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AEOD ENGINEERING EVALUATION REPORT*

UNIT: Brunswick 2
DOCKET NO.: 50-324
LICENSEE: Carolina Power & Light
NSSS/AE: GE/United Engineers and Contractors

EE REPORT NO. AEOD/E506
DATE: May 13, 1985
EVALUATION/CONTACT: C. Hsu

SUBJECT: VALVE STEM SUSCEPTIBILITY TO IGSCC DUE TO IMPROPER HEAT TREATMENT

EVENT DATE: August 4, 1982 (LER 82-088/03L-3)

SUMMARY

Licensee Event Report 82-088/03L-3, dated May 24, 1984, for Brunswick 2 describes an event in which a valve stem failure occurred while attempting to open the valve manually during a refueling outage. The valve was installed in the suppression pool suction line to the residual heat removal (RHR) system. The valve stem, made of type 410 stainless steel, had completely fractured approximately six inches from the valve stem T-head. Metallurgical examination showed that the stem had failed from intergranular stress corrosion cracking (IGSCC). IGSCC had reduced the valve stem cross-sectional area to 30% of its original area and the fracture was then completed by a sudden shear. The broken stem was found to have hardness higher than the specified value. A subsequent licensee investigation revealed that the excessive hardness was caused by improper heat treatment during manufacture of the stem material. Three additional events found in this review had similar valve stem failures. These defective stems were also made of type 410 stainless steel.

The additional events occurred at Farley 1, Browns Ferry 3 and Oconee 1. The valve stem failures at Farley 1 and Oconee 1 were found by examination to be caused by IGSCC, while the failure at Browns Ferry 3 can probably be related to the same cause although the examination in that case is inconclusive. The affected valves were installed in safety-related systems and are different in size and manufacturer.

Valve stems made of 400 series stainless steel and heat treated to high hardness are highly susceptible to intergranular stress corrosion under certain corrosive environmental conditions. The excessive hardness can result from improper heat treatment which may not be detected in either the licensee's or the supplier's QA programs. Furthermore, since the valve stem IGSCC cannot be observed without disassembly of the valve, the plant routine valve operability test program can not provide an early detection of stem stress cracking. As stress corrosion cracking can occur below the design stress limits, it is likely that IGSCC on a valve stem

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would go undetected until failure occurs with a sudden shear of the stem upon actuation of the valve during system operation. Such failures can prevent the system from performing its safety function. In view of this safety concern, this report suggests the following actions:

1. IE should consider issuing an IE Information Notice to inform licensees of the potential generic problem concerning improper heat treatment of valve stem material which could lead to intergranular stress corrosion.

2. RES should consider the adequacy of the existing code requirements with regard to assurance of proper hardness of martensitic stainless steel following the heat treatment process. If appropriate, RES should attempt to have such requirements included in the applicable code.

INTRODUCTION

LER 82-088/03L-3, dated May 24, 1984, reported that during a refueling outage at Brunswick 2, while manually opening the valve from the suppression pool suction supply line to RHR loop B on August 4, 1982 the valve stem of suction valve, 2-E11-F0048, turned freely beyond the full open position. A subsequent inspection of the valve's internal parts revealed that the valve stem, made of type 410 stainless steel, had completely fractured approximately six inches from the valve stem T-head. A new valve stem was installed; the valve was cycled satisfactorily, determined to be operable, and returned to service.

Metallurgical examination of the broken valve stem showed that the stem had failed due to intergranular stress corrosion cracking (IGSCC). It was found that IGSCC had reduced the valve stem cross sectional area to 30% of its original area and the fracture was then completed by a sudden shear. The stem was also found to have surface hardness in excess of the manufacturer's specifications, which was determined to be a contributor to the stem IGSCC damage. Investigation revealed that the excessive stem surface hardness was caused by improper heat treatment during manufacture of the stem material. In addition, it was noted that the stem displayed excessive pitting in the gland packing section and that the initiation of cracks was from pits or pitting. The valve was a 20" Anchor Darling gate valve.

As a result of this event, a review of all Anchor Darling valves in use at Brunswick Units 1 and 2 revealed that these valves were supplied from 36 heat treatment batches. An in-place hardness sample test program was conducted for the Anchor Darling valve stems by the licensee. In this test, over 60 valve stems were tested, representing samples from 34 of the 36 heat treatment batches. Twenty valve stems from five batches were determined to have hardness higher than specified. (Valve stems from the same batch as the failed stem were among the 20 valve stems which were found to have excessive surface hardness.) The licensee's review of the test results confirmed that the high hardness was a result of improper heat treatment. Although the inspection found no crack indications on the valve stems with excessive hardness, the licensee replaced all these valve stems, either in the subsequent refueling outages or whenever the valves became a[illegible]le for maintenance, to prevent the possibility of future stem fail[illegible] [illegible] IGSCC.

DISCUSSION

In this review, three additional events involving cracking of valve stems made of 400 series stainless steel were identified in a search of the LER and other operational experience data bases. The valve stem cracking in these three events was similar to the one at Brunswick 2 which is attributed to IGSCC brought on by excessive surface hardness resulting from improper heat treatment. The affected valves were also used in safety related systems such as the residual heat removal (RHR) and main steam isolation systems. These three events occurred at Farley 1, Browns Ferry 3 and Oconee 1. The failures of valve stems at Farley 1 and Oconee 1 were determined to be caused by IGSCC. Although the damage at Browns Ferry 3 was a direct result of stem overloading, there was evidence that the stem may have experienced IGSCC prior to overload fracture.

The event at Farley 1 was reported in LER 84-004. On February 29, 1984, during a refueling outage, linear indications were discovered on three of six main steam isolation valve (MSIV) shafts. The indications, which ranged from one to thirteen inches in length, were found during cleanup of the valve shafts prior to reassembly of the valves. All indications were in the operator side packing gland area. Two of the shafts had only longitudinal indications, while the third shaft had both longitudinal and circumferential indications. The MSIVs were Atwood-Morrill model 21261-H swing type check valves.

The three cracked shafts were all made of type 410 stainless steel with heat number HT 62687. The other three shafts with no indications were also type 410 stainless steel with heat number HT 536099. As a preventive measure, the licensee replaced all six shafts with A564 GR 630 stainless steel. The Unit 2 MSIV type 410 stainless steel shafts will also be replaced with A564 GR 630 stainless steel shafts during the next refueling outage.

Brookhaven National Laboratory performed a metallurgical evaluation of the cracks on the valve shafts. The evaluation (Ref. 1) concluded that the cracking was due to intergranular stress corrosion cracking resulting from a high hardness in the material making it susceptible to this type of attack. The Rockwell C hardness tests in this evaluation had an average of Rc 41.25. The licensee's documentation of the defective shafts' heat treatment revealed that they had been quenched from 1775°F±25°F in either air or oil, and then tempered at 950°F to a hardness of Brinell 345-370 (Rc 37-39.8). This hardness value is significantly lower than the actual measured hardness readings taken after failure. Further examination of the fracture surface indicated that the fractures had a thumbnail-like shape and were granular in appearance. The fracture surfaces were covered by a heavy oxide film which appeared black near the crack initiation areas and was lighter in appearance the greater the distance traversed from the initial cracked area. This sort of appearance is typical of cracks which have been pre-existing for a considerable time prior to propagation. The licensee indicated that the shafts had been dye penetrant inspected prior to installation, which precluded the possibility of pre-existing quenching cracks in the material. There was no gross evidence of fatigue contribution.

Browns Ferry 3 LER 84-04/01 described an event in which an injection valve (FCV 74-67) in the LPCI system was found to have a broken stem upon disassembly of the valve during the refueling outage on February 28, 1984. The valve stem was broken in two places, one place was below the stem packing area and the other at the gate connection. The upper stem break surface was battered from cycling the valve after the stem broke. The valve stem was made of type 410 stainless steel and was subsequently replaced with 17-4 PH stainless steel which is a stronger and more durable material. The valve was a 24-inch gate valve, manufactured by Walworth. Visual examination of the stem break surface showed an oxide deposit over approximately 50 percent of the total stem cross-sectional area, which indicated that the valve stem had been cracked for some period of time. These oxides were not corrosion products of the stem material, but were corrosion products deposited on the stem from the system. Metallurgical examination of the fracture indicated the failure mode was overload. However, there was evidence of unusual longitudinal cracking in both the tensile specimens and the valve stem. In addition, some cleavage was also noted in the tensile specimens, there was no indication of fatigue or chemical corrosion on the fracture surfaces of the stem. Tests revealed that the broken stem had excessive hardness which was determined to be a result of improper heat treatment. Improper heat treatment probably occurred during tempering or there may have been a complete lack of tempering. Although the fracture was the result of overload, the evidence of unusual longitudinal cracking on the valve stem and the excessive hardness suggest that the broken stem had experienced IGSCC before the overload fracture occurred.

The cracked valve stems at Oconee 1, as described in Nuclear Power Experience (Ref. 2), may also appear to be related to IGSCC failure as a result of excessive hardness due to improper heat treatment of the stem material. In December 1971, several globe valves were found to have severe stem packing leakage. The leakage could not be controlled by tightening the packing or by backseating. Disassembly revealed longitudinal cracks the entire length of the stems and more than half of the stem diameter in depth. Valve sizes involved were 1 1/2", 1" and 1/2". The stem material was also 400 series martensitic stainless steel (SS), heat treated to 36 to 40 Rockwell C hardness. The cause of failure in this case was traced to shop failure to stress relieve several batches of stems following heat treatment. While no mention was made of IGSCC, it seems likely that this was involved in the cracking observed. The licensee replaced all 400 series SS stems with either 300 series SS or 17-4 PH stems. The replacement involved a total of 2600 valves; 1100 of these were for Oconee 1, 1000 for Oconee 2, and 500 for Oconee 3.

In all these four events, the excessive hardness was determined by metallurgical examination of the failed stems. Review of both the licensee's and the supplier's documentations identified only the associated heat batch and the anticipated hardness of the valve stems. The actual hardness measured after failure by metallurgical test was higher than the value specified in the documentation. This implies that the available QA programs may be insufficient to identify the improper heat treatment causing excessive hardness found in the failed valve stems. This also indicates that the existing code requirements regarding actual testing to verify the hardness for martensitic stainless steels after heat treatment may not be adequate.

These events suggest a common-cause failure mode for the valve stems made of type 410 martensitic stainless steel. The stem failure seems to be caused or accelerated by IGSCC. High stem surface hardness is considered a contributing factor to the IGSCC. The high surface hardness was a result of improper heat treatment during the manufacture of the stem material. In manufacturing, heating such materials to a high temperature and rapidly cooling them in a quenching process, significantly increases the strength and hardness in the heated area. A certain specific tempering operation is needed to relieve the localized stress and control the hardness. For 400 series stainless steel, tempering in the range of 700 to 1050°F is not recommended (Ref. 3), because it results in low and erratic impact properties and poor resistance to corrosion and stress corrosion. The cracked valve stems at Farley 1 were tempered at 950°F, resulting in having a surface hardness significantly higher than specified. The excessive hardness on the affected valve stems at the other plants also appear to be related to an improper tempering operation during the heat treatment process.

Excessive hardness alone will not result in failure of valve stems by stress corrosion cracking. Generally, stress corrosion cracking requires the simultaneous presence of stress (either applied or residual), a susceptible material, and a corrosive environment. The high stress could have been locked-in quenching stress that had remained after the tempering operation, coupled with the applied load to the stems. The susceptible material condition was improperly heat treated martensite which has been shown to be susceptible to stress corrosion when tempered at too low a temperature. The source of a corrosive environment could be local concentrations of chlorides, sulfides or acids in the valve internals. The concentration of these materials in the coolant is generally very low. However, there is an opportunity for these materials to concentrate in parts of the system which may be alternately wet and dry. The initiation of stem cracking at the gland packing sections where the stem is alternately wetted and dried provides such a location where these corrodents could be concentrated enough to initiate IGSCC attack on the stems.

Metallurgical examination of the failed valve stems did not reveal evidence of fatigue or chemical corrosion attack on the fracture surface. The oxide deposit on the crack surface was corrosion products from the systems, not the stem material. The presence of these oxide deposits indicated that the valve stems had been cracked and the cracks remained undetected for some time. Crack indication on the valve stems can only be observed by disassembly of the valves. The routine valve operability tests provided in the plant inservice inspection programs are not capable of detecting valve stem degradation. As stress corrosion cracking can occur below the design stress limits, without detection of crack indication, the crack can propagate, further reducing the strength thus leading to sudden shear of the stem during actuation of the valve. There is the potential that valve stem failure could result in sudden disabling of the valve which in turn could prevent the associated system from performing its safety function.

Appendix B to 10 CFR Part 50, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," requires that measures be established to assure material control and control of heat treating and to assure performance of reliable testing programs. However, NRC regulatory guidance does not provide a specific acceptable method for implementing the above requirements with regard to control of the application and processing of martensitic stainless steel to avoid high hardness that could contribute to the development of IGSCC in certain environments.

FINDINGS AND CONCLUSIONS

Based on the preceding discussion and related follow-up activities conducted for this evaluation, the following findings and conclusions are provided:

1. Cracking of valve stems made of type 410 stainless steel has occurred at four plants; Brunswick 2, Farley 1, Browns Ferry 3 and Oconee 1. The cracked stems at Brunswick 2, Farley 1, Oconee 1 and Browns Ferry 3 appear to have been all caused by IGSCC brought on by improper heat treatment of the stem material which resulted in excessive hardness.

2. The valves in these four plants are different in size and manufacturer: 20" Anchor Darling gate valve at Brunswick 2; 32" 'twood Morrill check valves at Farley 1; 24" Walworth gate valve at Br Ferry 3; and several different sizes (1 1/2", 1" and 1/2") of Velan gl .alves at Oconee 1.

3. It was clearly evident in the metallurgical examination that the fracture of failed stems at Brunswick 2 and Farley 1 were predominantly intergranular in appearance. There was no evidence of fatigue or chemical corrosion indications on the fracture surface.

4. The chemical analysis of these cracked valve stems showed that the chemical composition of the material was consistent with the specifications; however, hardness measurements showed that the actual hardness was significantly higher than those anticipated by the heat treatments performed.

5. It is evident that discrepancies in hardness between the actual measurement and the documented value existed in all these four plants. From this it can be concluded that excessive hardness resulting from improper heat treatment cannot be identified by review of the available QA documentation.

6. The existing code requirements regarding assurance of proper hardness may not be adequate to provide assurance that actual hardness is verified. Consideration should be given to including such requirements in the existing codes.

7. The excessive hardness was caused by improper heat treatment during manufacture of the stem material. It was determined that the stem IGSCC damages were attributed to excessive hardness as a result of improper heat treatment of type 410 SS material.

8. Stress corrosion cracking requires the simultaneous presence of stress (either applied or residual), a susceptible material and a corrosive environment. The high stress could have been locked-in quenching stress, coupled with the applied load to the stems. The susceptible material was excessively hardened martensite which has been shown to be susceptible to stress corrosion when tempered at too low a temperature. The source of corrosive environments could be high local concentrations of chlorides, sulfides or acid in the valve internals.

9. The initiation of stem cracking at the gland packing sections indicates that the valve gland packing region could have been a place where high concentrations of the described corrodents (chlorides, sulfides or acid) accumulated.

10. The cracked valve stems described in this evaluation were discovered by inspections after disassembly of the valves during refueling outages of the plants. None of the cracked stems were detected by the routine valve operability test programs for the identified plants.

11. The presence of oxide deposit on the crack surfaces indicated that the valve stems had been cracked and remained undetected for some period of time. This being the case, it is likely that valve stem IGSCC would go undetected and lead to a sudden shear of the stem during valve actuation, resulting in disabling or impairing the operation of the associated safety system.

12. Appendix B to 10 CFR Part 50, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," requires that measures be established to assure material control and control of heat treating and to assure performance of reliable testing programs. However, NRC regulatory guidance does not provide a specific acceptable method for implementing the above requirements with regard to control of the heat treatment and tempering of stainless steel, other than unstabilized austenitic stainless steel. Lack of such controls could contribute to the development of stress corrosion cracking due to excessive hardening of martensitic steels.

SUGGESTIONS

1. IE should consider issuing an IE Information Notice which addresses the identified events and inform licensees of the potential problem concerning excessive hardness in 400 series SS valve stems which makes them susceptible to IGSCC attack.

2. RES should consider the adequacy of the existing code requirements with regard to assurance of proper hardness of martensitic stainless steel following the heat treatment process. If appropriate, RES should attempt to have such requirements included in the applicable code.

REFERENCES

1. C. J. Czajkowaski, "Evaluation of Cracks on the Joseph M. Farley Unit 1 Main Steam Isolation Valve (MSIV) Shaft," Brookhaven National Laboratory, Upton, New York, August 1984.

2. S. M. Stroller Corp., "Nuclear Power Experience," Vol. PWR 2, XV. Miscellaneous Systems, Sec. 2, "Valve Stem Cracks - Failure to Stress Relieve, and Valve Seat Cracks."

3. American Society for Metals, "Metal Handbook," 8th Edition, Vol. 2, "Heat Treating, Cleaning and Finishing," pp. 245, November 1964.