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WHAT CAUSED THE FAILURES OF THE SOLENOID VALVE SCREWS

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ABSTRACT

At Seabrook Station on May 5,1998 following a lengthy purge of the pressurizer steam space through Containment isolation sample valve 1-RC-FV-2830, the UL status light associated with this solenoid valve did not come on when the valve was closed from the plant's main control board. The UL status light is used to confirm valve closure position to satisfy the plant's Technical Specification requirements. The incorrect valve position indication on the main control board was initially believed to have resulted from excessive heat from a failed voltage control module that did not reduce the voltage to the valve's solenoid coil. This conclusion was based on a similar event that occurred in November of 1996. Follow-up in-plant testing of the valve determined that the voltage control module had not failed and was functioning satisfactorily. Subsequent investigations determined the root cause of the event to be excessive heat-up of the valve caused by high process fluid temperature and an excessively long purge of the pressurizer. The excessive heat-up of the valve from the high temperature process fluid weakened the magnetic field strength of the valve stem magnet to the extent that the UL status light reed switch would not actuate when the valve was closed. Since the voltage control module was tested and found to be functioning properly it was not replaced. Only the UL status light reed switch was replaced with a more sensitive reed that would respond better to a reduced magnetic field strength that results from a hot magnet. During reed switch replacement, three terminal block screws in the valve housing were found fractured and three other terminal block screws fractured during de-termination of the electrical conductors. This paper describes the initial plant event and ensuing laboratory tests and examinations that were performed to determine the root cause of the failure of the terminal block screws from the Containment isolation sample solenoid valve.

INTRODUCTION

Seabrook Station is a one unit, 1150 MWe nuclear power plant located adjacent to the Atlantic Ocean in the town of Seabrook, New Hampshire. North Atlantic Energy Service Corporation (NAESCo) operates Seabrook Station for the ten joint owners of the plant. The plant design includes a four loop, Westinghouse pressurized water reactor (PWR) system and a tandem compound, six-flow General Electric turbine generator. The plant's reactor coolant system (RCS), also called the primary system, consists of four similar heat transfer loops connected in parallel to the reactor pressure vessel. Each loop contains a reactor coolant pump, a Westinghouse Model F steam generator and associated piping and valves. In addition, the reactor coolant system includes a pressurizer, pressurizer relief tank, pressurizer relief and safety valves, interconnecting piping, pipe supports and instrumentation for operational control. All of the above components are located inside the plant's Containment building. Collectively, this equipment is often referred to as the nuclear steam supply system (NSSS). The RCS pressure is controlled by the use of the pressurizer, where water and steam are maintained in equilibrium by electrical immersion heaters and water sprays. Steam can be formed by the heaters or condensed by the pressurizer spray to minimize pressure variations due to contraction and expansion of the reactor coolant. The immersion heaters continuously vaporize a portion of the water mass in the pressurizer to maintain a steam bubble. The steam bubble pressure determines the pressure felt throughout the RCS by virtue of the pressurizer's connection to loop 3 in the RCS. Periodically, incondensable gases that buildup in the pressurizer steam space are purged through RCS sampling lines. This paper discusses the failure of the terminal block screws from a Containment isolation solenoid valve located in a sampling line used to purge incondensable gases from the pressurizer steam space.

CASE HISTORY

The case history presented in this paper involves an event that occurred at Seabrook Station on May 5, 1998. Following a lengthy purge of the pressurizer steam space through Containment isolation sample valve 1-RC-FV-2830, the UL status light associated with this solenoid valve did not come on when the valve was closed from the plant's main control board. The UL status light is used to confirm valve closure position to satisfy the plant's Technical Specification requirements. The incorrect valve position indication on the main control board was initially believed to have resulted from excessive heat from a failed voltage control module that did not reduce the voltage to the valve's solenoid coil. This conclusion was based on a similar event that occurred in November of 1996. Follow-up in-plant testing of the valve determined that the voltage control module had not failed and was functioning satisfactorily. Subsequent investigations determined the root cause of the event to be excessive heat-up of the valve caused by high process fluid temperature and an excessively long purge of the pressurizer. The excessive heat-up of the valve from the high temperature process fluid weakened the magnetic field strength of the valve stem magnet to the extent that the UL status light reed switch would not actuate when the valve closed. Since the voltage control module was tested and found to be functioning properly it was not replaced. Only the UL status light reed switch was replaced with a more sensitive reed that would respond better to a reduced magnetic field strength that results from a hot magnet. The solenoid valve configuration includes two (2) thermoplastic phenolic terminal blocks each having ten (10) brass screws that provide wiring terminations for the valve's four (4) reed switches and the solenoid coil. The brass screws are slotted binding head machine screws that are typically tightened to a "snug tight" condition. The nominal size of the brass screws is 6-20 x ¼. During reed switch replacement, three terminal block screws in the valve housing were found fractured in two pieces and three other terminal block screws fractured during de-termination of the electrical conductors. This solenoid valve, 1-RC-FV-2830 is located inside Containment in an area adjacent to the pressurizer. During normal plant operations, the solenoid housing temperature was approximately 200°F, the solenoid coil temperature was approximately 260°F and the process fluid temperature in the sample lines from the pressurizer was approximately 500°F. The initial hypothesis was that the brass screws failed due to over tightening.

LABORATORY EVALUATION

In order to establish the root cause of the brass screw failures, a laboratory evaluation plan was prepared by NAESCo and issued to Massachusetts Materials Research Incorporated, West Boylston, Massachusetts for implementation. The laboratory evaluation plan required Massachusetts Materials Research Incorporated (MMR) to perform the following tests and examinations on the fractured brass screws and a representative sample of whole screws that were recovered from 1-RC-FV-2830; (1) general photography to document the as-received condition of the terminal block, fractured brass screws and whole screws, (2) chemical analysis to establish the major elements of the screw material and the screw plating material, (3) microhardness to establish the mechanical properties of the screw material, (4) visual and binocular microscope examinations of the fractured screws to detect the presence of any anomalies that might have contributed to the screw failures, (5) scanning electron microscope analysis of the fractured surfaces to establish the fracture morphology and to determine the presence of any contaminants. MMR was also commissioned to prepare a final laboratory report (Ref. 1) documenting the results of these laboratory examinations and conclusions as to the nature and cause(s) of the fractured brass screws. The results from the MMR root cause analysis follows.

The as-received solenoid valve position switch terminal block showing failed screws and fractured piece of the phenolic terminal block is shown in Figure 1. The visual and binocular microscope examinations performed on the failed screws revealed that they all failed in a similar location, in the shank/bearing surface radius. The fracture surfaces revealed various hues of green, and yellow. These are indicative of oxides, suggesting environmental interaction. The fracture surfaces revealed multiple crack initiation sites. No significant deformation was observed at the fracture initiation areas. One representative view is shown in Figure 2.

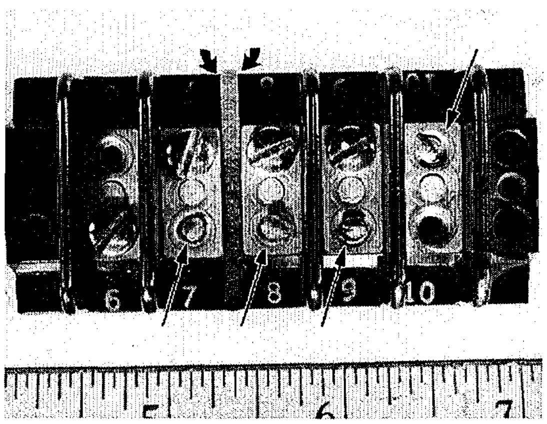

Figure 1: Solenoid valve position switch terminal block showing failed screws (thin arrows) and fractured piece of phenolic terminal block (heavy, curved arrows). Mag. 0.6X

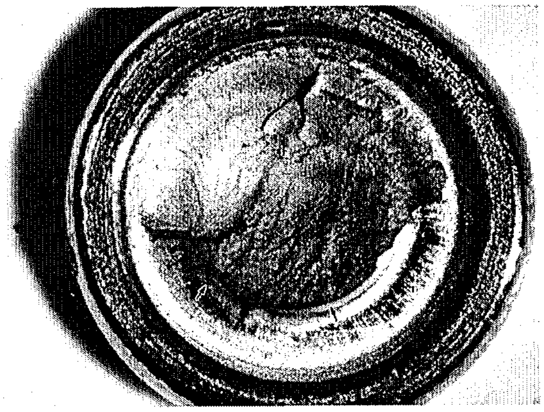

Figure 2: Fracture surface on terminal block screw head. Mag. 25X

Scanning electron microscope (SEM) analysis of the fracture surfaces revealed planar, brittle, and feathery features, Figure 3. The initiation area, mid-fracture area and the final fracture all revealed similar features. No evidence of fatigue was detected on the surfaces.

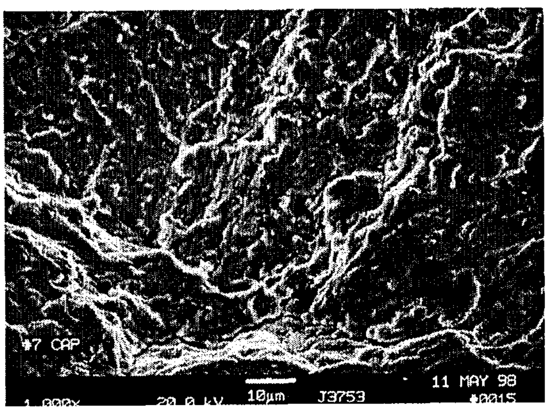

Figure 3: Fracture surface of origin of cracking on failed screw head. Mag. 630X

Energy dispersive x-ray spectroscopy (EDS, a qualitative microchemical analysis technique using equipment attached to the SEM) was performed on various areas of the fracture surfaces. In general, the fracture surfaces revealed copper and zinc which are indicative of the base metal, with trace amounts of silicon and carbon as contaminant elements from the environment. Minor amounts of oxygen were present all over the fracture surfaces indicating, in conjunction with the observed discoloration, evidence of corrosion. Further EDS analysis of the surface of the screws revealed nickel-cadmium plating.

Different failed and unfailed brass screw samples were cross-sectioned and prepared for optical microscope examination of the metallurgical structure (Figure 4). All the failed screws revealed secondary cracking parallel to the fracture surface (Figure 5). The primary and secondary cracks were predominantly transgranular and branched, showing the typical appearance of stress corrosion cracking (SCC) of copper-zinc alloys at mildly acidic or mildly alkaline pH (Ref. 2). The fracture progressed along the cold worked interface present in the head as a result of the cold heading process used in the screw manufacture (Figure 6).

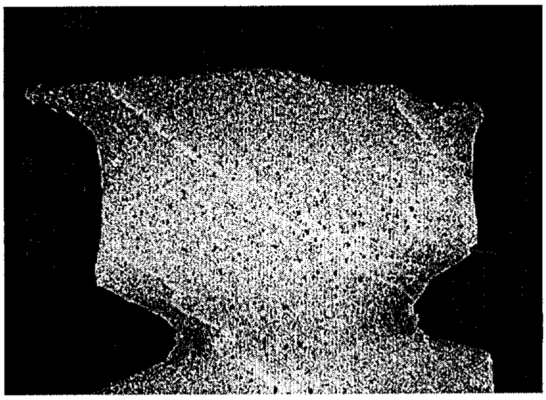

Figure 4: Longitudinal cross section through fractured terminal block screw. Fracture surface is along top of photograph. Mag. 25X

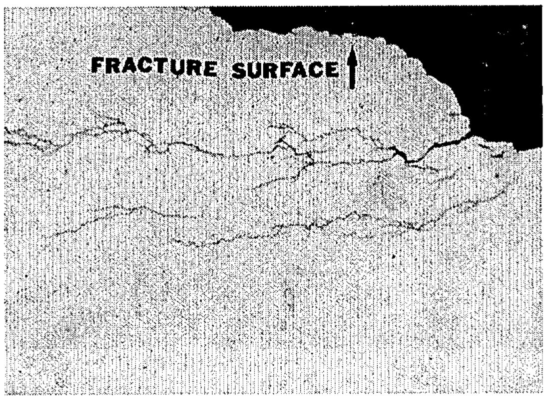

Figure 5: Secondary branched cracks parallel to primary fracture plane on fractured screw. Mag. 300X

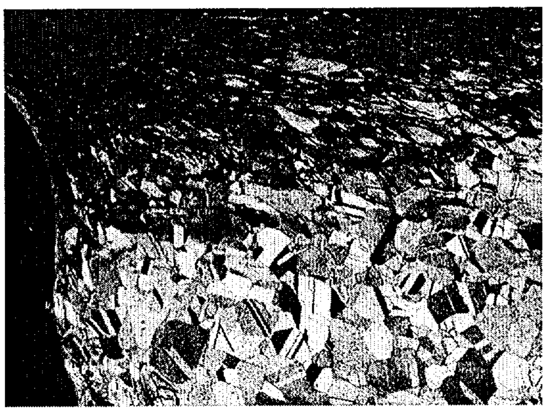

Figure 6: Part-through cracked terminal block screw showing crack propagation path at interface between cold worked and non-cold worked material. Mag. 60X

Microhardness measurements performed on a failed and good screw in the threaded area revealed similar values, approximately 90 Rockwell B. Chemical analyses performed on a failed and a good screw revealed both to be a copper-zinc alloy with 60.77 weight percent copper and 39.1 weight percent zinc, known as "muntz metal" (UNS C28000).

The analysis identified the failure mode of the screws to be SCC. All the fracture surfaces revealed feathery appearances which are typically associated with SCC of copper alloys and other face centered cubic metals. The SEM and optical microscope investigation did not reveal any evidence of tensile overload, fatigue or any other type of fracture features.

For SCC to occur, three factors are required simultaneously: a susceptible material, sustained stress of a sufficient magnitude and an aggressive environment. The screw material is very susceptible to SCC, due to more than 40 weight percent zinc content. The radius between the head and the shank is under sustained constant stress due to the tightening of the screws and due to the residual stress from the head forming operation. However, the EDS analysis was not able to detect an aggressive environment, since no aggressive elements were identified on the fracture surface. For SCC of copper-zinc alloys, the most common aggressive species is ammonia or ammonia compounds in the presence of oxygen and moisture. When ammonia is present, the moisture in the normal atmosphere can be enough to initiate SCC. Since ammonia is volatile, evidence of this species is usually not detected on the SCC fracture surface. In general, the susceptibility of copper-base alloys to SCC increases with temperature, consistent with the 500°F exposure to the pressurizer process fluid.

The next step in determining the root cause of the failure was to identify the source of the aggressive environment, since all metallurgical evidence shows an SCC fracture mode. Now, the solenoid position switch and terminal block are enclosed in a housing on the valve, and therefore the terminal block screws are essentially isolated from the environment; the most likely source of the aggressive species is within the solenoid housing. Fourier transform infrared (FTIR) spectroscopy performed on the terminal block identified the material to be phenolic novolac. The manufacture of phenolic resins involves a hardener which utilizes excess ammonia for its reaction (Ref. 3, 4).

To determine whether the phenolic terminal blocks liberate ammonia when exposed to elevated temperature, a new terminal block and a terminal block that had been in service at Seabrook Station in the same type of solenoid valve position switch, were analyzed for the gases that evolve when the material is heated. Direct insertion probe mass spectrometry (DIP – MS) and gas chromatography mass spectrometry (GC/MS) revealed that ammonia gas began evolving from the phenolic material at 400°F, and continued to evolve until the test was terminated at 600°F.

The exposure of the valve to the unanticipated higher temperature caused ammonia to be released from the phenolic terminal block. The ammonia was entrapped inside the solenoid housing making the environment aggressive for the brass screws, especially since the elevated temperature exposure increased the susceptibility to SCC. The subject solenoid valve was not hermetically sealed and it is likely that some moisture was trapped inside the valve, providing the other key component of the aggressive environment.

Background research revealed that, in general, phenolic materials can withstand a temperature of 300°F continuously. Only certain grades of phenolics are resistant to 500°F for short periods and 450°F for extended periods of exposure (Ref. 5).

A few months after the laboratory evaluation, a similar terminal block sustained screw failures in another solenoid valve in Seabrook Station due to an unintended exposure to high temperature. The failed and unfailed brass screws in the terminal block were examined in a similar fashion, and the screws revealed failure in exactly the same mode as was observed for the others. In some of the unfailed screws, the cracking propagated across almost 80% to 90% of the screw diameter starting at the cold worked interface and propagating in a transgranular, branched fashion. This again confirmed that the brass screws for both cases failed by SCC. In the same time frame some other failures were reported from other nuclear power plants on the same type of solenoid valves. Based on NAESCo's findings, the nuclear power industry group in conjunction with the original manufacturer of the solenoid valve required the phenolic novolac based terminal blocks to be baked at a high temperature prior to assembly to release any excess ammonia present, so that unanticipated high temperature exposures would not cause SCC failures of screws.

CONCLUSIONS

Based on the NAESCo event evaluation and the laboratory analysis performed at Massachusetts Materials Research Inc., the root cause of the failure of the brass terminal block screws was determined to be due to unanticipated inservice conditions that exposed the terminal block to abnormally high operating temperatures.

The failure mechanism for all brass terminal block screws was identified to be stress corrosion cracking.

The aggressive corrosive substance that caused the stress corrosion cracking was ammonia. The source of ammonia was determined to be the thermoplastic phenolic terminal block which when exposed to elevated temperatures caused the phenolic material to give off ammonia.

REFERENCES

1. F. Hossain and J. Scutti, Analysis of the Failed Screws on the Terminal Blocks of a Position Switch, Equipment Tag 1-RC-FV-2830.

2. J. A. Beavers, Stress-Corrosion Cracking of Copper Alloys, Stress-Corrosion Cracking: Materials Performance and Evaluation, ASM International, 1992, pp. 211 – 229.

3. Engineering materials Handbook, Vol. 2, Engineering Plastics, ASM International, 1995, p. 242.

4. M. Ezrin, Plastics Failure Guide, Hanser, Publisher/ Society of Plastics Engineers, 1996, p. 13.

5. Engineered Materials Handbook, Vol. 2, Engineering Plastics, ASM International, 1995, p. 244.