EROSION-CORROSION IN WET STEAM AND SINGLE PHASE LINES IN NUCLEAR POWER PLANTS

XN9500244

by

Mr. Antonio Tanarro and Mr. Emilio González
Tecnatom, S.A.
Avda. Montes de Oca, 1
28709 San Sebastián de los Reyes
Madrid-Spain

Abstract

Carbon Steel piping systems carrying wet steam in both boiling water reactor (BWR) and pressurized water reactor (PWR) plants are reported to undergo severe erosion/corrosion (E/C) damage all over the world. Significant degradation of pipe wall thickness as high as 1.0 to 1.5 mm/year has occurred and in a number of plants resulted in pipe ruptures necessitating costly outages and repairs.

Identifying the root cause of E/C specific to wet steam and single phase piping is important for proper selection of replacement materials and for effecting other system design improvements.

The inspection program guidelines provided in this paper were developed based on combining the results of the root cause research work and the firsthand site inspections with practical experience. Guidelines are provided for identifying problem systems or parts of systems and rating or prioritizing those most susceptible to severe E/C damage.

Criteria for identifying those components such as tees, elbows, and other discontinuities, within a system that are most susceptible to E/C were developed. A methodology for developing a reliable and cost effective inspection program is presented.

Finally it is describe in general terms a reliable ultrasonic procedure for inspecting E/C in piping.

1 ROOT CAUSE OF EROSION/CORROSION

1.1 General

Erosion/corrosion (E/C) in simple terms, as applied to carbon steel wet steam lines, can be conceived as an accelerated form of corrosion induced by flow due to the breakdown of a protective oxide film from the surface. The theory behind this mechanism is complex and encompasses electrochemical aspects of general corrosion phenomenon, mass transfer, and to a certain degree momentum transfer.

1.2 Wet Steam Lines

1.2.1 Factors of E/C

From data published to date, the following are the factors contributing to the rate of E/C in wet steam lines:

- Percent Moisture
- Material Composition
- pH and Water Chemistry
- Temperature
- Oxygen
- Flow Path Geometry

a) Percent Moisture

The fact that E/C has not been reported in dry steam lines decisively establishes that moisture is the root cause in wet steam lines. Since it is no possible to eliminate moisture completely in most BWR and PWR steam systems, the question obviously arises as to how the moisture variation could affect the E/C rate. Clear cut conclusive test data has not been found in this area.

The test results did not directly relate E/C rate to percent moisture; however, it was found that E/C rates were less sensitive to steam quality (moisture content) as compared to the amount of local dissolved iron. To accurately study the effect of steam quality on the rate of E/C, tests should be made at one velocity which approximates plant conditions, varying the moisture content and keeping other variables constant. However, precisely simulating the field condition in a laboratory is difficult. More than the moisture content, it is the morphology of the liquid phase (size of water droplets, film thickness on the wetted surfaces, and distribution between film and droplets) in the steam that affects the rate of E/C.

In BWR and PWR steam systems, the moisture percentage ranges up to approximately 15 percent and velocities up to 51 meters per second (167 feet per second). In areas of restrictions such as orifices where the velocities are very high or in drain lines carrying saturated and flashing mixtures, the erosion due to droplet impingement or cavitation type of attack could be more prominent.

Nondestructive examination (NDE) inspection reports from operating power plants indicate that piping systems or parts of systems with higher moisture content suffered higher rates of E/C.

b) Material Composition

E/C damage is most severe in carbon steel piping. Alloying elements such as chromium, copper, and molybdenum even when present at small percentage levels, can improve the E/C resistance of carbon steels. Tests showed that 12 percent Cr steels had excellent resistance; 2-1/4 Cr-1 Mo was better than steel containing copper, and steel with less than one percent Cr did not have adequate resistance.

The most widely used material in nuclear plants for wet steam piping is carbon steel. The turbine crossaround piping in some plants employ carbon steel with trace amounts of alloying elements, particularly Cu. Firsthand site inspections have identified each of these materials as susceptible to severe E/C degradation. As a result, utilities are using CR-Mo and austenitic stainless as replacement materials and some turbine suppliers are increasing the alloying content of the crossaround piping material. No evidence of severe E/C was found in either the Cr-Mo or austenitic steels.

c) pH and Water Chemistry

Damage in wet steam turbines and PWR turbine cycle piping has been reported when the condensate pH is below 9.3. Similar damage has been experienced in BWR (S) in Japan where pH are in the neutral range of 7.0.

d) Temperature

E/C is strongly temperature dependent with well defined maximum rates based on test data.

In the two-phase flow, lower rates of E/C at temperatures less than approximately 180°C are attributable to a slower rate of chemical reaction while at temperatures higher than 180°C, a lower E/C rate is attributed to the protective layer of magnetite formed on the metal surface.

e) Oxygen

Oxygen has a definite effect behaviour. It is beneficial based on the iron release data for carbon steel in neutral water (BWR condition). For example, in carbon steel the iron release rate may decrease by 100 times when raising the oxygen concentration from 1.0 to 200 ppb over the temperature range of 38 to 204°C in neutral water at six feet per second. This change in iron release rate has been experienced in wet steam lines in BWR plants.

f) Flow Path Geometry and Velocity

Flow path geometry is a significant factor attributing to the rare of E/C in wet steam piping.

Not all of the E/C problems that were investigated in detail were attributable to poor piping layout. Significant localized E/C was measured in numerous wet steam systems. Almost without exception though, the degradation was located in the vicinity of system discontinuities such as branch connections, elbows, and in areas of shop and field wed particularly where backing rings were used. Additionally, tiger striping was discovered in a number of wet steam piping systems. The most significant difference between tiger striping and the general localized form of E/C is that tiger striping in so limited to areas of flow discontinuities. Significant wall loss in the form striping has been documented in a number straight pipe sections and not necessarily throughout the full length of the piping.

1.3 Single Phase Lines

1.3.1 Factors of E/C

Three main groups if variables affect the rate of metal loss by erosion-corrosion under single-phase conditions:

- Material variables
- Water chemistry variables
- Hydrodynamic variables

A brief summary is presented below.

a) Material Variables

Erosion-corrosion occurs most readily in plain carbon steels. Austenitic stainless essentially are immune to erosion-corrosion and alloying elements such as chromium, molybdenum and copper can improve greatly the erosion-corrosion resistance of ferritic steels even when present at levels of one percent or less. The effect of steel composition depends on the severity of the hydrodynamic conditions in that as conditions become more demanding, higher alloy contents are required to confer the same resistance to erosion-corrosion. However,in the relatively mild situation typical of feedwater piping, significant effects of small changes in material composition would be anticipated based on the laboratory data.

b) Water Chemistry Variables

The effects on erosion-corrosion rate of water temperature, pH, and dissolved oxygen content have been studied by a number of investigators. The studies show that a marked decrease in erosion-corrosion rate accompanies increases of pH as well increases of oxygen content.

c) Hydrodynamic Variables

Plant experience indicates the geometry and flow rate are important factors in erosion-corrosion. Laboratory studies have confirmed that the mass transfer coefficient is the controlling parameter. For example, it is show that a cubic relationship exists between the erosion-corrosion rate of carbon steel in PWR type water and the mass transfer coefficient over a wide range of flow rates. Since the mass transfer coefficients for simple flow geometries can be calculated, the existence of these empirical relationship allows the erosion rate to be estimated for a variety of situations. Component redesign or flow path geometry improvements, aimed at reducing the mass transfer coefficient, can sometimes be used to remedy erosion-corrosion problems.

1.3.2 Implications for Condensate and Feedwater Piping

a) PWR Plants

The preceding review indicates that carbon steel feedwater piping in PWRs operates under conditions which make it potentially susceptible to erosion-corrosion.

The literature on erosion-corrosion shows that there are several reasons for anticipating that there are substantial plant-to plant differences:

- Erosion-corrosion is a progressive phenomenon with a fairly well defined maximum rate so, other things being equal, the extent of erosion-corrosion in older plants should be greater than in newer plants.

- The PWR Secondary Water Chemistry Guidelines recommend feedwater pH values in the range of 8.5 to 9.6 depending on plant specific considerations such as the presence of copper alloys and condensate polishers. Other factor being equal, plants which generally have operated near the bottom of this range would be expected to experience a greater rate of erosion-corrosion than plants which have operated at the top of the range.

- It is also recommendable that feedwater dissolved oxygen for PWRs be controlled below 5 ppb. As lower oxygen levels may enhance erosion-corrosion, plants which generally have operated consistently at lower feedwater dissolved oxygen levels. The integrated exposure to other impurities (such as chlorides) could also have an impact on the extent of attack.

- Feedwater system designs differ from plant to plant, and it is unlikely that the same combinations of flow rate, pipe geometry and temperature will be present in many different plants. Consequently, some plants may have designs leading to generally higher mass transfer coefficients in their feedwater piping than others, and therefore would be expected to see higher erosion-corrosion rates.

- Different heats of carbon steel contain different amounts of tramp alloying elements such as chromium and molybdenum. These variations depend on factors such as the steel making process, the amount to scrap used, and even the time the heat was melted. Accordingly, piping and fittings purchased to carbon steel specifications such as ASTM A106 Grade B or A234 Grade USPB are likely to exhibit differing resistance to erosion-corrosion. (Note that the alloy content in such steel will not normally be sufficient to provide complete immunity). This could lead not only to plant-to-plant differences in the extent of susceptibility but also to place-to-place differences within one plant.

b) BWR Plants

The BWR Water Chemistry Guidelines recommend that the dissolved oxygen content of BWR feedwater be maintained in the range 20 to 50 ppb for both normal and hydrogen water chemistry operation. Although the laboratory data for erosion-corrosion in neutral pH water are more limited than for pH -9, available evidence indicates that operation in this range should provide adequate protection from unacceptable erosion-corrosion in carbon steel piping. However, action is required by the Guidelines only of the dissolved oxygen level falls below 10ppb. At this level, significant erosion-corrosion may be possible. Therefore, BWRs which have consistengly operated at feedwater oxygen levels below 20 ppb may want to consider a carbon steel piping inspection program of the type described in the next section. The remarks in the previous subsection about plant-to-plant and component-to-component variabilities apply to BWRs as well as PWRs.

2 EROSION-CORROSION INSPECTION PROGRAM GUIDELINES

2.1 Wet Steam Lines

The methodology for establishing the criteria to develop and inspection program is presented below.

a) Selecting de systems part of balance of plant conducting wet steam and with carbon steel piping; with those two conditions normally the systems selected are:

- Main Steam
- Extractions of steam
- Heater and drain system
- Condenser

b) Selecting the portion of that systems where the circulating steam has some of the three following conditions:

- Moisture greater than 2%
- Temperatures in the range of 80 °C to 195 °C
- Flow velocity greater than 45m/s

c) Selecting the areas of that systems with the most favourable geometry to produce turbulences, that is

- Elbows
- Fittings
- Straight pipes downstream of orifices or control valves.

d) Finally, it is advisable to include in the E/C program those areas that are similar to those that have had E/C problems in other plants, as well as those areas that have had problems in the proper plant itself.

With all the above criteria from a) to d) the E/C Program shall include at least about 2.000 E/C susceptible areas, so it is necessary to implement a Data Base System.

For establishing the inspection program for each refueling outage the following criteria may be used.

- Base line inspection

  Selecting about 10% out of the total amount of susceptible areas, in such a manner that the sample take into consideration all the systems affected and have the most susceptible areas, that is, those with greater moisture and velocity. Also, in order to have a good base line all the possible configurations shall be included.

- Following inspections

  Take all those areas in yellow and red alert (see next para of this document). Inspect all the repaired and/or replaced areas.

  Include all the areas that had been affected in the other units if there are any. Include, also, those areas similar to those affected if any during the operation period in other plants. Finally a percentage of the total amount of the program shall be inspected.

2.2 Single Phase Lines

Although the E/C process is essentially the same in wet steam than in water lines, the criteria to select the areas is slightly different, as it is explained below.

a) Selecting the systems and subsystems with lines in carbon steel lines conducting water flow.

b) Selecting from that systems those with at least one of the following conditions:

   - Temperature range of 100°C and 160°C
   - pH lower than 9.5
   - Oxygen content less than 5 ppm
   - Flow velocity equal or greater than 3.5 m/s

c) Selecting the areas as a function of the most unfavourable geometry (see paragraph 2.1.c above).

d) Idem para 2.1.d.

   For establishing the inspection programs for every shutdown of the plant the criteria used for wet steam lines may be used.

3 METHOD OF INSPECTION AND EVALUATION CRITERIA

The most widely used method for detection of wall thinning caused bay E/C is manually applied ultrasonic thickness measurement conducted form the outside surface of the pipe, after insulation removal. This technique is the least complicated of the ultrasonic thickness measuring possibilities and is the basis of the more advanced techniques, such an automated scanning or performing the measurements from the inside.

The ultrasonic inspection can be carry out with normal angle beam technique with analogic or digital equipment. Presently there are digital equipment with storage capacity and with the possibility to connect with computers in order to manage all the E/C data in an automatic way.

A grid system should be used to identify locations of ultrasonic thickness measurements and to provide a method of recording results of examinations. It is recommended that the grid be permanently marked on the component surface. A high temperature resistant pencil should be used. A map of the grid should be provided with the ultrasonic thickness report. This map should be sufficiently detailed to provide an adequate understanding of grid intersection locations.

An evaluation criteria should be established. The following is a recommendable one.

CATEGORY	CRITERIA	ACTION
NON ACCEPTABLE	T ≤ one cycle of OPER.	REPAIR/REPLACEMENT
RED ALERT	1 cycle < T ≤ 2 cycles	INSPECT NEXT OUTAGE
YELLOW ALERT	2 CYCLES < T ≤ 4 cycles	INSPECT NEXT TWO OUTAGE
ACCEPTABLE	4 cycles < T	REMOVE FROM SURVEILLANCE

NOTE: T is the estimated time to reach the minimum design thickness.