P7A-5	0.14	13.06	0.071	0.74	0.07	0.22	0.018	0.35	0.42
11-P7A-6	0.10	12.16	0.077	0.83	0.12	0.43	0.021	0.22	0.34
11-P7A-7	0.13	12.97	0.073	0.65	0.06	0.22	0.017	0.35	0.42
11-P7B-5K	0.13	12.1	0.082	0.72	0.08	0.28	0.02	0.37	0.37
11-P7B-6K	0.12	12.0	0.079	0.7	0.078	0.27	0.02	0.29	0.37
11-P7B-7K	0.12	12.0	0.078	0.72	0.078	0.27	0.02	0.34	0.37

ns – not specified

Table 3-6: Surface Hardness Survey of Couplings

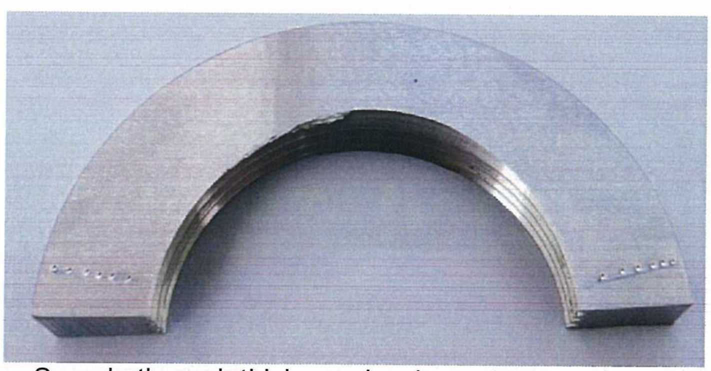
Coupling	End	Average (HRC)	Measurements (Rc)
11-P7C-1	top	30.5	30.1, 30.6, 30.2, 30.4, 30.7, 31.1
	bottom	27.3	29.1, 29.8, 25.0, 26.0, 26.1, 27.7
11-P7C-2	top	27.6	29.7, 25.5, 27.0, 30.2, 25.9, 27.1
	bottom	27.0	25.8, 26.0, 27.6, 27.5, 29.0, 26.0
11-P7C-3	top	27.9	26.5, 28.0, 26.0, 28.6, 29.8, 28.2
	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-7K	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	–	(c)
	bottom	32.1	33.7, 33.1, 32.8, 32.0, 30.2, 31.8, 31.2
11-P7A-5	top	32.5	32.5, 32.0, 32.5, 32.0, 33.0, 33.0
	bottom	29.9	28.0, 31.5, 31.5, 30.0, 30.5, 28.0
11-P7A-6	top	25.3	25.5, 25.5, 25.0, 25.5, 25.0, 25.5
	bottom	23.8	24.5, 23.5, 23.5, 25.0, 22.0, 24.0
11-P7A-7	top	31.5	31.0, 31.5, 32.0, 32.0, 32.5, 31.0
	bottom	28.7	28.0, 28.0, 27.0, 30.0, 29.0, 30.0
11-P7B-5K	top	27.6	28.0, 28.0, 27.5, 28.5, 26.5, 27.0
	bottom	26.1	25.0, 27.0, 26.5, 25.0, 27.0, 26.0
11-P7B-6K	top	29.9	30.0, 30.0, 30.5, 30.0, 30.0, 29.0
	bottom	28.5	27.5, 29.0, 28.0, 28.5, 28.5, 29.5
11-P7B-7K	top	28.3	28.0, 28.0, 28.5, 29.0, 28.5, 28.0
	bottom	26.1	25.5, 27.0, 26.0, 27.0, 24.5, 26.5

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) only bottom section of coupling 09-P7C-7F was received.

Table 3-7: Through Thickness Hardness of Couplings

Coupling	Location	Measurements from OD to ID (R_C)
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-7K	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
11-P7A-5	1	33.0, 29.9, 33.2, 33.0, 33.6, 32.2
	2	32.9, 32.9, 33.0, 32.6, 32.8, 33.1
11-P7A-6	1	24.0, 24.0, 24.0, 24.0, 24.0, 24.0
	2	24.5, 24.0, 24.0, 24.0, 24.5, 24.0
11-P7A-7	1	31.0, 31.5, 31.0, 31.5, 31.0, 31.0
	2	32.0, 31.5, 32.0, 31.0, 31.0, 31.0
11-P7B-5K	1	27.0, 27.5, 27.5, 28.0, 27.9, 27.5
	2	28.5, 28.0, 28.6, 28.0, 27.7, 28.1
11-P7B-6K	1	28.8, 29.0, 29.1, 29.4, 29.8, 29.8
	2	29.2, 29.9, 30.0, 30.0, 30.1, 30.2
11-P7B-7K	1	28.2, 28.0, 27.9, 27.9, 28.0, 28.5
	2	28.1, 28.8, 28.7, 28.5, 28.4, 28.6
09-P7C-6F	(a)	34.8, 35.9, 35.2, 36.0, 36.3, 36.8, 37.1

Notes: (a) Hardness measurements on 09-P7C-6F were taken at the mid-wall along the length of the coupling from the center to the end of the coupling.



Sample through thickness hardness test specimen.

Table 3-8: CVN Impact Test Results

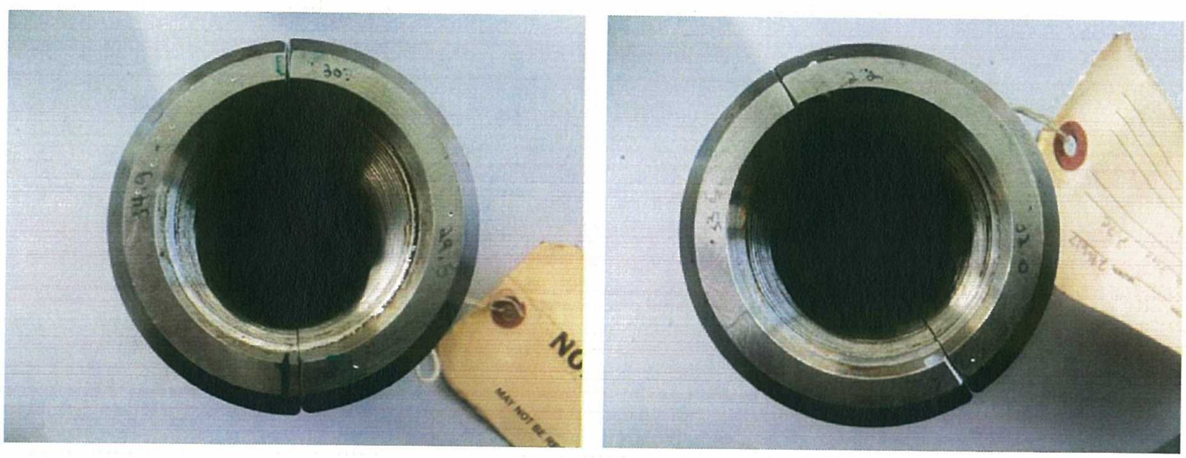
Coupling	Specimen Identification	Test Temperature (°F)	Absorbed Energy (ft-lb)	Lateral Expansion (in.)	Percent Shear (%)
11-P7C-5	5-C2	32	9	0.005	<10
	5-C4	32	9	0.006	<10
	5-C1	70	10	0.007	10
	5-C6	70	10	0.007	10
	5-C8	70	10	0.007	10
	5-C3	100	11	0.007	20
	5-C5	100	10	0.006	20
	5-C7	150	15	0.011	50
11-P7C-6F	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	153	14	0.008	50
11-P7C-7K	7-C2	32	7.5	0.003	<10
	7-C1	75	10	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
11-P7A-5	5-A3	32	7	0.003	<10
	5-A4	32	7	0.002	<10
	5-A1	75	8	0.006	10
	5-A2	75	9	0.005	10
	5-A5	100	13	0.009	30
11-P7A-6	6-A3	32	3	0.002	<10
	6-A4	32	3	0.002	<10
	6-A1	75	6	0.006	10
	6-A2	75	6	0.008	10
	6-A5	100	9	0.012	10
11-P7A-7	7-A3	32	11	0.005	<10
	7-A4	32	9	0.004	<10
	7-A1	75	12	0.009	20

Coupling	Specimen Identification	Test Temperature (°F)	Absorbed Energy (ft-lb)	Lateral Expansion (in.)	Percent Shear (%)
	7-A2	75	12	0.010	20
	7-A5	100	18	0.015	50
11-P7B-5K	B5-9	0	9	0.006	10
	B5-10	0	10	0.007	10
	B5-1	32	14	0.013	20
	B5-2	32	16	0.014	40
	B5-7	32	12.5	0.011	20
	B5-8	32	13	0.011	20
	B5-3	76	22	0.018	>90
	B5-4	76	29	0.018	>90
	B5-5	100	28	0.016	>90
	B5-6	150	26	0.017	>90
11-P7B-6K	B6-9	0	5	0.004	<10
	B6-10	0	5	0.004	<10
	B6-1	32	8	0.004	<10
	B6-2	32	5	0.005	<10
	B6-7	32	6	0.005	<10
	B6-8	32	5.5	0.003	<10
	B6-3	76	11	0.008	10
	B6-4	76	10	0.009	10
	B6-5	100	21	0.015	80
	B6-6	150	21	0.015	>90
11-P7B-7K	B7-9	0	8	0.007	10
	B7-10	0	9	0.007	10
	B7-1	32	12	0.008	20
	B7-2	32	11	0.009	20
	B7-7	32	11	0.009	10
	B7-8	32	13.5	0.013	20
	B7-3	76	11	0.015	50
	B7-5	100	22	0.016	>90
	B7-6	150	32	0.022	>90

Coupling 11-PC-7 in as-received form. Shaft numbers engraved on the ends. Coupling exhibited wrenching marks on outer diameter.

Figure 3-1: As-Received 11-P7C-7

Motor End **Impeller End**



Hardness measurement indentations are present on both ends. Measurement values were 34.9, 30.7, 29.5 and 29.4 on motor end and 33.5, 32.2, 32.0 and 32.5 on impeller end.

Figure 3-2: Hardness Indentation and Values Written on 11-P7C-7

Figure 3-3: 09-P7C-7F Fracture Surface Showing Elliptical Feature

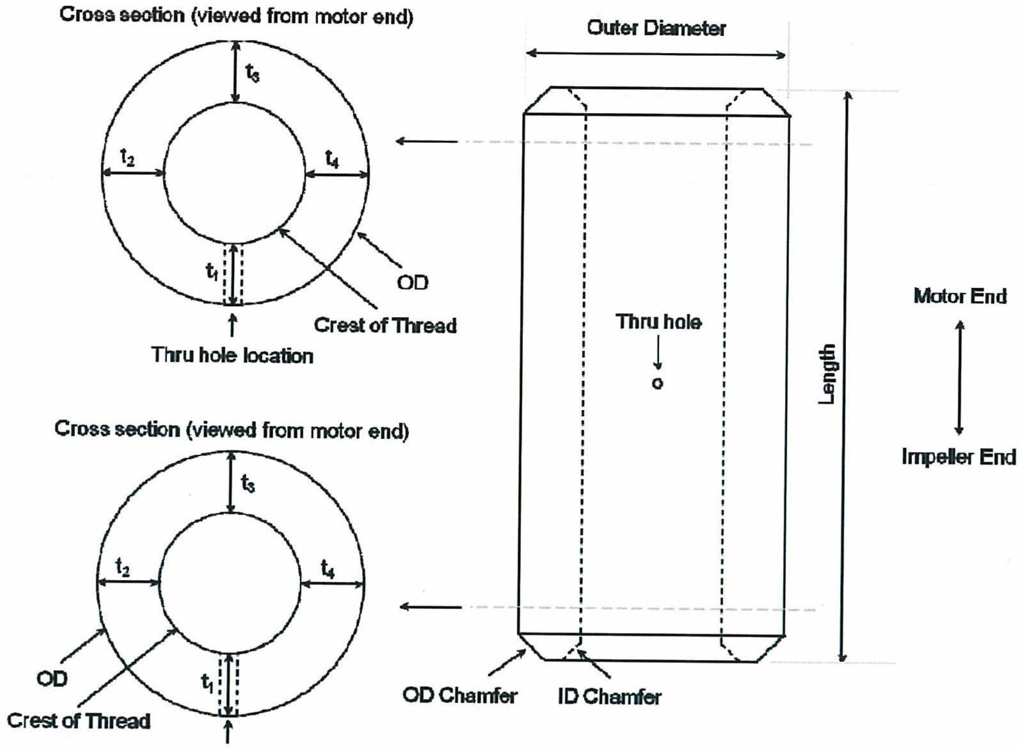
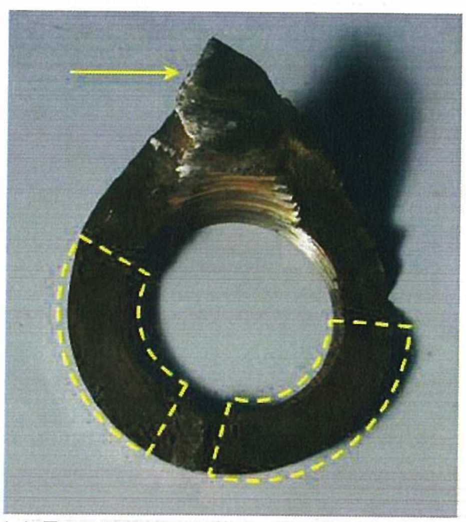


Figure 3-4: Coupling Dimensioning Scheme



(a) Fracture surface was sectioned from the coupling for analysis. Tip exhibited blunting from mechanical damage (arrow).

(b) Elliptical pattern of crack on flat fracture surface, relative to coupling axis. Also, red/brown corrosion product found on the insides of coupling threads (arrow)

Figure 3-5: Visual of Fracture Surface on Coupling 11-P7C-6F

Figure 3-6: 11-P7C-6F showing Corrosion Deposit