DNV·GL

Project name:	Preliminary Review of Acceptability of Fabricated Welds on the ATCO Shepard System	Det Norske Veritas (Canada) Ltd.
Customer:	ATCO Pipelines	DNV GL Oil & Gas
Address:	7210 42nd ST NW Edmonton, AB T6B 3H1	Integrity Solutions
Contact person:	Kalen Jensen	Suite 150, 2618 Hopewell Place NE
Date of issue:	June 24, 2016	T1Y 7J7 Calgary, AB
Project No.:	PP153056	Canada
Organization unit:	OAPCA853/OAPUS312	Tel: 403 250 9041 Fax: 403 250 9141

Objective:

Det Norske Veritas, U.S.A., Inc. (DNV GL) was contracted by ATCO Pipelines to perform an Engineering Critical Assessment of several girth welds with identified flaws on the ATCO Shepard System.

Prepared by:	Verified by:	Approved by:
		June 24, 2016
Shane Finneran Computational Modeling Group Leader Materials Advisory Services	David Kemp Computational Modeling Engineer Materials Advisory Services	Neil Bates, P.Eng Senior Engineer Integrity Solutions

APEGA Permit to Practice: P10603

DNV GL Distribution:

☐ Unrestricted distribution (internal and external)

☐ Unrestricted distribution within DNV GL

☐ Limited distribution within DNV GL after 3 years

☒ No distribution (confidential)

☐ Secret

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
0	2016-06-24	First issue			

Memo to:
ATCO Pipelines
7210 42nd ST NW Edmonton, AB
T6B 3H1

Attention: Kalen Jensen

Date:	**Our reference:**
24th June, 2016	PP153056

Preliminary Review of Acceptability of Fabricated Welds on the ATCO Shepard System

Background

Det Norske Veritas, U.S.A., Inc. (DNV GL) was contracted by ATCO Pipelines to perform an Engineering Critical Assessment (ECA) of several girth welds with identified flaws on the ATCO Shepard System. Radiography was performed on all of the girth welds in question for this study upon construction and installation of the pipeline system at the Shepard system, with no rejectable flaws. The pipeline system was thus put into service, having followed applicable standards for welding and constructability of the pipeline system. ATCO, upon further review of the original radiography reports, identified some concerns with the accuracy of the original radiography results and thus sought to re-radiograph the girth welds of concern on the Shepard system. The conclusions of the second radiography reports, performed after the pipeline system was in service, indicated multiple girth welds with flaws of various types and dimensions.

Typical welding procedures for constructability allow for an ECA to be performed, prior to construction, to increase the allowance for weld flaws during construction (i.e. CSA Z662-2015 (CSA Z662) Clause 7.10.4.3). In the absence of such an ECA during the planning and construction phase, the governing standard must be applied to the piping system, in this case CSA Z662. According to CSA Z662 Clause 7.10.6.1, welds that are deemed unacceptable "shall be removed, or repaired as specified in Clause 7.12." However, as the original radiography reports performed during construction indicated no rejectable welds, the system was commissioned and put into service. Therefore, the flaws identified by subsequent inspection have been in service for approximately two years (Fall 2014). Clause 7.10.6.2 of CSA Z662 allows for welds which have previously been accepted which are subsequently found to be unacceptable to be:

a) *Accepted provided that the weld imperfections are found to be acceptable on the basis of an engineering critical assessment involving consideration of service history and loading, anticipated service conditions (including the effects of corrosive and chemical attack), accurately established dimensions and location of the imperfections, and weld properties (including fracture toughness);*

b) *Repaired as specified in Clause 7.12; or*

c) *removed*

With these weld flaws being identified after the pipeline system was in service, a Fitness-for-Service (FFS) Assessment was performed to analyze the identified weld flaws. The weld flaws were assessed in accordance with API 579-1/ASME FFS-1 (API 579) Part 9 for assessment of crack-like flaws. Additionally, ATCO noted an observed lack of toughness at the minimum specified design temperature of -45°C, which led them to pursue the assessment of volumetric flaws as planar crack-like flaws. Further, API 579 guidance recommends that it is conservative and advisable to assess volumetric flaws, such as porosity or inclusions, as planar crack-like flaws as the inspection tools may not have the sensitivity to determine whether micro-cracking is associated with the flaws.

API 579 provides three levels of assessment for each Part of the FFS Standard, providing a balance in complexity and conservatism. In general, the complexity in data required and analysis increases with each level, with an expected increase in precision. The Level 1 FFS assessment is a generalized assessment based upon basic calculations and criteria for an identified flaw, this type of assessment is the most conservative utilizing simplified stress estimates. The Level 2 FFS assessments provide a more detailed assessment, requiring multiple steps and more detailed calculations to account for stress concentrations and reference stresses for membrane and bending stress. The Level 3 assessment requires a detailed stress analysis of the component under consideration.

This memo describes the assessment performed by DNV GL to evaluate each of the identified girth weld flaws to determine if they satisfy the allowable conditions per API 579 for a crack-like flaw, and are considered fit for continued service. The assumptions to allow for appropriate levels of conservatism in the analysis are outlined in further detail in the following sections. The results of this analysis are intended to be used as supplemental information for ATCO to prioritize repairs and further assessment.

Assessment Information and Assumptions

The geometry of the welded assemblies were provided by ATCO along with the pipe grade, outer diameter (OD), and wall thickness. Additionally, results of a detailed stress analysis, performed by Stantec for the Mainline Valve assemblies and risers was provided to DNV GL. However, the stations were not included in the stress analysis performed by Stantec. The results from the radiography reports were also provided by ATCO, to appropriately classify and evaluate each of the noted weld flaws. As the Shepard pipeline system is currently in service, no mechanical testing was performed on material samples. ATCO had previously performed material testing to obtain Charpy V-Notch (CVN) properties at their North East Calgary Connector station, for which DNV GL performed a similar ECA during the construction phase. As the pipe grades and operating environments were similar between the North East Calgary Connector and the Shepard system, it was agreed by DNV GL and ATCO to use the same CVN properties from the previous assessment in assessing the welds at the Shepard system. Material testing was performed as part of a previous project (DNV GL PP153212) at a temperature of -45°C, corresponding to the minimum system design temperature, which resulted in a minimum weld CVN energy of approximately 11 J. Additionally, ATCO provided a conservative CVN energy of 18 J, at a temperature of -20°C, as part of the previous assessment. ATCO indicated to perform the FFS Assessment considering the CVN energies of 11 J and 18 J, at -45°C and -20°C, respectively, to determine correlated toughness values necessary for assessment of the crack-like flaws in the Shepard system. These CVN values correspond to a fracture toughness value (K_{IC}) of 48 MPa$\sqrt{m}$ (at -45°C) and 62 MPa$\sqrt{m}$ (at -20°C), using the Sailors and Corton correlation as specified in API 579.

Several of the weld locations did not have corresponding stress results from the Stantec model, as these welds were below grade or associated with the piping stations, and thus were not modeled. For these cases, the axial stress was approximated using CSA Z662, Section 4.7.2.1 which indicates a maximum allowable stress state based upon circumferential, axial, and bending stress components for constrained pipe segments as shown below in Equation 1.

$$S_h - S_L + S_B \leq S \times T$$

Where

S_h = hoop stress due to design pressure, MPa

S_L = longitudinal compression stress, MPa

S_B = absolute value of beam bending compression stresses resulting from live and dead loads, MPa

S = specified minimum yield stress, MPa

T = temperature factor

Equation 1 Maximum Design Allowable Stress per CSA Z662

In the absence of further details, the circumferential stress (S_h) was calculated based upon the licensed maximum operating pressure (LMOP) of the pipeline, assuming the piping was designed in accordance with CSA Z662. As indicated in Table 1, and the longitudinal stress (S_L) was assumed to be zero. The longitudinal stress (S_L), as defined here in CSA Z662, is a compressive stress resulting from the internal pressure and thermal growth in the constrained pipe segment. Assuming the longitudinal stress to be zero, allows for the calculation of the maximum allowable bending stress (S_B) for each of these regions where further stress details are unavailable. This maximum allowable bending stress (S_B) was used as the primary stress component for the FFS Assessment.

A summary of the dimensions and applied loads for the welds which failed the recent inspections, based on the general arrangement drawings and Stantec stress models, is shown in Table 1. Values shown in green were estimated by ATCO while axial stresses shown in blue were the maximum allowable bending stresses, calculated as described above, applying the CSA Z662 method for weld locations without detailed stress model results.

Table 1 –Membrane and Longitudinal Stresses at Failing Weld Locations

Node on Drawing	Pipe Grade (MPa)	Pipe OD (mm)	Pipe Wall Thickness (mm)	LMOP (kPa)	Axial stress (kPa)	Bending stress (kPa)	Total Axial stress (kPa)	Hoop (Membrane) stress (kPa)
Site: Carbon Loop Launcher/ Receiver Valve Assembly (Rosebud)								
X15	483	508	9.52	6,240	77,765.00	12,703.00	90,468.0	166,487.4
X15	483	508	9.52	6,240	77,765.00	12,703.00	90,468.0	166,487.4
X22	483	508	9.52	5,400	78,478.10	4,468.10	82,946.2	144,075.6
X23	483	508	9.52	5,400	78,478.00	1,888.50	80,366.5	144,075.6
X23	483	508	9.52	5,400	78,478.00	1,888.50	80,366.5	144,075.6
X23	483	508	9.52	5,400	78,478.00	1,888.50	80,366.5	144,075.6
X23	483	508	9.52	5,400	78,478.00	1,888.50	80,366.5	144,075.6
X35	359	323.8	9.52	6,160	NA	NA	25,241	104,758.8
X35	359	323.8	9.52	6,160	NA	NA	254,241	104,758.8
X77	359	323.8	9.52	5,250	NA	NA	269,717	89,283.1
X80	359	323.8	9.52	6,240	NA	NA	252,881	106,119.3
X85	359	323.8	9.52	5,250	NA	NA	269,717	89,283.1
Node on Drawing	Pipe Grade (MPa)	Pipe OD (mm)	Pipe Wall Thickness (mm)	LMOP (kPa)	Axial stress (kPa)	Bending stress (kPa)	Total Axial stress (kPa)	Hoop (Membrane) stress (kPa)
X128	359	219.1	8.179	5,400	36,597.00	0.00	36,597.0	72,327.9
Site: Site #1 Carbon Loop to Shepard Lateral Tie-in								
X2	483	508	9.525	5,400	66,307.40	11,512.40	77,819.8	144,000.0
X2	483	508	9.525	5,400	66,307.40	11,512.40	77,819.8	144,000.0
X3	483	508	9.525	5,400	64,878.30	17,086.00	81,964.3	144,000.0
X5	483	508	9.525	5,400	64,878.30	25,522.80	90,401.1	144,000.0
X5	483	508	9.525	5,400	64,878.30	25,522.80	90,401.1	144,000.0
X5	483	508	9.525	5,400	64,878.30	25,522.80	90,401.1	144,000.0
X5	483	508	9.525	5,400	64,878.30	25,522.80	90,401.1	144,000.0
X5	483	508	9.525	5,400	64,878.30	25,522.80	90,401.1	144,000.0
X8	483	508	9.525	5,400	68,086.00	12,814.00	80,900.0	144,000.0
X8	483	508	9.525	5,400	68,086.00	12,814.00	80,900.0	144,000.0
X8	483	508	9.525	5,400	68,086.00	12,814.00	80,900.0	144,000.0
X12	483	508	9.525	5,400	67,882.70	7,969.70	75,852.4	144,000.0
X39	359	406.4	9.525	5,400	NA	NA	243,800	115,200.0
X40	359	406.4	9.525	5,400	NA	NA	243,800	115,200.0
X45	359	406.4	9.525	5,400	53,443.60	3,057.20	56,500.8	115,200.0
X45	359	406.4	9.525	5,400	53,443.60	3,057.20	56,500.8	115,200.0
X45	359	406.4	9.525	5,400	53,443.60	3,057.20	56,500.8	115,200.0
X49	359	406.4	9.525	5,400	54,128.60	1,748.00	55,876.6	115,200.0
X58	359	323.8	9.52	5,400	51,626.00	14,723.70	66,349.7	91,834.0
Site: Site#3 Shepard Energy Center Delivery Station Tie-in								
X3	483	508	9.52	5,400	62,255.80	42,818.00	105,073.8	144,075.6
X10	483	508	9.52	5,400	62,022.80	41,560.30	103,583.1	144,075.6
X29	359	406.4	9.52	5,400	53,287.00	8,419.80	61,706.8	115,260.5
X35	359	406.4	9.52	5,400	NA	NA	243,739	115,260.5
X49	359	406.4	9.52	5,400	NA	NA	243,739	115,260.5
X89	359	323.8	9.52	5,400	NA	NA	267,166	91,834.0
X89	359	323.8	9.52	5,400	NA	NA	267,166	91,834.0
Site #4: Shepard Energy Transfer Point								
X2	483	508	9.52	5,400	67,042.30	13,569.40	80,611.7	144,075.6
X2	483	508	9.52	5,400	67,042.30	13,569.40	80,611.7	144,075.6
X4	483	508	9.52	5,400	67,042.30	37,544.30	104,586.6	144,075.6
X4	483	508	9.52	5,400	67,042.30	37,544.30	104,586.6	144,075.6
X4	483	508	9.52	5,400	67,042.30	37,544.30	104,586.6	144,075.6
X5	483	508	9.52	5,400	63,504.60	33,676.50	97,181.1	144,075.6
X7	483	508	9.52	5,400	72,835.30	28,024.70	100,860.0	144,075.6
X10	359	406.4	9.52	5,400	53,163.30	17,101.30	70,264.6	115,260.5
X24	359	323.8	9.52	5,400	42,021.40	5,451.70	47,473.1	91,834.0
Site #2: Chestermere Lateral Control Station tie-in								
XR-03	483	508	9.52	5,400	NA	NA	338,924	144,075.6
X83	359	219	8.179	5,400	NA	NA	286,705	72,294.9
X121	483	508	9.52	5,400	NA	NA	338,924	144,075.6
X121	483	508	9.52	5,400	NA	NA	338,924	144,075.6

Radiography Reports

All of the flaws assessed as part of this study were circumferential flaws, and the majority of the flaws were mid-wall flaws. For most- of the identified weld flaws, the circumferential location, length, and flaw type were provided with sufficient detail in the radiography reports. However, the radiography reports did not provide sufficient details to determine the depth of the flaws within the pipe wall. Thus, to remain conservative, all flaws were assessed as surface breaking flaws, occurring on the outer-diameter surface of the pipe, to assess a worst-case scenario.

Flaws identified during the recent radiography inspections were classified in the reports as follows:

- Porosity
- Isolated Slag
- Incomplete Penetration
- Lack of Fusion
- Elongated Slag
- Internal Undercut

While these were all evaluated as circumferential flaws occurring on the outer diameter surface, the flaw height was only provided for the porosity flaws in the radiography reports. Flaw height measurements were unavailable for the incomplete penetration, lack of fusion, isolated/elongated slag, and internal undercut due to limitations of the inspection technique. Thus, for all flaws other than the porosity flaws, the maximum allowable flaw height, per the API 579 FFS Assessment, was determined for each case to allow for further assessment and prioritization by ATCO.

Two of the flaws classified as Internal Undercut (IUC), did not have any further measurements for height or length of the flaw due to limitations of the inspection technique. Thus CSA Z662 was consulted to evaluate a conservative "worst case" length of the flaw in the API 579 FFS Assessment. The radiography reports indicated a single circumferential location at each weld for the internal undercut anomalies. Per CSA Z662 7.11.6.2 in evaluating acceptability of internal undercut features, the cumulative length of IUC features in any 300 mm length of weld shall not exceed 50 mm. Thus based upon CSA Z662, it can be assumed that the maximum length of the anomaly is 300 mm, as there was only one circumferential location indicated at each weld. The allowable flaw height was then calculated from the API 579 FFS Assessment based upon this assumed, worst case length for the IUC flaws.

With regards to the porosity flaws, these are typically volumetric flaws which are not necessarily expected to behave as a crack-like flaw. However, in order to remain conservative, API 579 guidance recommends assessment of porosity flaws as planar crack-like flaws, as the NDT may not be sensitive enough to identify or exclude the presence of micro-cracking associated with the porosity. As such, this procedure was followed for all of the porosity-classified flaws, using the details from the radiography reports for flaw height and length.

Details from the Radiography reports indicated several weld locations which had more than one flaw in the girth weld. For these cases, API 579 outlines a procedure for evaluating interaction between multiple crack-like flaws, accounting for each individual flaw length and the separation distance between flaws. Multiple adjacent interacting flaws can be evaluated as a single flaw as shown below in Figure 1. This procedure was used to determine the appropriate combined flaw length(s) for each weld location, to perform the FFS assessment.

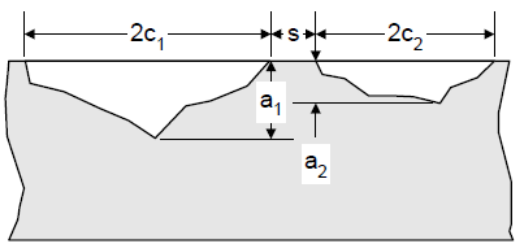
Multiple Crack-Like Flaw Configuration	Criterion For Interaction	Effective Dimensions After Interaction
	$c_1 + c_2 \geq s$	$2c = 2c_1 + 2c_2 + s$ $a = \max\left[a_1,\ a_2\right]$

Figure 1 API 579 Determining Interaction of Multiple Crack-Like Flaws

A summary of the overall flaw list is shown below in Table 2 through Table 6 for each of the Shepard system sites which were identified to have flaws in the girth welds. For each row in the tables, each number refers to a single girth weld. If there is a letter accompanying the index number, there were multiple indications at the particular girth weld which were evaluated as individual distinct flaws or multiple sets of combined flaws due to the separation distance between adjacent flaws. In addition to the measured flaw lengths and heights, the overall equivalent length is presented for flaws which were deemed to be interacting. This equivalent length was used in the analysis as the crack length, 2c, as indicated in Figure 1 above. Again, axial stresses shown in blue were the maximum allowable bending stresses, calculated using the CSA Z662 method for weld locations without detailed stress model results.

Table 2 Carbon Loop Launcher / Receiver Valve Assembly (Rosebud) Failing Weld Flaws

Site: Carbon Loop Launcher/ Receiver Valve Assembly (Rosebud)											
Anomaly Index	**Node on Drawing**	**Pipe Grade (MPa)**	**Pipe OD (mm)**	**Pipe Wall Thickness (mm)**	**LMOP (kPa)**	**Total Axial stress (kPa)**	**Hoop (Membrane) stress (kPa)**	**Anomaly Type**	**Measured Height (mm)**	**Location**	**Equivalent Length (mm)**
1a	X15	483	508	9.52	6,240	90,468.0	166,487.4	Incomplete Penetration	N/A	@Side of Root 24-30cm (62mm)	62.0
1b	X15	483	508	9.52	6,240	90,468.0	166,487.4	Incomplete Penetration	N/A	@34-35cm (12mm)	12.0
2	X22	483	508	9.52	5,400	82,946.2	144,075.6	Incomplete Penetration	N/A	@130cm (10mm), @131-135cm (39mm), @136-138cm (15mm)	75.0
3a	X23	483	508	9.52	5,400	80,366.5	144,075.6	Incomplete Penetration	N/A	@30cm (5mm), @31.5-33.5cm (19mm), @35cm (14mm), @36cm (5mm)	65.0
3b	X23	483	508	9.52	5,400	80,366.5	144,075.6	Incomplete Penetration	N/A	@45cm (4mm)	4.0
3c	X23	483	508	9.52	5,400	80,366.5	144,075.6	Incomplete Penetration	N/A	@46cm (7mm), @47-48.5cm (10mm)	20.0
3d	X23	483	508	9.52	5,400	80,366.5	144,075.6	Incomplete Penetration	N/A	@50-52.5cm (22mm)	22.0
4	X35	359	323.8	9.52	6,160	254,241	104,758.8	Porosity	3.0	@19cm (3mm)	3.0
5	X35	359	323.8	9.52	6,160	254,241	104,758.8	Lack of Fusion	N/A	@ 97-98.5cm (15mm)	15.0
6	X77	359	323.8	9.52	5,250	269,717	89,283.1	Lack of Fusion	N/A	@ 44.5-47cm (22mm)	22.0
7	X80	359	323.8	9.52	6,240	252,881	106,119.3	Porosity	3.0	@ 0cm (3mm)	3.0
8	X85	359	323.8	9.52	5,250	269,717	89,283.1	Porosity	4.0	@ 18cm (4mm) (wormhole)	4.0
9	X128	359	219.1	8.179	5,400	36,597.0	72,327.9	Isolated Slag	N/A	@ 60-62cm (1.5x15mm)	15.0

Table 3 Carbon Loop to Shepard Lateral Tie-in Failing Weld Flaws

Site: Site #1 Carbon Loop to Shepard Lateral Tie-in											
Anomaly Index	**Node on Drawing**	**Pipe Grade (MPa)**	**Pipe OD (mm)**	**Pipe Wall Thickness (mm)**	**LMOP (kPa)**	**Total Axial stress (kPa)**	**Hoop (Membrane) stress (kPa)**	**Anomaly Type**	**Measured Height (mm)**	**Location**	**Equivalent Length (mm)**
10	X2	483	508	9.525	5,400	77,819.8	144,000.0	Elongated Slag	N/A	@70-80cm (90mm), @82.5-96cm (140mm), @103-110cm (70mm), @114-125cm (115mm)	555.0
10b	X2	483	508	9.525	5,400	77,819.8	144,000.0	Elongated Slag	N/A	@135-137cm (25mm), @140-148cm (90mm)	140.0
11	X3	483	508	9.525	5,400	81,964.3	144,000.0	Lack of Fusion	Not Failing		
12	X5	483	508	9.525	5,400	90,401.1	144,000.0	Elongated Slag	N/A	@0-22cm (sum=180mm), @25,27-35cm (sum=80mm), @120-125cm (35mm), @128-0cm (sum=250mm)	726.0
12b	X5	483	508	9.525	5,400	90,401.1	144,000.0	Elongated Slag	N/A	@63-68cm (sum=26mm)	26.0
12c	X5	483	508	9.525	5,400	90,401.1	144,000.0	Elongated Slag	N/A	@77.5-78.5cm (10mm)	10.0
12d	X5	483	508	9.525	5,400	90,401.1	144,000.0	Elongated Slag	N/A	@88-94cm (sum=28mm)	28.0
12e	X5	483	508	9.525	5,400	90,401.1	144,000.0	Elongated Slag	N/A	@106-112cm (sum=39mm)	39.0
13	X8	483	508	9.525	5,400	80,900.0	144,000.0	Incomplete Penetration (side of root)	N/A	@1cm, @2-6cm (sum=30mm)	30.0
13b	X8	483	508	9.525	5,400	80,900.0	144,000.0	Incomplete Penetration (side of root)	N/A	@10-15cm (50mm)	50.0
13c	X8	483	508	9.525	5,400	80,900.0	144,000.0	Incomplete Penetration (side of root)	N/A	@154-157cm (sum=25mm)	25.0
14	X12	483	508	9.525	5,400	75,852.4	144,000.0	Isolated Slag	N/A	@119-120cm (2.0x 18mm)	18.0
15	X39	359	406.4	9.525	5,400	243,800	115,200.0	Porosity, Internal Undercut	Not Failing		
16	X40	359	406.4	9.525	5,400	243,800	115,200.0	Porosity	Not Failing		
17	X45	359	406.4	9.525	5,400	56,500.8	115,200.0	Isolated Slag	N/A	@54cm (1.5x 5mm)	5.0
17b	X45	359	406.4	9.525	5,400	56,500.8	115,200.0	Isolated Slag	N/A	@55cm (2.0x4.5mm)	4.5
18	X45	359	406.4	9.525	5,400	56,500.8	115,200.0	Porosity	4.0	@116,117cm (4 mm)	4.0
19	X49	359	406.4	9.525	5,400	55,876.6	115,200.0	Intermittent Elongated Slag	N/A	@120-125.5cm (45mm)	45.0
20	X58	359	323.8	9.52	5,400	66,349.7	91,834.0	Porosity	3.5	@27.5cm (3.5mm)	3.5

Table 4 Shepard Energy Center Delivery Station Tie-in Failing Weld Flaws

Site: Site#3 Shepard Energy Center Delivery Station Tie-in											
Anomaly Index	Node on Drawing	Pipe Grade (MPa)	Pipe OD (mm)	Pipe Wall Thickness (mm)	LMOP (kPa)	Total Axial stress (kPa)	Hoop (Membrane) stress (kPa)	Anomaly Type	Measured Height (mm)	Location	Equivalent Length (mm)
21	X3	483	508	9.52	5,400	105,073.8	144,075.6	Internal Undercut	N/A	@161.5cm	300*
22	X10	483	508	9.52	5,400	103,583.1	144,075.6	Porosity	3.5	@38 cm (3.5mm)	3.5
23	X29	359	406.4	9.52	5,400	61,706.8	115,260.5	Porosity	3.0	@108 cm (3mm)	3.0
24	X35	359	406.4	9.52	5,400	243,739	115,260.5	Porosity	3.0	@14 cm (3mm)	4.0
25	X49	359	406.4	9.52	5,400	243,739	115,260.5	Incomplete penetration	N/A	@0.5 cm to 3 cm (25mm)	25.0
26	X89	359	323.8	9.52	5,400	267,166	91,834.0	Incomplete penetration	N/A	@2 cm to 11.5 cm (95mm), @21.5 cm to 32.5 cm (110mm)	305.0
26b	X89	359	323.8	9.52	5,400	267,166	91,834.0	Incomplete penetration	N/A	@93 cm to 95.5 cm (23mm)	23.0

*Assumed worst-case length per CSA Z662

Table 5 Shepard Energy Transfer Point Failing Weld Flaws

Site #4: Shepard Energy Transfer Point											
Anomaly Index	Node on Drawing	Pipe Grade (MPa)	Pipe OD (mm)	Pipe Wall Thickness (mm)	LMOP (kPa)	Total Axial stress (kPa)	Hoop (Membrane) stress (kPa)	Anomaly Type	Measured Height (mm)	Location	Equivalent Length (mm)
27	X2	483	508	9.52	5,400	80,611.7	144,075.6	Incomplete Penetration	N/A	@6-8cm (17mm)	17.0
28	X2	483	508	9.52	5,400	80,611.7	144,075.6	Internal Undercut	N/A	@40cm	300*
29	X4	483	508	9.52	5,400	104,586.6	144,075.6	Incomplete Penetration	N/A	@74-75cm (10mm)	10.0
29b	X4	483	508	9.52	5,400	104,586.6	144,075.6	Incomplete Penetration	N/A	@77.5-79cm (15mm), @80-82cm (20mm)	45.0
29c	X4	483	508	9.52	5,400	104,586.6	144,075.6	Incomplete Penetration	N/A	@84-85cm (10mm), @86-90cm (40mm), @91-92.5cm (15mm)	85.0
30	X5	483	508	9.52	5,400	97,181.1	144,075.6	Incomplete Penetration	N/A	@90-94cm (36mm), @97-101cm (40mm)	110.0
31	X7	483	508	9.52	5,400	100,860.0	144,075.6	Porosity	4.0	@155cm (4mm)	4.0
32	X10	359	406.4	9.52	5,400	70,264.6	115,260.5	Porosity	4.0	@38cm (3.5mm)	3.5
33	X24	359	323.8	9.52	5,400	47,473.1	91,834.0	Cluster Porosity	N/A	@34.5cm to 39cm (50.8mm)	50.8

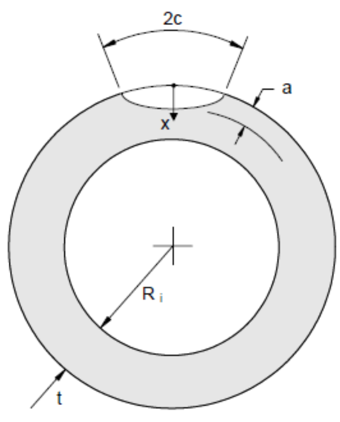
*Assumed worst-case length per CSA Z662

Table 6 Chestermere Lateral Control Station Tie-in Failing Weld Flaws

Site #2: Chestermere Lateral Control Station tie-in											
Anomaly Index	Node on Drawing	Pipe Grade (MPa)	Pipe OD (mm)	Pipe Wall Thickness (mm)	LMOP (kPa)	Total Axial stress (kPa)	Hoop (Membrane) stress (kPa)	Anomaly Type	Measured Height (mm)	Location	Equivalent Length (mm)
34	XR-03	483	508	9.52	5,400	338,924	144,075.6	Incomplete Penetration	N/A	@70-73cm (30 mm in root) due to misalignment	30.0
35	X83	359	219	8.179	5,400	286,705	72,294.9	Incomplete Penetration	N/A	@8-15cm (75mm), @18,20,21,23cm	75.0
36	X121	483	508	9.52	5,400	338,924	144,075.6	Incomplete Penetration	N/A	@1,5-31cm (270mm)	270.0
36b	X121	483	508	9.52	5,400	338,924	144,075.6	Incomplete Penetration	N/A	@138-141cm (30mm), @ 148.5-162cm (130mm) incomplete filling to side of root caused by misalignment	235.0

API 579 Fitness-for-Service Assessment

API 579 Part 9 organizes crack-like flaws into multiple categories depending upon crack orientation, shape, and loading scenarios. All of the flaws included in this assessment were circumferential flaws, as indicated in the radiography reports. API 579 provides guidance for minimum flaw depth for crack-like flaws to be considered “mid-wall.” For flaw depths closer to the surface, it is recommended to assess as “surface breaking.” Many of the reported flaws were indicated as occurring within the pipe wall; however the location within the pipe wall to confirm adequate depth was unavailable. Thus, it was required that all flaws were assessed as semi-elliptical surface breaking flaws at the outer diameter surface. Figure 2 below indicates the typical geometry of a semi-elliptical circumferential surface flaw along with the designations for crack width (2c) and crack height (a).



(b) Outside Surface

Figure C.16
Cylinder – Surface Crack, Circumferential Direction, Semi-elliptical Shape

Figure 2 Semi-Elliptical Circumferential Surface Crack Geometry, per API 579, Annex C

A Level 3 FFS Assessment was performed using the Stantec stress results, where applicable, in conjunction with the provided pipe grade, geometry, LMOP, and flaw dimensions. In cases where a detailed stress analysis was unavailable, the maximum design allowable axial stress was used for the assessment, which would technically be classified as a Level 2 FFS Assessment. The procedure for both the Level 2 and Level 3 FFS Assessment is similar, with the primary difference being the calculation of the component stresses used in the analysis. By definition, the Level 3 FFS Assessment requires a detailed stress analysis to be performed, such as Finite Element Analysis (FEA), which was performed by Stantec. As part of the FFS Assessment, these stresses are used in multiple equations, which account for varying safety factors and residual stresses, resulting from the girth weld. The final criteria for allowance of acceptability, per API 579, is a function of the Load ratio (L^P_r), based upon primary stresses, and the material toughness ratio (K_r). The toughness ratio is defined as the ratio of the stress intensity caused by the primary and secondary stresses and the material fracture toughness.

CVN mechanical test data was unavailable for the Shepard system, thus CVN data provided as part of a previous ECA project with ATCO was provided as a conservative estimate. The material testing and analysis performed previously at a separate ATCO piping station indicated a conservative minimum weld CVN energy of 11 J at a temperature of -45°C and 18 J at a temperature of -20°C. The Sailors and Corton correlation for static fracture toughness was used to convert the provided CVN data to a K_{1C} value (using equations F.64 and F.65 from section F.4.5.2 paragraph c of API 579) for use in the FFS assessment. The CVN energies provided for the analysis resulted in fracture toughness values of 48 MPa√m (at -45°C) and 62 MPa√m (at -20°C), which were used in the analysis presented below.

One of the controlling factors throughout this analysis, aside from the relatively low fracture toughness, was the residual weld stress. API 579 approximates residual weld stress, based upon an effective yield stress (σ^r_{ys}) estimated in API 579 as the specified minimum yield strength (SMYS) of the base material plus 69 MPa. This approximation of the effective yield stress, used in residual stress calculations, accounts for the typical localized elevation of material properties above minimum requirements. As discussed previously, all flaws considered in this assessment were evaluated as surface breaking flaws, thus the residual stress distribution at the outer diameter surface of the weld was calculated in API 579 by multiplying the effective yield stress (σ^r_{ys}) by a reduction factor, R_r. This reduction factor accounts for test pressure of the pipeline as well as any post weld heat treatment (PWHT) which may relieve residual weld stresses. Figure 3 is an excerpt from API 579, E.4.1.1, outlining the definition of the reduction factor, R_r used for determining the surface residual stress distribution.

c) Effects of Test Pressure – The reduction in residual stress resulting from the test pressure as a percentage of the residual stress in the as-welded condition may be determined using the equations shown below or Figure E.3.

$$R_r = 1.0 \qquad T_p < 75\% \qquad \text{(E.33)}$$

$$R_r = \frac{168.5063 - 2.26770T_p + 9.16852(10)^{-3}T_p^2}{100} \qquad 75\% \le T_p \le 110\% \qquad \text{(E.34)}$$

$$R_r = 0.30 \qquad T_p > 110\% \qquad \text{(E.35)}$$

$$T_p = \left(\frac{\sigma_{mc,t}}{\sigma_{ys}^r}\right)\cdot 100 \qquad \text{(E.36)}$$

d) Effects of $PWHT$ – If the weld is known to have been subject to post weld heat treatment per the original construction code, then the residual stress is given by:

$$\sigma^r(x) = 0.2\sigma_{ys}^r \qquad \text{(E.37)}$$

e) The effects of test pressure and $PWHT$ shall be evaluated separately, not in combination.

Figure 3 API 579, E.4.1.1, Definition of R_r for Approximating Residual Stress Distribution

ATCO indicated there was no post weld heat treatment applied to the welds in question, thus no reduction due to PWHT could be accounted for in the assessment. ATCO further indicated that the piping system was pressure tested to a pressure equivalent to 1.4 x LMOP. However, the designated LMOP for the Shepard system is based upon a pressure well below the material SMYS. Thus, the resulting ratio of circumferential membrane stress as a percentage of the effective yield stress (T_p) ranged from 24%-42% for the welds considered in the analysis. As indicated in Figure 3, when T_p is less than 75%, the reduction in residual stress, R_r, is taken as 1. Thus a reduction in residual stress at the girth welds was not permitted, as outlined in API 579.

The flaws were assessed per API 579 when sufficient data was available for the flaw length and height. Many of the flaws identified as part of the radiography inspection did not indicate a height for each of the flaws. In these cases, the FFS assessment was used to calculate a maximum allowable flaw height, based upon surface breaking flaws occurring at the OD surface and API 579 allowances.

Preliminary Conclusion on Acceptability per API 579

The maximum allowable flaw height, in accordance with API 579, was found to be highly dependent upon the fracture toughness and the residual stress at the welded joint. The CVN data used for the assessment was a conservatively low assumption at two different temperatures to account for differences in mechanical properties at each of the welds due to variations in welding procedures at each of the welds. The residual stresses at each of the welds were assessed based upon API 579, without accounting for any reduction due to pressure testing or post weld heat treatment. Additionally, many of the welds had multiple flaws around the circumference, as indicated by the radiographic examination, which were deemed to be interacting flaws, as outlined in API 579. The combination of these multiple flaws increased the equivalent flaw length to approximately half of the overall pipeline circumference in some cases. As the circumferential flaw length is increased, the allowable height can decrease significantly. All of these assumptions allow for a conservative, worst case assessment of the individual flaws.

The maximum allowable height for each of the flaws, per API 579, is indicated below in Table 7 through Table 11. As discussed previously, values highlighted in green were approximated by ATCO, while axial stresses highlighted in blue correspond to the maximum bending stresses, calculated using CSA Z662 for locations where Stantec model stresses were unavailable. For the porosity flaws, having measurements for both flaw height and length allowed for an unacceptable or acceptable conclusion, based upon the FFS Assessment and API 579, as indicated in the tables below. The maximum allowable height is noted for CVN data at temperatures of -20°C and -45°C in the columns titled "*Maximum Allowable Height (mm) T= - 20C*" and "*Maximum Allowable Height (mm) T= - 45 C*," respectively.

Table 7 Carbon Loop Launcher / Receiver Valve Assembly (Rosebud) Failing Weld Flaws

Site: Carbon Loop Launcher/ Receiver Valve Assembly (Rosebud)												
Anomaly Index	**Node on Drawing**	**Pipe Grade (MPa)**	**Pipe OD (mm)**	**Pipe Wall Thickness (mm)**	**LMOP (kPa)**	**Total Axial stress (kPa)**	**Hoop (Membrane) Stress (kPa)**	**Anomaly Type**	**Measured Height (mm)**	**Equivalent Length (mm)**	**Maximum Allowable Height (mm) T = - 20C**	**Maximum Allowable Height (mm) T = - 45C**
1a	X15	483	508	9.52	6,240	90,468.0	166,487.4	Incomplete Penetration	N/A	62.0	0.9	0.5
1b	X15	483	508	9.52	6,240	90,468.0	166,487.4	Incomplete Penetration	N/A	12.0	0.9	0.5
2	X22	483	508	9.52	5,400	82,946.2	144,075.6	Incomplete Penetration	N/A	75.0	0.9	0.5
3a	X23	483	508	9.52	5,400	80,366.5	144,075.6	Incomplete Penetration	N/A	65.0	0.9	0.5
3b	X23	483	508	9.52	5,400	80,366.5	144,075.6	Incomplete Penetration	N/A	4.0	4.2	0.7
3c	X23	483	508	9.52	5,400	80,366.5	144,075.6	Incomplete Penetration	N/A	20.0	0.9	0.5
3d	X23	483	508	9.52	5,400	80,366.5	144,075.6	Incomplete Penetration	N/A	22.0	0.9	0.5
4	X35	359	323.8	9.52	6,160	254,241	104,758.8	Porosity	3.0	3.0	Unacceptable	Unacceptable
5	X35	359	323.8	9.52	6,160	254,241	104,758.8	Lack of Fusion	N/A	15.0	0.4	0.2
6	X77	359	323.8	9.52	5,250	269,717	89,283.1	Lack of Fusion	N/A	22.0	0.3	0.1
7	X80	359	323.8	9.52	6,240	252,881	106,119.3	Porosity	3.0	3.0	Unacceptable	Unacceptable
8	X85	359	323.8	9.52	5,250	269,717	89,283.1	Porosity	4.0	4.0	Unacceptable	Unacceptable
9	X128	359	219.1	8.179	5,400	36,597.0	72,327.9	Isolated Slag	N/A	15.0	6.5	1

Table 8 Carbon Loop to Shepard Lateral Tie-in Failing Weld Flaws

Site: Site #1 Carbon Loop to Shepard Lateral Tie-in												
Anomaly Index	Node on Drawing	Pipe Grade (MPa)	Pipe OD (mm)	Pipe Wall Thickness (mm)	LMOP (kPa)	Total Axial stress (kPa)	Hoop (Membrane) stress (kPa)	Anomaly Type	Measured Height (mm)	Equivalent Length (mm)	Maximum Allowable Height (mm) T = - 20C	Maximum Allowable Height (mm) T = - 45C
10	X2	483	508	9.525	5,400	77,819.8	144,000.0	Elongated Slag	N/A	555.0	0.9	0.5
10b	X2	483	508	9.525	5,400	77,819.8	144,000.0	Elongated Slag	N/A	140.0	0.9	0.5
11	X3	483	508	9.525	5,400	81,964.3	144,000.0	Lack of Fusion	Not Failing	Not Failing	Not Failing	Not Failing
12	X5	483	508	9.525	5,400	90,401.1	144,000.0	Elongated Slag	N/A	726.0	0.9	0.5
12b	X5	483	508	9.525	5,400	90,401.1	144,000.0	Elongated Slag	N/A	26.0	0.9	0.5
12c	X5	483	508	9.525	5,400	90,401.1	144,000.0	Elongated Slag	N/A	10.0	0.9	0.5
12d	X5	483	508	9.525	5,400	90,401.1	144,000.0	Elongated Slag	N/A	28.0	0.9	0.5
12e	X5	483	508	9.525	5,400	90,401.1	144,000.0	Elongated Slag	N/A	39.0	0.9	0.5
13	X8	483	508	9.525	5,400	80,900.0	144,000.0	Incomplete Penetration (side of root)	N/A	30.0	0.9	0.5
13b	X8	483	508	9.525	5,400	80,900.0	144,000.0	Incomplete Penetration (side of root)	N/A	50.0	0.9	0.5
13c	X8	483	508	9.525	5,400	80,900.0	144,000.0	Incomplete Penetration (side of root)	N/A	25.0	0.9	0.5
14	X12	483	508	9.525	5,400	75,852.4	144,000.0	Isolated Slag	N/A	18.0	0.9	0.6
15	X39	359	406.4	9.525	5,400	243,800	115,200.0	Porosity, Internal Undercut	Not Failing	Not Failing	Not Failing	Not Failing
16	X40	359	406.4	9.525	5,400	243,800	115,200.0	Porosity	Not Failing	Not Failing	Not Failing	Not Failing
17	X45	359	406.4	9.525	5,400	56,500.8	115,200.0	Isolated Slag	N/A	5.0	7.2	4.3
17b	X45	359	406.4	9.525	5,400	56,500.8	115,200.0	Isolated Slag	N/A	4.5	7.2	4.3
18	X45	359	406.4	9.525	5,400	56,500.8	115,200.0	Porosity	4.0	4.0	Acceptable	Acceptable
19	X49	359	406.4	9.525	5,400	55,876.6	115,200.0	Intermittent Elongated Slag	N/A	45.0	2.9	0.9
20	X58	359	323.8	9.52	5,400	66,349.7	91,834.0	Porosity	3.5	3.5	Acceptable	Acceptable

Table 9 Shepard Energy Center Delivery Station Tie-in Failing Weld Flaws

Site: Site#3 Shepard Energy Center Delivery Station Tie-in												
Anomaly Index	Node on Drawing	Pipe Grade (MPa)	Pipe OD (mm)	Pipe Wall Thickness (mm)	LMOP (kPa)	Total Axial stress (kPa)	Hoop (Membrane) stress (kPa)	Anomaly Type	Measured Height (mm)	Equivalent Length (mm)	Maximum Allowable Height (mm) T = - 20C	Maximum Allowable Height (mm) T = - 45C
21	X3	483	508	9.52	5,400	105,073.8	144,075.6	Internal Undercut	N/A	300*	0.8	0.5
22	X10	483	508	9.52	5,400	103,583.1	144,075.6	Porosity	3.5	3.5	Acceptable	Unacceptable
23	X29	359	406.4	9.52	5,400	61,706.8	115,260.5	Porosity	3.0	3.0	Acceptable	Acceptable
24	X35	359	406.4	9.52	5,400	243,739	115,260.5	Porosity	3.0	4.0	Unacceptable	Unacceptable
25	X49	359	406.4	9.52	5,400	243,739	115,260.5	Incomplete penetration	N/A	25.0	0.4	0.2
26	X89	359	323.8	9.52	5,400	267,166	91,834.0	Incomplete penetration	N/A	305.0	0.2	0.1
26b	X89	359	323.8	9.52	5,400	267,166	91,834.0	Incomplete penetration	N/A	23.0	0.3	0.1

*Assumed worst-case length per CSA Z662

Table 10 Shepard Energy Transfer Point Failing Weld Flaws

Site #4: Shepard Energy Transfer Point												
Anomaly Index	Node on Drawing	Pipe Grade (MPa)	Pipe OD (mm)	Pipe Wall Thickness (mm)	LMOP (kPa)	Total Axial stress (kPa)	Hoop (Membrane) stress (kPa)	Anomaly Type	Measured Height (mm)	Equivalent Length (mm)	Maximum Allowable Height (mm) T = - 20C	Maximum Allowable Height (mm) T = - 45C
27	X2	483	508	9.52	5,400	80,611.7	144,075.6	Incomplete Penetration	N/A	17.0	0.9	0.5
28	X2	483	508	9.52	5,400	80,611.7	144,075.6	Internal Undercut	N/A	300*	0.9	0.8
29	X4	483	508	9.52	5,400	104,586.6	144,075.6	Incomplete Penetration	N/A	10.0	0.8	0.5
29b	X4	483	508	9.52	5,400	104,586.6	144,075.6	Incomplete Penetration	N/A	45.0	0.8	0.5
29c	X4	483	508	9.52	5,400	104,586.6	144,075.6	Incomplete Penetration	N/A	85.0	0.8	0.5
30	X5	483	508	9.52	5,400	97,181.1	144,075.6	Incomplete Penetration	N/A	110.0	0.8	0.5
31	X7	483	508	9.52	5,400	100,860.0	144,075.6	Porosity	4.0	4.0	Acceptable	Unacceptable
32	X10	359	406.4	9.52	5,400	70,264.6	115,260.5	Porosity	4.0	3.5	Acceptable	Acceptable
33	X24	359	323.8	9.52	5,400	47,473.1	91,834.0	Cluster Porosity	N/A	50.8	3	1

*Assumed worst-case length per CSA Z662

Table 11 Chestermere Lateral Control Station Tie-in Failing Weld Flaws

Site #2: Chestermere Lateral Control Station Tie-in												
Anomaly Index	Node on Drawing	Pipe Grade (MPa)	Pipe OD (mm)	Pipe Wall Thickness (mm)	LMOP (kPa)	Total Axial stress (kPa)	Hoop (Membrane) stress (kPa)	Anomaly Type	Measured Height (mm)	Equivalent Length (mm)	Maximum Allowable Height (mm) T = - 20C	Maximum Allowable Height (mm) T = - 45C
34	XR-03	483	508	9.52	5,400	338,924	144,075.6	Incomplete Penetration	N/A	30.0	0.2	0.1
35	X83	359	219	8.179	5,400	286,705	72,294.9	Incomplete Penetration	N/A	75.0	0.2	0.1
36	X121	483	508	9.52	5,400	338,924	144,075.6	Incomplete Penetration	N/A	270.0	0.1	0.1
36b	X121	483	508	9.52	5,400	338,924	144,075.6	Incomplete Penetration	N/A	235.0	0.1	0.1

In general, many of the flaws analyzed as part of this FFS Assessment had a fairly considerable length for crack-like flaws. Due to the proximity and length of many of the weld flaws, the adjacent flaws were classified as interacting flaws, which resulted in even more extreme flaw lengths, up to 726 mm. As such, the maximum allowable flaw height (a), per API 579 was low in many cases. For the porosity flaws where the flaw height and length measurements were available, four of the thirteen flaws were unacceptable, considering CVN data at -20°C, while six of the thirteen flaws were unacceptable, considering CVN data at -45°C, per API 579. The remaining porosity flaws were either Not Failing from the radiography reports or were acceptable per API 579. Of the Porosity flaws which were found to be unacceptable per API 579, most of these weld locations were not included in the Stantec stress model, and thus utilized the maximum allowable bending design stress per CSA Z662. Two porosity flaws, anomaly 22 in Table 9 and anomaly 31 in Table 10, were found to be acceptable, per API 579, using CVN data at a temperature of -20°C, but were found to be unacceptable when considering CVN data at -45°C.

Best Regards,

Shane Finneran, P.E.
Computational Modeling Group Leader
Materials Advisory Services

David Kemp, P.E.
Computational Modeling Engineer
Materials Advisory Services