Evaluation of Erosion/Corrosion Damage at Two Nuclear Power Plants

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ABSTRACT

Two instances of erosion/corrosion damage at nuclear power plants were evaluated at Brookhaven National Laboratory (BNL).

A. SURRY UNIT 2

A metallurgical failure analysis was performed on pieces from a catastrophically failed 18-inch (45.7 cm) diameter feedwater line from the Surry Unit 2 Nuclear Power Station. Mechanical tests indicated that the materials of construction met the appropriate specification requirements. A failed elbow had been globally thinned on the inside surface and had a scalloped appearance. The elbow material had been reduced in some areas to below 0.040 inch (1.02 mm) from an installed thickness of 0.50 inch (12.7 mm). Fractography disclosed a dimpled ruptured (ductile) appearance on all fracture faces and no evidence of cold work on the pipe's inside surface. The conclusion drawn from the investigation was that the Surry failure occurred due to a single phase erosion/corrosion mechanism.

B. TROJAN POWER STATION

Prior to the Surry incident, a single phase erosion/corrosion event occurred at the Trojan Nuclear Power Plant. The materials of construction were normal for A106 Grade B material and the mechanical properties met specification requirements. The event was considered a single phase erosion/corrosion failure.

SURRY UNIT 2

In December 1986, an 18-inch suction line to the main feedwater pump A for the Surry Unit 2 power plant failed in a catastrophic manner. Four of the eight men working nearby on another pipe were killed during the event.

The condensate feedwater system flows from a 24-inch header to two 18-inch suction lines each of which supplies one of two feedwater pumps. The line temperature at this location is approximately 370°F (188°C), with a pressure of approximately 370 psig and a maximum flow rate of 5 million lb./hr. The fluid in the pipe at this point is considered to be liquid phase with no vapor present.

A preliminary description of the incident was documented by the U.S. Nuclear Regulatory Commission (USNRC) in SSINS No. 6835, Information Notice 86-106, dated December 16, 1986, entitled, "Feedwater Line Break."

Additional information about the incident derived either from the Information Notice or in discussion with utility personnel follows:

1. The pipe material is ASTM A-106 Grade B carbon steel. The pipe is 18-inch (46 cm) diameter with a nominal wall thickness of 0.50 inches (1.27 cm).

2. The elbow material is ASTM A-234 Grade WPB carbon steel, also with a nominal wall thickness of 0.50 inches (1.27 cm).

3. Localized areas measured on the elbow were thinned to as low as .046 inch (1.17 mm).

4. The flow velocity of the header was 12 fps (3.05 m/s) while the pipe was 17 fps (4.32 m/s).

5. The elbow developed two ruptures. Both ruptures in the elbow were separated by four inches and approximately two inches from the weld.

As a result of this incident, the USNRC, Office of Nuclear Reactor Regulation (ONRR) PWR-A and USNRC, Region II Office (Atlanta, GA) initiated an independent failure analysis of some sections of the failed elbow adjacent pipe at Brookhaven National Laboratory (BNL). The analysis was to encompass an evaluation of the failure mechanism and a confirmation of the pipe-elbow-weld mechanical, chemical and impact properties. The test methods utilized in this analysis were:

a. Visual/Photography
b. Optical Microscopy/Metallography
c. Chemical Analysis/Impact Testing/Bend Testing/Hardness Testing/Tensile Testing
d. Scanning Electron Microscopy (SEM)/Energy Dispersive Spectroscopy (EDS)

<u>Visual/Photography</u>

A total of five specimens from the failure were evaluated at BNL. Additionally, one replica of the inside surface of the elbow (casting made by Failure Analysis Associates [FaAA]) was visually examined. Note: FaAA was employed by Virginia Electric Power Co. to evaluate the failure for the utility.

All interior surfaces of the specimens examined exhibited a matted and granular appearance. The inside surfaces also had two distinct types of oxide present, a blackish tight adherent film (magnetite) and a rust colored, powdery oxide (similar to hematite) appearance.

On January 9, 1987, pieces of the joint between the header and the fabricated "tee" joint were received at BNL. These had been mechanically ground and then macroetched (10% Nital) by FaAA prior to shipping to BNL. When the two pieces were put in close juxtaposition to one another, a definite wear pattern was seen on the inside surfaces. The inside surfaces of these specimens were similar in appearance to those of the previously discussed specimens. These two specimens were photographed and then left intact for shipment back to FaAA.

Visual examination of the fracture surfaces on the specimens disclosed no gross indications of fatigue (beach marks, ratchetting, etc.).

Optical Microscopy/Metallography

Sections were removed for metallurgical mounting, grinding and polishing. These were etched in a 10% Nital solution and then examined. The pipe weld appeared to be multipass, shielded metal arc weld (not verified by utility) welded from one side only.

A metallurgical cross section was also made of the worn area of one of the specimens. This cross section showed the extent of thinning seen by the elbow. The thinnest section of the mount measured approximately .015 inch (0.38 mm).

Chemical Analysis

A chemical analysis was performed on the piping material (A106 Grade B), the elbow material (A234 Grade WPB) and the weld metal deposit (assumed to be E7018). In each instance, the obtained result fell within the requirements of the quoted specification.

Impact Testing

A total of eighteen subsized impact specimens were machined. Six each were machined from the piping material, the elbow material, and the specimens with the notch in the center of the weld. All of the subsized specimens were machined in accordance with the dimensions of ASTM E23 "Standard Methods for Notched Bar Impact Testing of Metallic Materials." Three of each group of six specimens were tested at room temperature (70°F/21°C) and three at 375°F (190.6°C), the estimated temperature at which the failure occurred. After impact testing, the fracture faces were examined under the SEM to verify the morphology of the failure.

The piping material had average values of absorbed energy of 26 ft./lb. at (70°F/21°C) and 34 ft./lb. at 375°F/190°C. The weld metal averaged 19 ft./lb. at 70°F/21°C and 21.5 ft./lb. at 375°F/190°C. The elbow material averaged 13.3 ft./lb. at 70°F/21°C and 13.25 ft./lb. at 375°F/190°C. No attempt was made to determine the nil ductility transition temperature (NDTT) for the various materials. It appears, however, that the elbow material was in the "upper shelf" range for all six specimens. (The upper shelf is a region of relatively constant toughness which occurs after the NDTT has been surpassed).

Bend Testing

Two face bend specimens were machined from specimen 1A and subjected to a bending moment similar to that depicted in Part OW-466.1 of Section IX of the ASME Boiler and Pressure Vessel Code. With the exception of one small tear (a possible inclusion) (<0.030 inch/0.76 mm), all of the weld/HAZ/base metal welds showed no cracks or defects after bending.

Hardness Testing

Knoop (microhardness) hardness measurements were performed. All of the values recorded are consistent with those expected of the materials.

Tensile Testing

A total of six subsized tensile specimens were machined in accordance with ASTM A-370, "Standard Methods and Definitions of Mechanical Testing of Steel Products." Two specimens were machined from the elbow, piping, and weld material (with weld in center of specimen). Note: due to a machining error, only one tensile specimen was cut from the pipe section.

Both the tensile and yield strengths for the elbow and pipe material exceed the minimum, requirements of the referenced standards. The values of total elongation in two instances (1 pipe, 1 elbow) fall slightly below the required minimum, but this difference is considered negligible due to the use of the subsized specimens for the testing.

The overall results show that the materials had good tensile and ductile properties and are considered to have met the specification requirements.

Scanning Electron Microscopy

Various areas around the fast fracture edges of the specimens were examined by the SEM. All of the fractures examined exhibited a dimpled ruptured (ductile) appearance with characteristics typical of a fast ductile fracture. In no instances was there any evidence of any mechanism other than ductile overload apparent in the examination. None of the specimens examined at BNL had the probable initiation area of the failure on them.

The inside surfaces of both the elbow and the piping material were examined by SEM at BNL. Low magnification fractographs showed a scallop-like, almost peened appearance, with areas of dense oxide film. The elbow material (visually) appeared to be in general more highly oxidized than the piping material.

Energy Dispersive Spectroscopy

Various EDS scans were performed on the inside surface of the pipe and elbow in search of any potential contaminants which may have been present. This investigation was prompted by comments made during a USNRC generic meeting that the extent of an erosion/corrosion process could be enhanced through demineralize leakage. None of the scans showed any contaminants.

CONCLUSIONS

The metallurgical evaluation led to the following conclusions regarding the Surry Unit 2 pipe failure:

1. The chemical and mechanical properties of the pipe, elbow and weld materials involved in the Surry failure were consistent with the expected properties of the specified materials.

2. The impact tests performed on the elbow, piping and weld material indicate that these materials had adequate toughness properties at temperature of operation.

3. The overall thinning of the elbow and pipe material coupled with the ductile tearing of the examined fractures by SEM provide adequate

indication that the Surry Unit 2 feedwater pipe failed as a result of an erosion/corrosion mechanism which thinned the wall sufficiently to cause a rapid, ductile tearing of the material after its design stress had been exceeded.

TROJAN POWER STATION

A review of the available literature revealed that Surry Unit 2 was not unique in being the first nuclear unit to have a rupture caused by single phase erosion/corrosion. The first event took place at the Trojan Station and is described in part by NUREG/BR-0051 as follows:

> "...On the evening of March 9, 1985, the plant was operating at 100% power. Average coolant temperature was 585 degrees F and reactor coolant system (RCS) pressure was 2235 psig. At about 9:50 p.m., a reactor trip occurred from automatic actuation of the reactor protection system, due to a main turbine trip. The turbine trip was caused by a spurious main turbine bearing high vibration signal. The reactor protection system and plant safety systems functioned as designed during the transient. Following the turbine trip, the resulting automatic main feedwater isolation produced a pressure pulse to approximately 875 psig in the heater drain and feedwater systems, as expected. However, the pressure surge caused an eroded section of the 14-inch diameter heater drain pump discharge piping to rupture, resulting in the release of a steam-water mixture of approximately 350 degrees F into the 45-foot (ground-level) elevation of the turbine building. In addition to the fire suppression (deluge) system actuation by heat sensors in the turbine building and damaged secondary plant equipment, one member of the plant operating staff received first and second degree burns on 50% of his body from the high temperature fluid. He was treated at a local hospital for three weeks before being released..."

Discussions with both USNRC Region V personnel and Portland General Electric (PGE-owner of Trojan) disclosed that a failure investigation was performed by the utility and that the cause of the failure was a single phase (water only) erosion/corrosion phenomenon.

A "scalloped" surface typical of erosion/corrosion was seen on the inside surface of the pipe. The chemical and mechanical properties of SA 106 Gr.B material were satisfied. The chemical analysis also showed that the alloying content of the failed pipe (Cr, Ni, Cu) were very low - .02%. These elements have been shown to reduce the propensity of erosion/corrosion attack, if they are present in sufficient concentration.

The failure investigation also documented that the microstructure of the pipe material was normal for A 106 Gr.B material. This failure was considered by the utility to be caused by erosion/corrosion in a single phase system (450 psig and 350°F, with a bulk flaw rate of 20-24 fps). This being the case, the Surry Unit was actually the second instance of this type of accelerated attack which appears to make the problem potentially generic.

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