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July 21, 2008

Ms. Anne Soiza
Pipeline Safety Director
Washington Utilities and Transportation Commission
1300 South Evergreen Park Drive SW
P.O. Box 47250
Olympia, Washington 98504-7250

Subject: Final Report on PBV Valve Project
Docket PG-080292

Dear Ms. Soiza:

In accordance with the conditions established by the Washington State Utilities and Transportation Commission in the March 13, 2008 Order granting an exemption for known and suspected valves manufactured by PBV-USA from WAC 480-93-100, and the conditions stipulated in the June 27, 2008 letter from the Pipeline and Hazardous Materials Safety Administration (PHMSA), NW Natural is providing Staff with a final report summarizing the company's investigation and remediation efforts.

NW Natural is pleased to report that the project to identify and remediate PBV valves that are susceptible to cap screw ("bolt") failures is complete in the State of Washington. The entire inventory of PBV valves susceptible to bolt failures has either been replaced or remediated. The investigation identified a total of four valves that required additional action. One valve was removed from service, and the bolts were successfully replaced on the other three valves while the valves remained in service.

Enclosed is a copy of NW Natural's forensic report detailing the results of the PBV cap screw failure analysis. The forensic investigation concluded that the root cause of the cap screw failures was the result of environmental cracking due to hydrogen embrittlement of excessively hard bolts with carburized surfaces.

NW Natural intends to resume routine valve inspections in Washington in full compliance with 192.745 and WAC 480-93-100 during the next inspection cycle commencing in January, 2009. The company would be pleased to provide a detailed briefing to Staff on the project.

NW Natural wishes to thank the Washington Utilities and Transportation Commission for your support on this important pipeline safety issue.

Sincerely,

Bruce L. Paskett, P.E.
Manager Code Compliance

Cc: David Lykken

kak545

Enclosure

SEA, Ltd. PROJECT NO. 148643	ISSUE DATE: July 7, 2008

NORTHWEST NATURAL GAS COMPANY
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S-E-A

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S-E-A

I. PROJECT SUMMARY

PROJECT ASSIGNMENT

On December 5, 2007, Mr. Ross Lisle of Northwest Natural Gas Company requested SEA, Ltd. to investigate the failure of cap screws from 12" PBV Ball Valves. This investigation was assigned to the direction of SEA Senior Analyst Robert S. Carbonara, Ph.D., as SEA Project No. 148643.

SCOPE OF PROJECT

Specifically, SEA was requested to render, if possible, a professional opinion regarding the cause of the cap screw failures.

CONCLUSIONS

- **The cap screws from the 12" PBV Ball Valves failed by intergranular fracture caused by environmental conditions, viz. hydrogen migration into the grain boundaries.**
- **The intergranular fracture occurred as a result of the cap screws carburized surfaces and high hardness.**
- **A carburized surface in the cap screws is NOT in compliance with ASTM A 574.**
- **The presence of carburized surfaces on the cap screws is a manufacturing defect.**
- **The hardness (>HRC 41) of the cap screws was above the level (HRC 40) for materials susceptible to environmental cracking, as noted in literature on environmental cracking.**

II. PROCEDURES

- SEA examined and photographed cap screws from several buried and unburied 12" PBV Ball Valves.
- The examinations and photographs were performed using optical and scanning electron microscopy (SEM).
- Several cap screws were sectioned and metallographically analyzed.
- The following documents were reviewed:

1. ASTM Standard A 574 (92a and 04) on Alloy Steel Socket-Head Cap Screws.
2. ASTM F788/F788M (92) on Surface Discontinuities of Bolts, Screws, Studs, Inch and Metric Series.
3. B. F. Brown, "Stress Corrosion Cracking Control Measures," NBS Monograph 156, June 1977.
4. L. W. Jones, "Metals Selection, Design and Handling Considerations," OGCI Publications, Chapter 7, pp. 53-60, 1988.
5. T. J. Hughel, "Delayed Facture of Class 12.8 Bolts in Automotive Rear Suspensions," SAE Technical Paper 820122, February 1982
6. J. Buda, "Why Bolts Fail," Machine Design, Vol. 66, No. 22, November 1994.
7. M. Kanao, " Delayed Fracture of High-Strength Bolts," Trans. of the Iron and Steel Institute of Japan, Vol. 22, No. 6, 1982.
8. SAE Standard J 1199, "Mechanical and Material Requirements for Metric Externally Threaded Steel Fasteners," 1981.
9. The Hendrix Group Reporter, "Hydrogen Embrittlement of High Strength Steel Fasteners," June 1997, Rev. February 1998.
10. Report from ZY-TECH Global Industries, dated January 15, 2008, authored by Engin Gulgun, Director of Quality and Technical Manager.
11. Report from Anderson and Associates, dated January 15, 2008, authored by Edward V. Bravenec, Ph.D., P.E., FASM, FASME; Vice President – Engineering.
12. Report from Anderson and Associates, dated January 17, 2008, authored by Edward V. Bravenec.

III. DISCUSSION

THE INCIDENTS

It was reported that six trunnion cap screws failed on a PBV 300 Class 12" Ball Valve. This valve (Serial No. 1296251) was put into service in June 1997 by Northwest Natural Gas. The valve was in a pipeline that carried natural gas and operated between 350 and 375 psi. As part of their normal operations in August 2007, Northwest Natural Gas closed this valve and reopened it later that same day. The following morning, a leak was detected in the area of this valve. When the valve was excavated six cap screws on the valve trunnion were found with their heads broken off and the trunnion separated from the valve body. This prompted Northwest Natural Gas to inspect other PBV 12" Ball Valves that were part of their gas pipeline system.

EVIDENCE RECEIVED BY SEA

The following cap screws were received and examined by SEA, Ltd. in Columbus, Ohio. All of the cap screws are 1/2" in diameter and 2" in length, including the head, which contains a hexagonal Allen socket:

- 3 x cap screws – Valve No. 1296251 - failed buried valve
- 3 x cap screws – Valve No. 1304471 - new uninstalled valve
- 6 x cap screws – Valve No. 0297306 - failed buried valve
- 5 x cap screws – Valve No. 1095426 - above ground in service valve

SEA also received pieces of mastic that had covered Valve 0297306.

EXAMINATION OF THE CAP SCREWS

SEM examination and analysis was performed on the fracture surfaces of three cap screws from the PBV Valve with Serial No. 1296251. These three samples were designated as A, B, and C. Also, Sample C was transversely sectioned. Hardness measurements were made on the transverse cross section of Sample C. Also, metallography was performed on the transverse cross section of Sample C.

Three cap screws (Nos. 1, 2, and 5), taken from the PBV Valve with Serial No. 0297306, were longitudinally sectioned and metallographically analyzed, and micro-hardness measurements were made on Samples 1 and 5.

Also, the cap screw, designated as No. 1 from the PBV Valve with Serial No. 1095426, was longitudinally sectioned and metallographically analyzed. Micro-hardness measurements were also made on this sample.

RESULTS OF THE CAP SCREW EXAMINATIONS

The SEM results show crack initiation at the outside diameter surface of all three cap screws from PBV Valve No. 1296251. The fracture morphology is primarily intergranular, for almost the entire fracture surface.

The hardness value, measured on the transverse cross section of Sample C from PBV Valve 1296251, was over 41 HRC. The micro-hardness (μHRD) values for Samples 1 and 5 from PBV Valve 0297306 and for Sample 1 from PBV Valve 1095426 were taken at or near the outside diameter of the cap screw. The results are shown in the following table, "Table of Hardness Values." (Note: The HRC values in this Table are converted from the μHRD values.)

Table of Hardness Values

Sample No.	Valve No.	HRC
C	1296251	41.5 *
1	0297306	41.6 *
5	0297306	42.8 *
1	1095426	34.3 *

* HFC values converted from μHRD values.

The metallographic examination of the microstructure of Sample C from Valve 1296251 showed it to be tempered martensite.

The metallographic results show the failed cap screws Nos. 1 and 5 from PBV Valve 0297306 had a carburized layer at the outside surfaces (see **Figures 1 and 2**), whereas the unfailed cap screw No. 1 from PBV Valve 1095426 showed no carburization or decarburization (see **Figure 3**). It should also be noted that the μHRD values taken in the near surface area of the failed cap screws Nos. 1 and 5 from PBV Valve 0297306 were higher than the μHRD values in the unfailed cap screw No. 1 from PBV Valve 1095426.

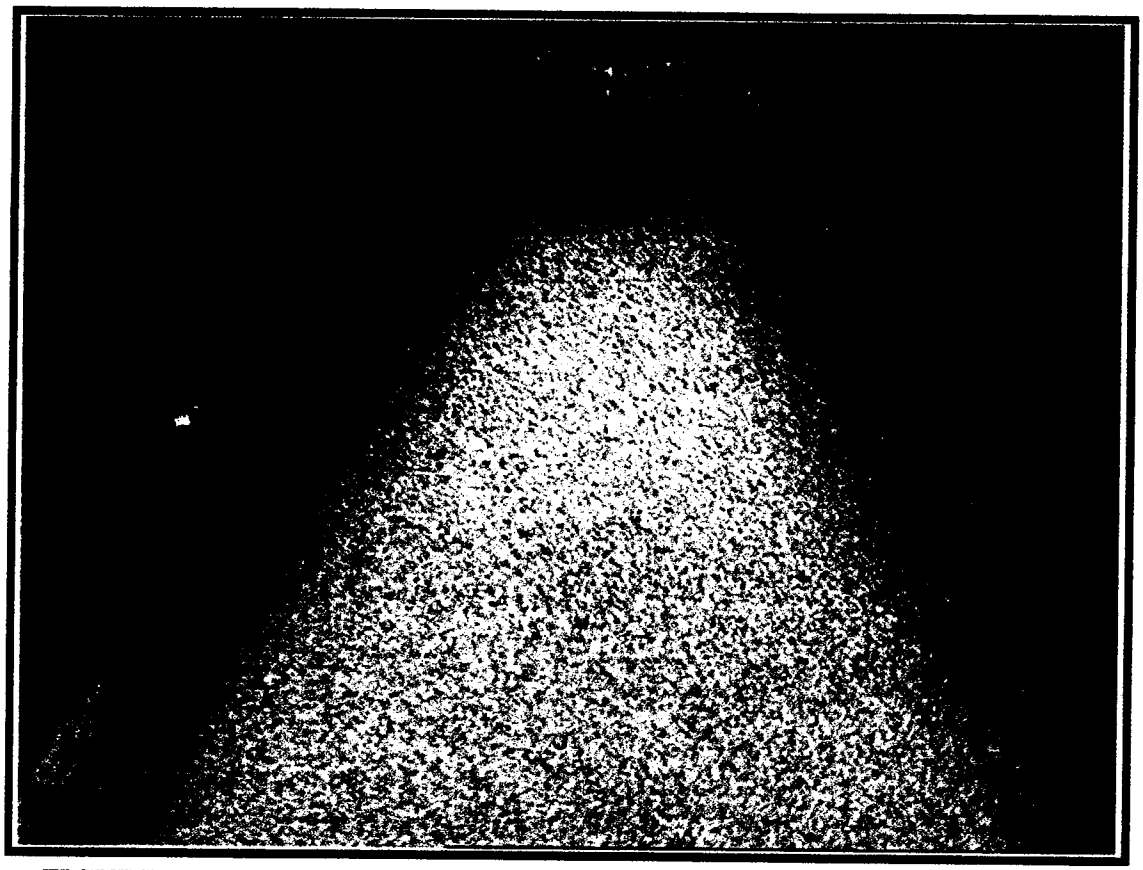

FIGURE 1: Optical image of cross section of Sample 1 from PBV Valve 0297306. Arrow indicates the carburized layer at the outer surface of the cap screw thread.

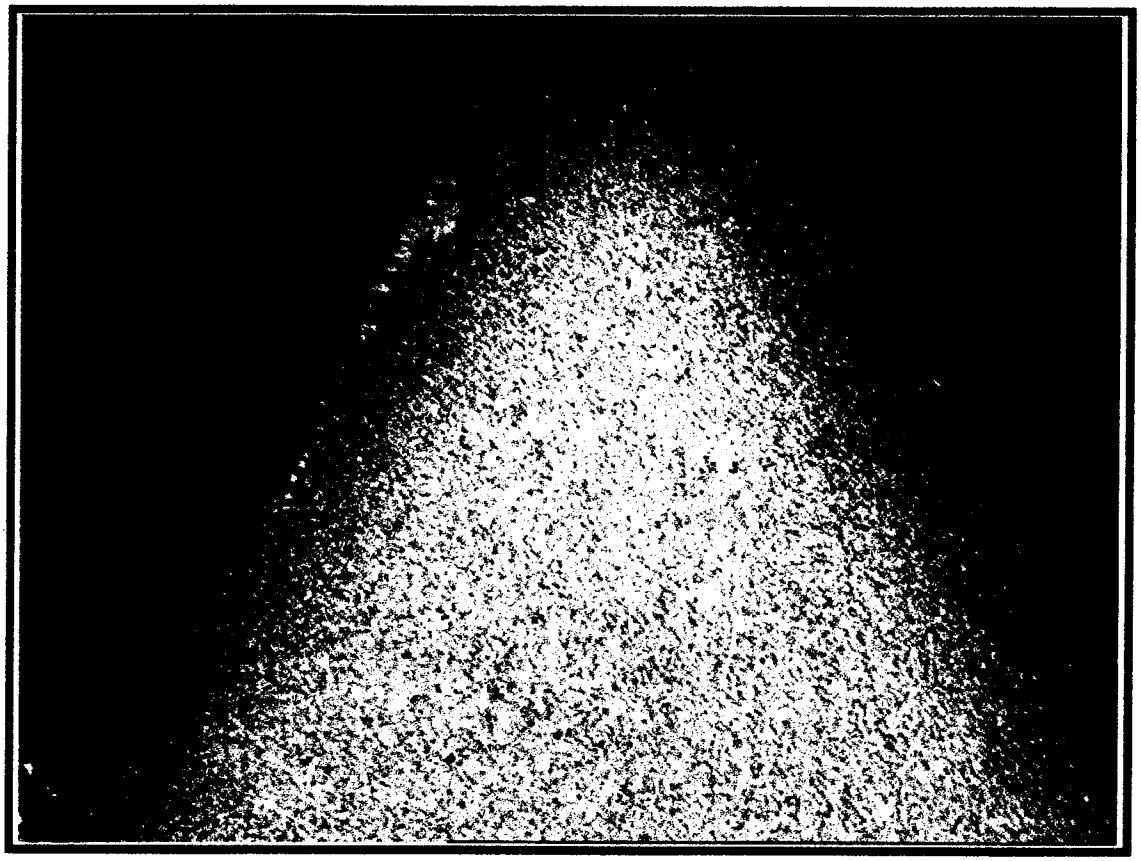

FIGURE 2: Optical image of cross section of Sample 5 from PBV Valve 0297306. Arrow indicates the carburized layer at the outer surface of the cap screw thread.

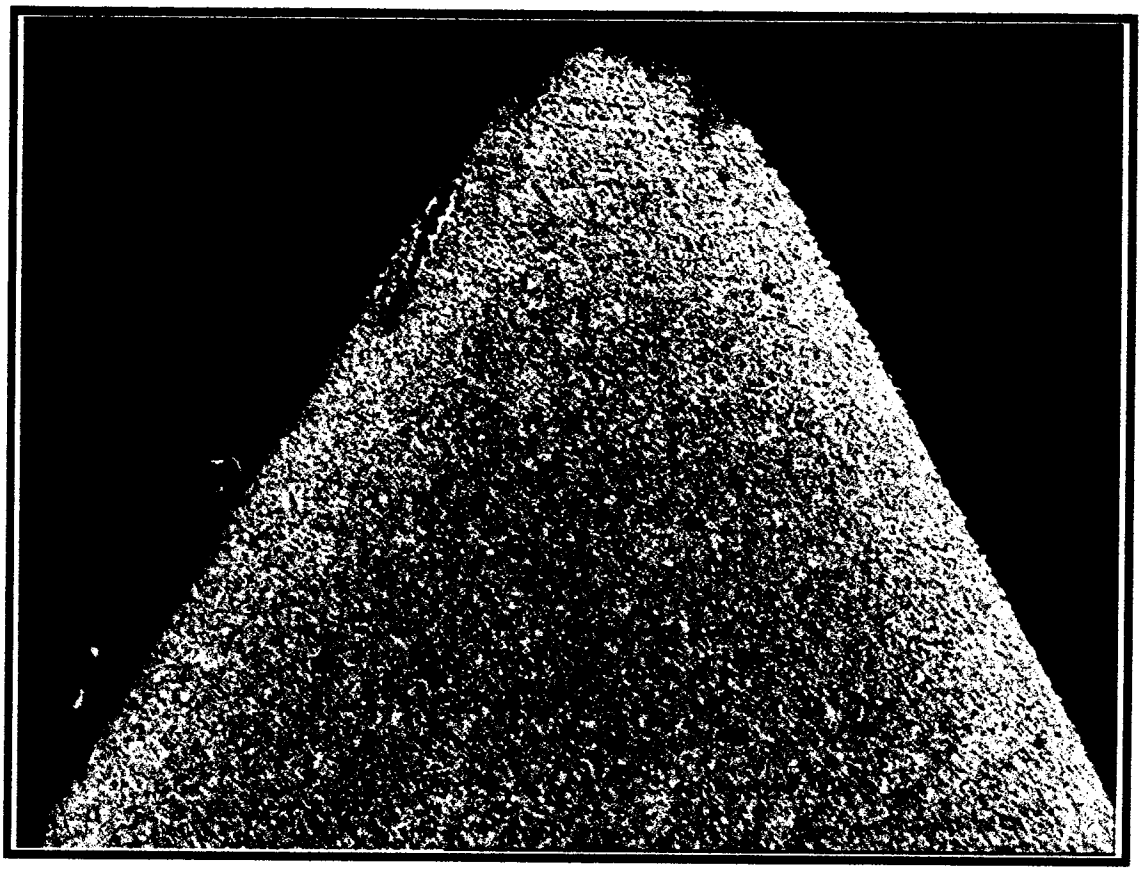

FIGURE 3: Optical image of cross section of Sample 1 from PBV valve 1095426. Note the absence of the carburized layer of the outer surface of the cap screw thread.

ENVIRONMENTAL CRACKING

Environmental cracking in metals can be the result of hydrogen penetration of grain boundaries. There are several environments that can lead to hydrogen penetration of metallic grain boundaries. The common factor in all of these environments is the production of hydrogen in and around the surface of the metal. In the case of ferrous-based metals, it has been found that the ultimate tensile strength (UTS) or hardness is related to the metal's susceptibility to environmental cracking.

Testing and field experience noted in the literature shows that ferrous fasteners will fail by environmental or hydrogen cracking if the hardness is HRC 40 or above. All the cap screws from the buried valves have a hardness above HRC 40.

In addition to the high hardness, the cap screws from the buried valves showed a carburized layer, as noted above. The carburized outer layer has an even higher hardness (7 to 12 HRC numbers) than the interior of the cap screws. This higher hardness causes a cap screw to be even more susceptible to hydrogen cracking, since the susceptibility increases as the hardness increases.

As the hydrogen penetrates the grain boundaries of the cap screws, it causes a weakness in those boundaries, allowing fracture to occur along those pathways. Hydrogen penetration is enhanced by localized stresses and geometric discontinuities. The stresses and discontinuities raise the effective stress that makes cracks form and propagate. Such places as thread roots and the transition area of the shank to the cap screw head are areas where localized stress is high. In addition, the stresses associated with the clamping forces that result from torqueing the cap screw also increases localized stresses at cap screw heads and thread roots. Almost all the cap screws failed in the area of the cap screw head where the localized stresses are high.

Finally, it should be noted that there is a great deal of similarity between the some of the forms of environmental cracking. Many forms of environmental cracking involve hydrogen penetration and migration along grain boundaries. The major differences in these various forms are the source and mechanism of generating the hydrogen. However, once the hydrogen is generated and penetrates the grain boundaries, the mechanism that weakens those grain boundaries and causes the material to fracture is basically the same.

ANALYSIS

The carburized layer and the high hardness of the PBV Valve failed trunnion cap screws made them susceptible to environmental cracking; e.g., stress corrosion cracking (SCC) and hydrogen cracking. The intergranular fracture mode of the failed trunnion cap screws is consistent with environmental stress cracking.

Although ASTM A574 allows for the hardness of 0.500-inch cap screws to be between 39 and 45 HRC, the literature (noted in References 3, 5, 6, 7, and 9 in the Procedures section of this report) identify the need to limit the strength/hardness of ferrous materials to avoid SCC and hydrogen cracking. All of these references indicate the hardness level must be less than 40 HRC to avoid this form of environmental cracking.

In addition to the hardness levels of the failed cap screws, being above HRC 41, the carburized surface layer made the surface even harder and even more susceptible to environmental stress cracking.

This carburized layer is considered a manufacturing defect, since these cap screws must <u>not</u> be made with a carburized or a total decarburized surface, per ASTM A 574.

IV. SIGNATURES

SEA, Ltd. hereby certifies the expressed opinions and conclusions have been formulated within a reasonable degree of professional certainty. They are based upon all of the information known by SEA, Ltd. at the time this report was issued, as well as knowledge, skill, experience, training, and/or education.

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Director

RSC:sc