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Surge Line Welding Issue
Southern California Edison (SCE) – SONGS Unit 3

By

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WSI Document #: 102987-WP-001, Rev. 0

Executive Summary

Cracking was identified in the first three beads of the initial layer of Alloy 52M weld overlay applied to the piping portion of the surge line nozzle configuration at SONGS Unit 3. Initial efforts to alter the welding conditions within the bounds of the qualified WPS did not corrected the problem. This paper describes the circumstances associated with the cracking issue and concludes that the nature of the cracking is known as solidification or hot cracking – a phenomenon associated with dilution in the nickel base weld puddle from iron, sulfur, phosphorus and silicon plus a source of tensile stress tied to weld shrinkage.

Surge Line Description

The surge line is a 12-inch diameter piping system attached to a nozzle penetration located in the bottom center of the pressurizer vessel. The nozzle is a P-No. 3 SA 508 Class 2 low alloy steel and is interfaced to the piping by use of a cast stainless steel (SA 351 CF8M) safe-end transition piece. The weld joining the two (designated 03-005-031) is made using F-43 Inconel (I-182 SMAW butter on the low alloy steel (LAS) and completed using I-82 and GTAW).

The surge line is fabricated of SA 376 Type 316 stainless steel seamless tubing and is attached to the bottom of the safe-end using stainless steel filler material. The surge tube is a nominal 12-inch diameter Schedule 160 (12.75 inches OD and 1.312 inch wall thickness) supplied by Curtis Wright to Guyon Alloys Inc. and ultimately to Pullman Power Products. The chemical composition is shown in the CMTR given in Appendix 1. The records indicate 0.017% S, 0.025% P, and 0.40 Si – all well within the specification for SA 376 Type 316 material. It is also noted that the carbon level is 0.065%.

The two welds are being overlaid with Alloy 52M to mitigate the potential for PWSCC of the dissimilar metal weld between the LAS nozzle and the cast stainless steel safe-end. In addition the weld between the stainless steel surge pipe and the cast stainless steel safe-end is also being included in the overlay design to facilitate improved ultrasonic inspection of both welds.

The Overlay Welding Process

The WSI temperbead welding procedure used for the overlay is a unique welding procedure assigned to the SONGS Unit 3 pressurizer overlay project for the surge nozzle overlay (WPS 03-08-T-801-102987 Rev. 0) and is similar to welding procedures used by WSI for other nozzles similar to the surge nozzle in the pressurizer at SONGS Unit 3. It is supported by the following PQRs that have been reviewed and accepted at SONGS:

1. PQR 03-03-T-801 Rev. 3
2. PQR A08202.3-3 Rev. 1
3. PQR 43-43-T-001 Rev. 0

The qualification is based on the rules provided by ASME for temperbead welding. In addition to the minimum requirements of ASME, the WSI procedure stipulates a Power Ratio target designed to control dilution into the weld deposit. The parameters used in this procedure have been used successfully multiple times to apply weld overlays on other surge nozzle configurations similar to SONGS Unit 3. It is also proven by multiple mockups inspected to the PDI UT procedures.

The surge nozzle assembly extends vertically from the bottom of the pressurizer vessel (2G orientation using horizontal machine GTA welding). The overlay is initiated on the stainless steel pipe at the bottom end and progresses upward bead by bead until the entire length of the overlay is completed. After the first layer is deposited, a second layer is deposited from the bottom progressing towards the top and so on until the designed thickness has been completed plus allowance for mechanically surfacing the overlay to facilitate the PDI UT inspections. A 48 hour hold is maintained after the overlay has cooled to ambient temperature before inspections are performed to ensure that low temperature hydrogen cracking has not occurred. Hydrogen cracking is a very low probability event in these materials and when welded using the GTA welding process, but the 48 hour hold is the current requirement of the ASME Nuclear Code Cases governing temperbead repairs.

Welding Chronology for the Surge Nozzle Overlay

Shortly after the beginning of day shift on 10/25/2006 welding was initiated on the surge line at the bottom overlay position located on the Type 316 stainless steel pipe material. Approximately 2 inches of the first bead was welded. It was noted that the characteristics of the weld puddle were unusual for Alloy 52M filler material welds. The weld puddle viscosity was low and active, and appeared to be overly hot (i.e. too much energy applied to the weld). Alloy 52M deposits typically are sluggish and normally appear cold. There was concern that an equipment problem might be present. Initially the IF cable was changed but that did not resolve the amperage indication problem. Next the weld power supply was changed. Subsequent shunting tests demonstrated that both power supplies were supplying the 230 amps designed for the weld overlay.

After the power supply was changed, welding recommenced. The weld puddle still appeared hot and overly fluid for an Alloy 52M deposit. The initial bead shape appeared to have a tendency to roll over, and the site manager lowered the amperage from 230 amps to 210 amps in an attempt to cool the weld puddle. These parametric changes are within the boundaries of the qualified WPS. In addition, the torch tilt angle was increased upward from 5 degrees to approximately 11 degrees to improve the bead profile. These measures appeared to smooth the bead profile, and welding was continued even though the weld puddle still appeared to be reactive as compared to experience with this filler material.

Just before the third bead was completed the breaker in the welding machine tripped, and as a result welding terminated without downslope. After getting the machine back online it was noticed that a crater-type crack had formed due to the abrupt weld stop and the tungsten had plunged into the molten puddle. The tungsten stick and crater crack were removed, and welding resumed; however, further cracking was noticed. It was decided to remove a portion of the welded bead just applied and perform an informational liquid penetrant (PT) inspection. The crater crack was gone but small linear, crack-like indications were noticed that appeared to be associated with the second and third weld beads.

The area containing the indications was buffed lightly, and a portion of the weld layer approximately 12 inches from the initial indications also was removed. A PT inspection of both areas was performed and similar indications were found in both areas. All indications were oriented in similar directions – principally 90 degrees to the surface contours of the bead. It appeared that the indications were associated with the thicker portions of the deposited beads. In addition, the PT results showed that the indications were surface connected. See Figures 1 through 3. Eventually the weld deposit was ground approximately flush with the surface of the pipe in an attempt to remove the defects and that condition is shown in Figure 4. Note the clearly defined cracking on either side of the second bead (i.e. at the interface between the first and second bead and at the interface between the second and third bead). It was noted that the initial bead appeared to be free of surface cracking.

Immediate Actions Taken

The following immediate actions were taken:

1. Stop Welding and Grinding on the Surge Nozzle.
2. Verify Travel Speed setting on the weld head (checked OK)
3. Unmount weld head and check calibration (Checked OK)
4. Site initiated an AR on this issue
5. Requested Base Material (Pipe) CMTRs (see discussion below)

Immediate Actions taken to Resolve the Cracking Issue

Corrective actions to reduce weld dilution were discussed in detail and the following approach was identified that could be taken within the boundaries of the qualified welding procedures. First, the torch tilt angle would be lowered to approximately five degrees. Second, the amperage on the first layer would be lowered to 200 amps, and finally the wire feed on the first layer be increased to 90 inches per minute (IPM) to lower the Power Ratio. All three steps have the effect of reducing weld puddle dilution.

Welding experiments were conducted to support the approach. An initial task was undertaken to replicate the defective conditions seen on the surge nozzle piping that appeared to be traditional "hot" or solidification cracking (discussed later). A 12-inch diameter Schedule 100 Type 316 stainless steel pipe section was located and set up in the 2G (vertical pipe) position. The same welding machine used on the surge line was mounted on the pipe and the initial weld parameters used on the surge nozzle piping were applied to this pipe. The specific chemistry of this pipe was not known, but it was believed to be an older vintage pipe. A cracking condition similar to that observed on the surge pipe was observed, although the severity of the condition was not as great (i.e. lower concentration of defect indications).

A second weld sample was prepared on the same pipe but using the alternate parameters identified above. No crack indications were generated using those welding parameters and it appeared that the lower heat and lower dilution (lower Power Ratio) coupled with the change in tungsten position was sufficient to eliminate cracking.

These test results were confirmed by repeating the test an additional time and similar crack-free results were obtained. It was noted that the alternate parameters could be applied within the boundaries of the existing weld procedure specified for the surge nozzle overlay.

Finally a third test was performed with water in the pipe, and welded using essentially the same parameters described above except that the oscillation width was lowered slightly, from 0.15 to 0.12, and all dwells were lowered by 0.1 from the original settings. The travel speed was not changed for any of the tests. The surface of the first layer was ground slightly and no indications were found with the PT examination. Second and third layers were welded using the parameters suggested in the original weld procedure technique sheets. A technique sheet showing the revised first layer parameters is shown in Figure 5.

The three weld overlay pads welded with the revised parameters were also inspected using the linear phased array (LPA) UT examination and no indications were detected in the overlay volume.

Based on these results it was decided to remove the deposit and existing indications using manual grinding techniques then verify defect removal with a PT inspection. Figure 4 shows the indications as shown by PT after the deposit was manually ground approximately flush with the surface of the pipe. Additional grinding slightly below the surface of the pipe was required to remove the indications. It was noted that in no case did the grinding encroach on the minimum wall thickness. After indication removal the plan was to deposit a first layer using the modified parameter changes used in the final test weld. The second and subsequent layer welding would proceed in accordance with the original technique sheets (the wire feed rate on subsequent layers is already 90 ipm and thus the Power Ratio and thus dilution already is low).

These procedures were applied to a new location between the weld deposit just applied and removed and the lower side of the safe-end to pipe weld. The weld start location was about 1.5 inches below the lower toe of the safe-end to pipe weld, and the three beads applied finished approximately ¾ inch below the lower toe of the safe-end to pipe weld. A PT examination was to be performed after the first three or four beads to ensure that the revised procedures eliminated the cracking issue. Visual inspection using the magnified images provided by the video system from the welding camera was also to be performed during the first layer to verify that surface cracking did not occur.

The new overlay deposit was applied as planned and examined by PT after three beads were deposited. The results indicated that the new process lessened the extent of the defect condition but the condition was not eliminated. At this point further welding was stopped to determine the next step.

Discussion of Indications

Several important information items are known to aid in determining the cracking issue and what might be done to mitigate the tendency for cracking. These are as follows:

1. The weld puddle was highly reactive and appeared to be over heated (direct welding supervision observation)
2. The welding parameters used for this weld have been used successfully multiple times to deposit Alloy 52M filler material on both stainless steel and low alloy steel.
3. The appearance of the weld puddle was not due to equipment malfunction nor an erroneous current and voltage setting. (shunting tests verified that the current and voltages were correct according to the values set for welding)
4. The CMTR for the pipe material indicates that the average sulfur, phosphorus and silicon are within the material specification for this grade of material, but these levels are known to be high for welding nickel base filler materials.
5. Defects appear to be limited to the volume of material melted by the welding arc (reports from depth of grinding required to remove defects).
6. Defects appear to be located primarily at the interface between adjacent weld beads but not on the first bead by itself (Figure 4)
7. The orientation of defects appears to be perpendicular to the bead solidification front. (Figures 3 & 4)
8. Adjusting the welding parameters within the qualified welding procedure lowered both the penetration and weld dilution but still produced a highly reactive weld puddle that appeared to be overheated (subjective observation by supervisory welding personnel)
9. Adjusting the welding parameters within the qualified welding procedure lowered both the penetration and weld dilution definitely improved the condition by lessened the extent of indications (based on the removal of the weld from the restart of welding)

10. Seamless pipe can have areas where the chemical composition is not homogeneous. Sometimes sulfide inclusions will be biased to the surface of the component due to metal flow during pipe extrusion (experience statement)
11. Overlay experiments conducted on-site demonstrated that it is possible to eliminate a cracking condition by altering welding conditions known to affect weld puddle dilution (site weld testing)

The information described above definitely points to a metallurgical phenomenon known as solidification cracking (sometimes described as hot cracking). This form of cracking occurs on cooling at temperatures just below the solidus temperature for the alloy where the interdendritic boundaries are weakest. In this phenomenon cracking is restricted to the volume of material melted during the weld pass. Anything that weakens or strengthens the near molten dendrite grain boundaries will influence the potential for hot cracking.

At least two metallurgical conditions are known to increase the potential for hot cracking in nickel base materials. These are the impurity content and an increase in the temperature range over which solidification occurs. Impurity elements such as sulfur phosphorus, and silicon tend to be concentrated at the dendrite boundaries and are known to weaken the boundaries. Iron dilution into a nickel base material tends to widen temperature range over which solidification occurs. Thus welding over ferritic materials that are high in impurity content creates conditions known to favor solidification cracking.

Another concurrent condition is needed to support hot cracking, and that condition is the application of a tensile load applied across the weakened boundaries. This is the basis for the multiple hot cracking tests procedures used to evaluate hot cracking. These tests include the Varistrant test, the Gleeble test, and others. It is relatively straightforward to visualize high shrinkage stresses associated with restrained groove applications; however, it is less obvious to visualize tensile stresses in unrestrained weld overlay applications. The obvious load in overlays is shrinkage of the weld bead itself on cooling. A tensile load developed from this shortening of the weld bead would favor transverse cracks. However, the indications observed in this application are oriented at an angle to the transverse direction. There is another source of stress documented in the literature that can develop in an overlay that is based upon the shape of the weld bead. If the overlay bead is tear-shaped with a concave edge, a tensile load will be generated on solidification and cooling that is perpendicular to the solidification front. This condition fits the observed cracking geometry shown in Figures 3 and 4. Note the different cracking directions depending upon the direction of welding. If the concavity can be minimized one of the necessary concurrent conditions can be reduced.

The CMTRs for the surge pipe at SONGS Unit 3 was examined and found to have overall impurity values of 0.017% S, 0.025% P, and 0.40% Si, all of which are within the material specification. However, these values are high for welding nickel based filler materials. These values also are high by today's melting standards even though the material specification permits rather high levels. For example typical sulfur contents of today's stainless steels are less than 0.010 % and many times will be near 0.003%. For example the material recently purchased to produce the EPRI UT Calibration Block for surge nozzle PDI examinations had sulfur content of 0.003%. It was welded with the same type equipment and similar welding parameters as the SONGS Unit 3 surge line pipe with no problems and no recordable indications in the overlay volume even though the Power Ratio was elevated (113 KW/in^2). On the other hand the initial PWOL 1 mockup also applied to seamless stainless steel pipe was welded using a much lower Power Ratio of 60 KW/in^2 without solidification cracking even though the sulfur content was slightly higher than the SONGS Unit 3 stainless steel piping. The problem with using very low Power Ratios is that the potential for fusion defects is greater. There are multiple issues that can contribute to fusion defects but if the Power Ratio is too low then weld penetration can be a problem. Thus a proper balance must be maintained to be successful.

A study of the chemistry expected in stainless steel pipe was available from several GE and EPRI research projects related to IGSCC studies in the 1970s. these studies showed that the high sulfur and phosphorus contents are not unusual in vintage material with Type 316 being slightly higher than Type 304 material. The sulfur and phosphorus contents of the surge line piping at SONGS Unit 3 are on the upper side of the expected values, but not unusual. It was noted in these studies that the contents of impurity elements varies widely depending upon which organization melted the material and is related to the refining techniques sulfur and the specific melt charge compositions. It is also noted that this information is based on CMTRs and is not necessarily an accurate representation of the chemistry at specific locations within the component. Segregation is always present and sulfides can be concentrated towards the surface of a pipe during fabrication.

The real key for understanding the chemistry effects rests with dilution factors. As the welding arc melts the surface the weld puddle developed will consist of a mixture of the pipe surface material combined with the weld filler material (Alloy 52M in this case). The degree to which this mixing incorporates these impurity elements including iron will determine if a susceptibility to hot cracking is developed. If the stress developed during solidification and cooling is sufficiently high to overcome the grain boundary strength between dendrites then hot cracking will occur.

Increasing the torch tilt angle upward likely increased the base material dilution thus increasing the iron and impurity concentration in the weld puddle. The increased torch tilt angle would also tend to enhance the development of the tear shaped bead concavity and thus help to generate tensile stress at the solidification contours. Lowering the tilt angle helps to minimize dilution and lower susceptibility to hot cracking. In addition the use of a lower heat input and increasing the wire feed rate for this initial layer will also lower dilution. All three factors are in the right direction, but may be insufficient to eliminate cracking if the impurity content is too great. The second and subsequent layers should be much less susceptible to hot cracking because the impurities and iron content will be much lower since those beads are welded over material that has been significantly diluted by the nickel-base filler material

The second factor to be considered is that the heavy wall of the stainless steel is slow to conduct heat away from the weld even when water is inside the pipe. The effect is to hold more heat around the molten puddle as it is solidifying. The result is that the material is held near the solidus temperature for a longer duration. Thus the solidification loads will have a greater opportunity to act upon a weakened grain boundary. Lowering the heat input will improve this issue.

All of the above information points to hot cracking as the mechanism producing the defect condition. In addition, corrective actions within the boundaries of the qualified welding procedure designed for the surge line are not sufficient to eliminate cracking and alternate methods are needed to mitigate the condition. It is believed that the particular heat of pipe used for the surge line is on the high side for impurity elements, but other pipe having this level of sulfur have been welded successfully without hot cracking. Therefore impurity segregation appears to be the problem. It is not possible to define this condition without destructive sampling the pipe and that is not considered a reasonable option. Therefore other methods of applying the overlay to the stainless steel portion are needed and should be explored.

Conclusions

The cracking seen in the initial overlay beads at SONGS Unit 3 is the result of hot cracking most likely due to impurity content of the pipe base material. Since similar cracking was replicated in the lab and that condition was eliminated by minimizing weld puddle dilution the mechanism is confirmed.

Minimizing weld dilution within the boundaries of the qualified welding procedure does not appear to be adequate to eliminate the potential for hot cracking in this specific heat of material. Since other heats of material have been welded successfully with similar nickel base filler materials by minimizing dilution and such steps were not completely successful with this heat, then it is concluded that chemistry of the surge line pipe likely is segregated and possibly has a concentration of sulfides near the surface that are being incorporated into the molten weld puddle.

The observation of a highly reactive weld puddle for Alloy 52M is a clear indicator of a chemistry issue since the weld procedure used has been validated many times. Even though the observation of the weld puddle is subjective, it will be obvious to a welder experienced with applying Alloy 52M overlays if impurity levels are too high for the process.

The following measures are recommended:

1. Examine the CMTR of the stainless steel pipe before welding to determine if special measures are needed to minimize welding.
2. Welder supervision should pay close attention to the appearance of the weld puddle to look for highly reactive puddles when they should not be present. If so

stop welding and look for alternate approaches. For these materials the behavior will be as if too much welding heat is applied.

3. Research alternate methods to deal with high impurity content substrates.
    a. Investigate stainless steel butter layer before applying the Alloy 52M fillers
    b. Investigate special welding techniques for the stainless steel portion of the overlay that produce minimum dilution
    c. Investigate other methods as appropriate

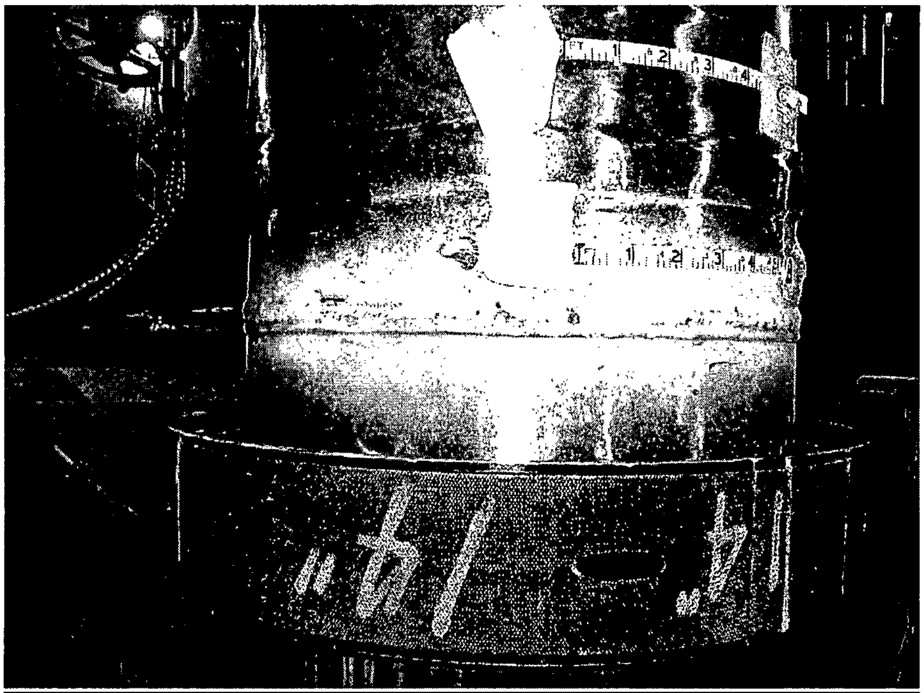

Figure 1 Overall Photograph of Initial Indications observed in the Surge Line Overlay Deposit

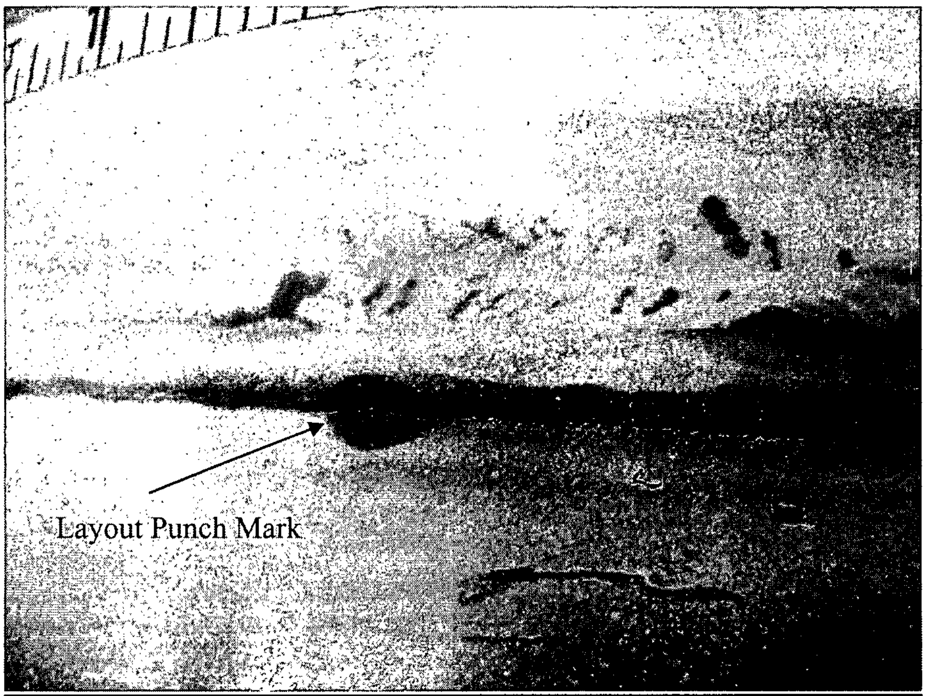

Figure 2 Close-up Photograph of the Initial PT Indications where Bead was Ground

Figure 3 Closeup of Weld Layer Surface (notice roll on bottom bead from reactive weld puddle)

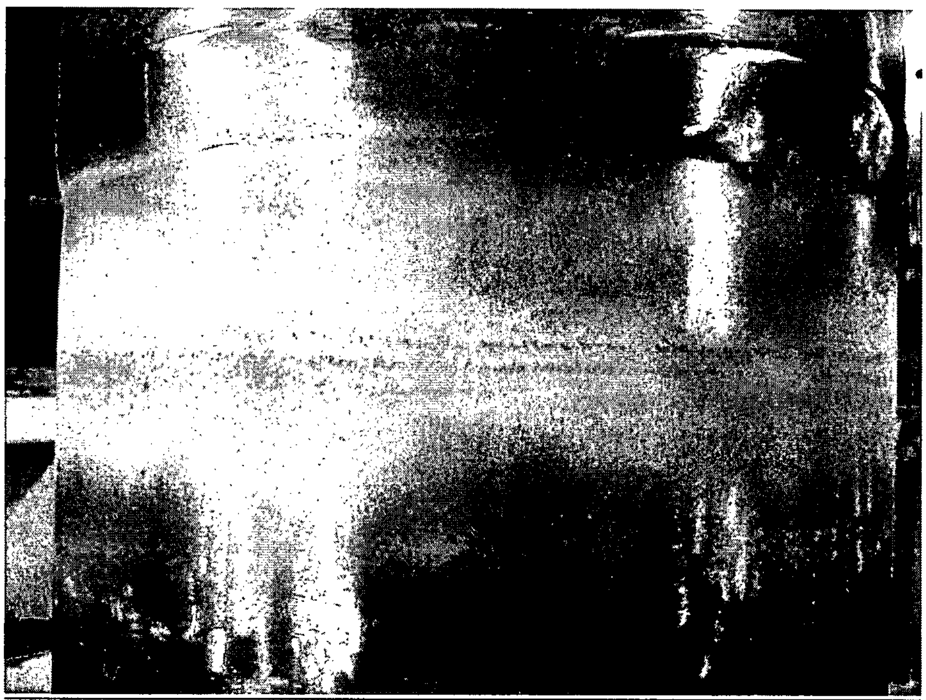

Figure 4 Photograph of PT Indications in Initial Overlay after weld deposit has been ground approximately flush with the Surge Pipe (note the pipe to safe-end weld above the indications)

Figure 5

Removed on NonProprietary Version because Welding Parameters are Considered Proprietary to Welding Services Inc.

Figure 5 Technique Sheet for Alternate Procedure to Minimize Weld Dilution

Appendix 1 – CMTR for Surge Line Piping

☒ ASTM A-312 ☒ ASME SA-312
☐ ASTM A-376 ☐ ASME SA-376
☐ CW 1401-F

Extrusion Facility

Curtiss-Wright Corporation

60 Grider Street Buffalo, New York 14215

DATE July 22, 1977

CUSTOMER GUYON ALLOYS, INC.
CUSTOMER P.O. A14069-NW

PART NUMBER 12.750" O.D.X 1.312" A.W. (Sch 160)
SALES ORDER NO. 2994

PART NAME Seamless Tubing
SPECIFICATIONS TYPE 316

Pullman Power Products
Division ...
QVR IDENTIFICATION
2740 F-944
1T 1-2 1T 81-1

	REQUIRED	MILL HEAT NO. 4-058 C-W Code 2994-2	MILL HEAT NO.
ELEMENT		HEAT LOT NO. 9159	HEAT LOT NO.
CARBON	0.04 - 0.08	0.065	
MANGANESE	2.00 MAX.	1.57	
SILICON	0.75 MAX.	0.40	
CHROMIUM	16.0 - 18.0	16.95	
NICKEL	11.0 - 14.0	12.00	
PHOSPHORUS	0.030 Max.	0.025	
SULPHUR	0.030 MAX.	0.017	
MOLYBDENUM	2.0 - 3.0	2.16	

Pullman Power Products
2740-146
Item 1680

Pullman Power Products
Paramount, Calif.
Q.A. APPROVAL
By ___
Date 3/20/79

BECHTEL
149

Q. A. APPROVED
BY: ___ DATE: 8-8-7
GUYON ALLOYS, INC.

TEST	TRANSVERSE	PHYSICAL PROPERTIES	
TENSILE, PSI	75,000 MIN.	83,000	
YIELD, PSI	30,000 MIN.	42,400	
ELONG, % IN 2 IN.	20 MIN.	56	
FLATTENING		OK	

Marking paint or ink used to apply normal marks required by specifications did not contain low melting point elements such as lead, zinc, sulphur, copper and mercury nor chlorides or other hali[des] in other than trace amount[s]

PARTS WERE HYDROSTATICALLY TESTED AT 2800 P.S.I. FOR A MINIMUM OF 5 SECONDS. NO DEFECTS NOT[ED]

Parts were Ultrasonically tested to a 5% Notch in accordance with the 1974 Edition, including Addenda thru Summer 1976, of ASME Code Section III, Para. NB 2552 and were accepted.

Parts were annealed at 1950°F ± 25°F for 1/2 hour minimum at temperature and water quenched.

Parts were ground as a final cleaning operation.

We hereby certify to the chemical analysis and physical tests reported herein.

Supervisor of Metallurgy G. G. Weart

Sworn to before me this 22nd day of July 1977. Charles B. Diehl; Notary Public, State of New York, Qualified in Erie County, My Commission expires March 30, 1978.