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Flow accelerated corrosion and its control measures for the secondary circuit pipelines in Indian nuclear power plants

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ABSTRACT

A plain carbon steel feeder pipeline in the secondary circuit failed downstream of a flow measurement device (orifice meter) during operation at nuclear power plant. A detailed failure analysis done on the failed pipeline is described in this paper. The results established the fine surface pattern of ‘Horseshoe pits’ at the affected regions. X-ray diffraction analysis on the samples far from the failed regions showed presence of magnetite but on the sample from the failed region showed peaks due to base metal only, indicating dissolution of the oxide. Thickness profiling of the pipeline indicated reduction of thickness from the design 7.62 mm to a minimum of 0.4–1.4 mm at the location of the failure. These observations are characteristic of single phase flow accelerated corrosion. This paper details the extent of flow accelerated corrosion in various Indian power plants and the remedial measures for replacement and possible design and water chemistry changes to combat it.

1. Introduction

Flow accelerated corrosion (FAC) related failures have occurred in large number pipelines in the secondary section of light water reactors worldwide [1–5]. Normally, the deoxygenated water chemistry in the secondary circuit allows formation of a protective magnetite film on the ID surfaces of carbon steel components. This magnetite film keeps the corrosion rates low in the system and protects the carbon steel components. Such a film forms in the temperature range 95–260 °C over a period of time that is dependent on the temperature. Solubility of metal ions in process fluid and mass transfer in a flowing condition results in thinning and is strongly influenced by fluid velocity, water chemistry, temperature, piping configuration and alloy content. This type of flow-assisted acceleration in dissolution is referred to as single phase FAC. This is primarily a corrosion process enhanced by (electro) chemical dissolution and mass transfer, rather than a mechanical process. This is an extension of the generalised carbon steel corrosion process in stagnant water. The appearance of single phase FAC is characterized by overlapping horseshoe pits that give an orange peel appearance. However, two phase FAC gives a tiger stripping appearance.

Some other factors typical of FAC in feed water systems in nuclear reactors are as follows [3]: FAC is the most destructive corrosion mechanism for high energy (temperature 100–260 °C) carbon steel components in light water reactors. The maximum in FAC rate appear at ~150 °C [3–5]. It has caused rupture of large, medium and small diameter pipelines carrying either single phase or two phase (wet steam) flow. It is reported to be the only mechanism that has significant potential for large leaks in the secondary circuit.

A pipe segment in the 10% feed line, immediately downstream of flow element (orifice meter) ruptured releasing steam in boiler room on February 9, 2006, in Kakrapar Atomic Power Station unit-2 (KAPS # 2). The process details and other specifications of the ruptured pipe segment were: process fluid - feed water (liquid), operating temperature - 171 °C, design pressure - 72 kg/cm^2, flow and velocity - 35 m^3/hr (2.33 m/sec), material - A 106 Grade B, size and thickness - 80 NB (7.62 mm). This pipeline carries 10% of the feed water to the steam generator and the failure occurred after approximately 10 years of operation. Fig. 1 gives the schematic of the failed piece of the pipeline showing the location of the fracture with respect to the welds and the location of the orifice meter used for flow measurement. The pipelines are covered with insulation from the OD side. However, there was no indication of any degradation from the OD side in any of the affected pipelines. The analysis of this failure and the extent of FAC in Indian nuclear power plants are described in this paper along with remedial measures.

2. Failure analysis

2.1. Material

Chemical analysis of chips taken from the failed pipeline was done and is given in Table 1. Except for silicon content, the

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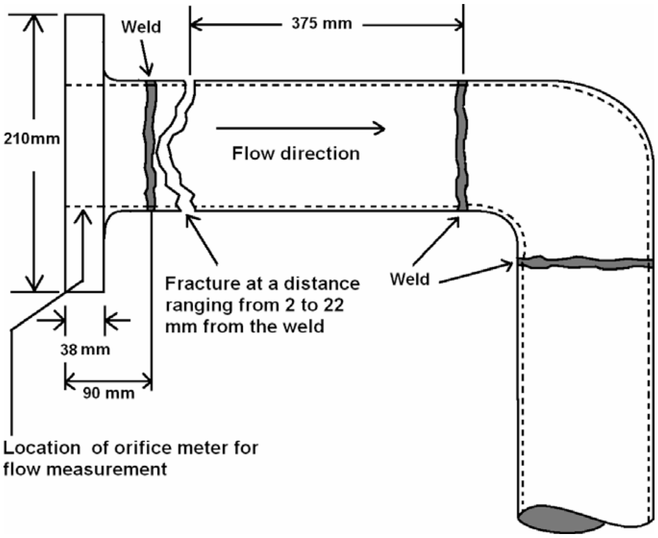

Fig. 1. Schematic of the failed pipeline indicating the location of the fracture surface, welds and the orifice meter for flow measurement.

Table 1
Chemical composition of the affected pipeline obtained by analysis

Element	Specified for A106 Grade B (wt%)	Analysed (wt%)
Carbon	0.30 max	0.22
Manganese	0.29–1.06	0.61
Phosphorus	0.035 max	0.019
Sulfur	0.035 max	0.008
Silicon	0.10 max	0.33
Unspecified elements		
Chromium	0.40 max	0.032
Copper	0.40 max	0.009
Molybdenum	0.15 max	0.001
Nickel	0.40 max	–
Vanadium	0.08 max	0.003

chemical composition of the material used corresponds to A 106 Grade B of ASTM. It may be noted that the Cr and Mo contents of the material are very low (and are typical of A 106 Grade B) in the pipeline material.

2.2. Visual examination

The failure had occurred on the pipeline side of the weld between the flange reducer and the pipeline. The failure was all along the circumference but was not at a uniform distance from the weld as shown in Fig. 2. The observations clearly indicate that the failure is not in the heat-affected zone (HAZ) due to welding. The fracture surface is at varying distances from the weld (at a distance ranging from 2 to 22 mm). Fracture in the HAZ region would approximately be equidistant from the weld all around unlike what is seen here. There is an orifice meter located in the flange for flow measurement and the fracture is downstream the orifice meter. The inner surface that had undergone FAC shows a distinct pattern. This pattern is much finer in the regions severely affected by FAC while it is quite coarse at other locations. The thickness of the pipeline had reduced from the original (measured) value of 7.11 mm to a minimum of 0.4 mm at the location of the failure.

2.3. Microscopic examination

2.3.1. Stereomicroscopic examination

The failed pipeline section was examined under a digital stereomicroscope. The ID surfaces showed a distinct pattern. Fig. 3 shows the main features of the ID surfaces near the fracture surfaces. Fig. 3(a) shows the features near the fracture surface, which has a finer pattern, and Fig. 3(b) shows the features away from the fracture surface, which shows a coarser pattern.

Fig. 2. The failed pipeline showing circumferential fracture and excessive thinning at the location of fracture.

2.3.2. Scanning electron microscopic examination

Samples were cut from the pipeline section of the failed component and examined under SEM. The OD, ID and the fracture surfaces were examined. The main results are shown below in Fig. 4. The fracture surface (Fig. 4(a)) shows a clear ductile failure with no indication of cleavage facets. This indicates an overload failure. Since there was excessive thinning observed at this region, the overload failure is due to the pipeline thickness reducing to a level at which it can not withstand the operating load. Similar observations have been reported earlier [1]. The ID surfaces showed features similar to those observed by stereomicroscopy. Fig. 4(b) shows the ID surfaces near the fracture region and removal of material from the ID surfaces can be seen in this figure. The Figs. 3 and 4(b) clearly show the horseshoe-pitting (orange peel) appearance of the ID surfaces in the affected regions as has been reported earlier [2].

A sample was taken from the other end of the pipeline (after the elbow section) that was not affected by FAC. The thickness at this section was 7.11 mm (design thickness was 7.62 mm). The ID surfaces had a dark brownish appearance. The sample was ultrasonically cleaned to remove any loose products before the examination in SEM. The SEM examination revealed rough surfaces with coarse pattern (Fig. 5(a) and (b)). Compared to this, the pattern (orange peel) in Fig. 4(b) is much finer and that structure also showed horseshoe-pitting type of attack.

2.4. Optical microscopic and microhardness examination

Samples from the affected (thinned) regions and from unaffected regions were metallographically prepared for microstructural examination. Since polishing was done, the surface examined was just underneath the ID surface. The microstructures showed a typical ferrite – pearlite microstructure of carbon steel that is typical microstructure of A 106 material. This structure also confirmed that the material was not in a deformed state (e.g. forged etc.) and contained low carbon content. There was no difference in the microstructure at the affected and the unaffected regions.

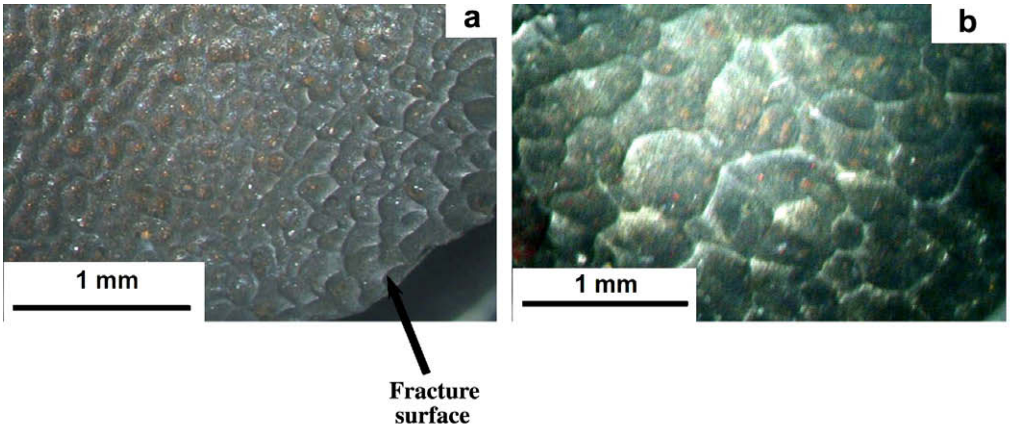

Fig. 3. Typical patterns on the ID surfaces as observed by stereomicroscope (a) showing fine pattern near the fracture surfaces (at locations most affected by FAC) and (b) a much coarser pattern at a location that is least affected by FAC.

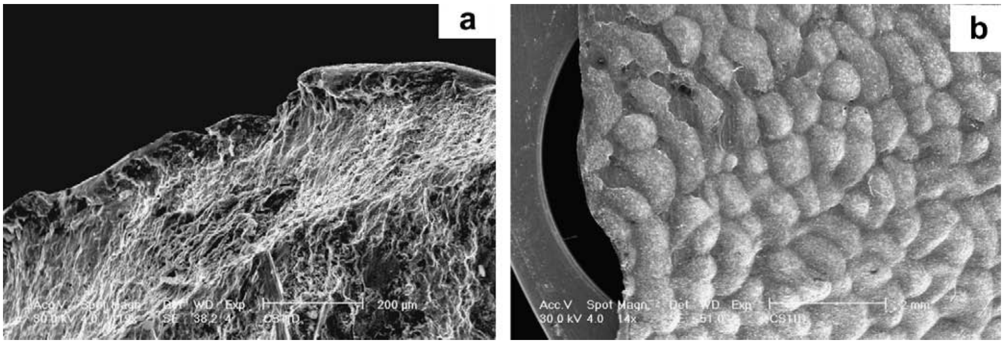

Fig. 4. The SEM photomicrographs showing (a) the fracture surface and (b) appearance of the ID surfaces near the fracture establishing horseshoe pits and orange peel appearance.

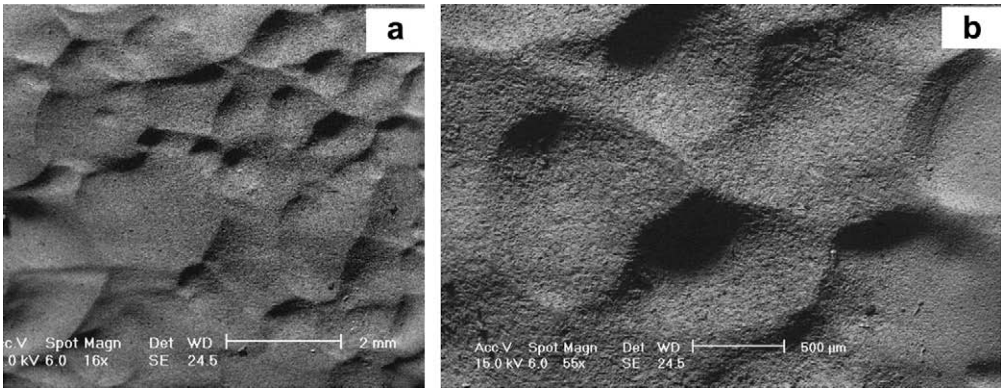

Fig. 5. The SEM photomicrographs of ID surfaces at regions far away from FAC affected regions showing (a and b) rough surfaces with coarse pattern compared to that at the FAC affected regions.

The hardness measurement was done using a microhardness tester on samples that were examined for microstructure. The ID surfaces from affected regions (at the failed location) and at locations that were not at all affected by FAC showed hardness of 173 HV and 170 HV, respectively. The hardness values measured on the cross sectional surface at the unaffected region was 160 HV. These are typical values for carbon steel and show no significant change in hardness at the affected regions.

2.5. XRD analysis

XRD analysis was done on two samples. The sample taken from regions far away from the failed regions showed presence of magnetite at the ID surfaces. Haematite was not detected in this sample. The sample from the failed region showed peaks due to base metal only. The results of the XRD analysis are shown in Fig. 6. The absence of magnetite (or any other oxide) confirmed that the oxide (magnetite) was getting dissolved at the regions of failure.

2.6. Thickness mapping

The thickness of the pipe was mapped by ultrasonic method. The thinning was maximum near the flange and it gradually reduced away from it as indicated in the Fig. 7 but the reduction in thickness had occurred over a long distance. The thickness was measured at eleven equidistant locations all along the

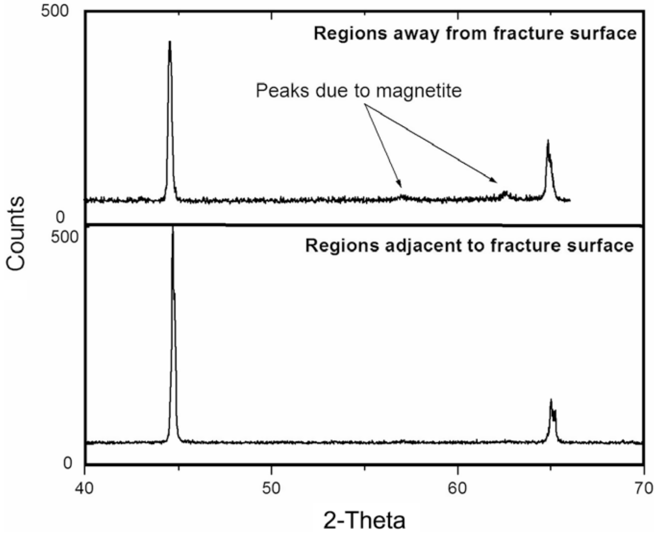

Fig. 6. XRD analysis showing presence of magnetite on the sample taken at unaffected regions and peaks due to base metal only for the sample taken from the FAC affected regions.

circumference and also at one-inch intervals along the length. The region near the fracture was very uneven. Hence, thickness mapping was started at a distance of approximately 50 mm from the fracture surface. The wall thickness at the extrados region was monitored and was found to be around 6.5 mm. This could be attributed to flow disturbance due to the elbow geometry. The maximum thinning took place near the flow disturbance due to orifice meter, as shown in Fig. 7.

3. Extent of FAC and steps to avoid failures due to FAC

From the failure analysis reported in this paper, it is clear that the failure had occurred due to FAC. An extensive FAC monitoring plan and a number of approaches to avoid failures due to FAC in the secondary circuit of nuclear reactors have been implemented in India.

3.1. FAC monitoring program: secondary cycle piping in Indian nuclear power plants

Ultrasonic thickness (UT) inspection and monitoring of secondary cycle piping components for checking degradation existed in Indian NPP even before Mihama incident. This was based on individual station experience and judgment. Many of the stations had noticed degradation and replaced the material. But after rupture of condensate line at Mihama Unit-3 (Japan), efforts were made to review all the secondary cycle systems, so as to prevent a similar incidence in Indian NPP's. A systematic periodic inspection program was prepared for UT thickness measurements of components pertaining to high energy systems of secondary cycle which are vulnerable to FAC.

The components or the locations which are prone to thinning due to FAC in high energy systems of secondary cycle were identified based on following criteria: (i) areas where velocity is high, (ii) areas where local flow disturbances are expected, (iii) areas where wetness is high, (iv) where two phase flow is expected, (v) locations based on piping configurations and where layout is congested and (vi) industry experience on failures available from literatures.

Based on above FAC program, approximately around 350 FAC susceptible components pertaining to various high energy systems were identified for inspection for each station. Components from almost all high energy systems are included for inspection in this program.

The rupture 10% feed water line of KAPS-2 in February 2006 called for a still more in depth study of the failure and to suggest further steps to strengthen FAC management program.

- After KAPS-2 pipeline rupture some more additional locations (around 380) pertaining to various high energy systems of secondary cycle of KAPS-1 &2 were inspected. This was done to

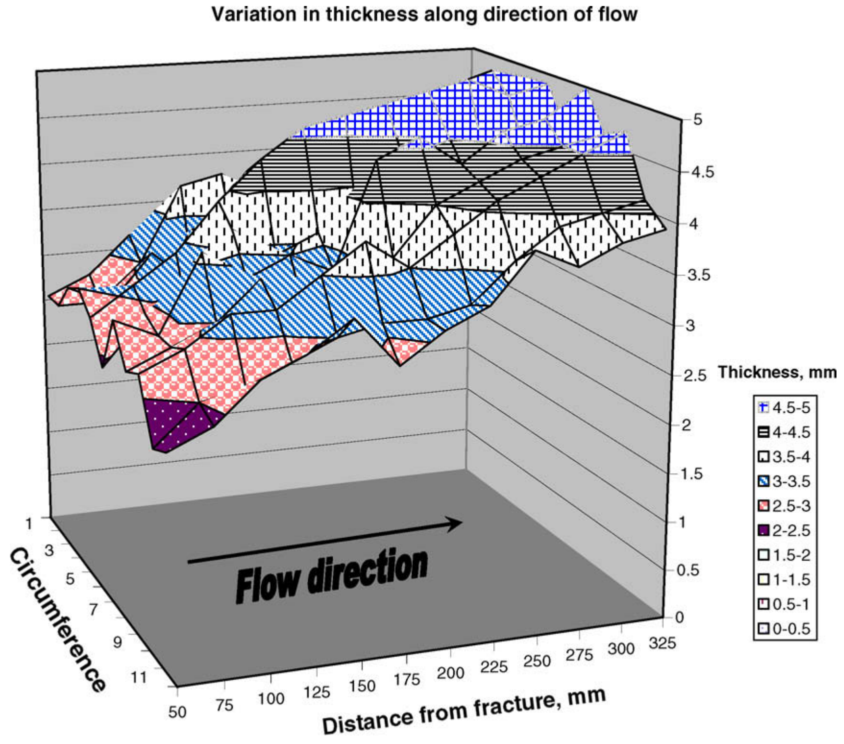

Fig. 7. Variation in the thickness of the pipe in the direction of flow.

asses overall healthiness of the plant. All the degraded components were removed from the system and replaced with new components.
- It was thought prudent to enhance the scope of examination to include all high energy system piping component to generate base line data. The feedback and information was disseminated to all projects and stations.
- Guidelines for UT examination, repair/replacement and procedure for examination, weld overlay, grid size criteria for inspection and format for recording inspection data etc. have been prepared and issued to all stations and projects.
- Decision was taken to replace the carbon steel material with low alloy steel A-335 Gr. P22 (2¼% Cr, 1% Mo) in case of FAC prone systems/lines/locations and to use pipes & fittings with one schedule higher than the required schedule.

3.1.1. *Identification of commonly affected locations*

After reviewing the results of UT thickness examination carried out for 10 power stations, the systems/lines/portion of piping which are commonly vulnerable to FAC were identified. These are: 10% feed water line down stream of control valves, downstream of control valve of reheater drain, separator drain, bleed steam drain alternate & main path, extraction lines, steam drain system (down stream of restriction orifices (RO's), heater vents down stream of RO's and heater drain system down stream of control valves (CV's).

Based on the UT measurements done on high energy components for the Kaiga Generating Station during July–August 2006 (after 5.5 hot operating years), the prevalence of FAC has been well documented. Out of the 3060 components examined on the secondary side, 54% components had initial thickness less than the nominal thickness. There was thickness reduction of more than 12.5% of the nominal thickness in 11% of the components. Other findings of UT examination are:

- Most of the UT examination results are analyzed comparing the measured minimum thickness with nominal wall thickness in absence of the pre-service inspection data. To overcome all such uncertainties guideline is given to repair/replace the degraded component before 50% of residual life is over.
- Degradation is noticed in many of the single phase, two phase and wet steam systems in secondary cycle on components such as elbows, reducers, pipe down stream of restriction orifice, flow element etc.
- Thickness reduction is noticed in blow down system, moisture separator and re-heater drain system etc. where the bulk velocity is lower than normal recommended velocities.
- Degradation is noticed in the secondary cycle components in the temperature range of 90–250 °C.
- Average wear rate of 150–200 microns/year is noticed in some of the commonly vulnerable systems.
- In one of the station, thickness reduction was noticed almost in the middle of the 8.3 m straight portion of pipe at the bottom portion.

3.2. *Steps taken/initiated in Indian NPP's to overcome FAC*

3.2.1. *UT thickness monitoring program in Indian plants*

Periodic inspection program for UT thickness measurements of components which are most vulnerable to FAC pertaining to high energy systems of secondary cycle has been prepared and issued for all stations/projects. Subsequently scope of examination was enhanced by recommending to stations for monitoring all the potential locations of high energy secondary cycle piping (i.e. around 3000 components) to develop base line data. Few of the stations have already completed one cycle of such enhanced inspection.

Guidelines and procedures issued to all stations and projects as part of FAC management program:

- To provide a step by step method to be followed regarding initial examination, first examination and successive examination of components selected for inspection.
- Criteria for replacement/repair of degraded components.
- Criteria for grid size marking on the components to be inspected.
- Procedure for UT thickness measurement.
- Steps to identify the suitable material for replacing the degraded components and generating its base line data.
- Guidelines for inspection of balance items which are not included in the periodic inspection program but pertaining to secondary cycle system.

System forrecording inspection data and review: A comprehensive excel sheet (format for recording data) to bring out uniformity in the reporting of inspection data has already been prepared and used by all stations and projects. This sheet facilitate in recording present inspection data, previous inspection data and replacement history, system, line, component detail, material used, dimensional details, process parameters etc. This sheet facilitates quick assessment and residual life analysis.

3.2.2. *Replacement of existing carbon steel material for operating stations and projects under construction*

Decision was taken to replace the existing carbon steel pipe and fittings of the systems/portion of piping which are prone for FAC with low alloy steel ASTM, A-335 Gr. P22 (2¼% Cr, 1% Mo) [6].

The FAC rates for a 90° elbow predict that FAC rate reduces to one tenth of the FAC rates for a carbon steel pipeline when Cr content is increased [5] from 0.03% to 0.5%. A better grade of carbon steel (ASTM A 335 Grade 22 containing 1.9–2.6% Cr and 0.87–1.13% Mo [6]) has been used in many plants with much better resistance to FAC. The surface oxide changes from Fe_3O_4 to $FeCr_2O_4$ with addition of Cr in carbon steel.

Replacement of carbon steel piping components with low alloy steel materials has been used successfully to mitigate FAC. The materials are readily welded to one another, and both have similar physical properties such as tensile and yield strength, density, and thermal expansion coefficient. As these low alloy steels have almost the same mechanical properties at the operating temperatures of interest, replacement piping of this material can be installed with the same geometry and unit weight as the original carbon steel components. Additionally, the thermal stresses and nozzle loadings are of little consequence due to the similarities in the coefficients of thermal expansion. As a result, the substitution of either of these grades is generally straightforward, and any design analysis should be minimal for the same configuration.

Stainless steel and alloy steel were found to be possible alternate replacement materials for carbon steel as these are significantly less susceptible to FAC (with SS grade 316L being the most suitable material). But the substitution with austenitic stainless steels will require some additional engineering aspects. These materials have a thermal expansion rate, which averages 1.4 times greater than plain carbon steel. Susceptibility to chlorides stress corrosion of austenitic grade is another concern related with the chloride contaminants in thermal insulation.

In view of the above, it has been decided to use low alloy steel pipes and fittings as the replacement material. Another important aspect is to establish replacement with the same grade A 106, grade B (but containing 0.25–0.40% Cr) would be effective.

3.2.3. Provision of increased corrosion allowance

It has been decided to use pipes & fittings of one schedule higher than required schedule for FAC prone areas.

3.2.4. Analysis of cut and removed components

It has been decided to analyze and systematically study FAC phenomena from the cut and removed degraded) pipes and fittings from the secondary cycle piping.

3.2.5. Water chemistry changes

The pH of the feedwater has a strong influence on the FAC rates. As the pH is increased beyond 9.0, the FAC rates decrease upto 10.0 at the operating conditions. It has also been shown [3] that the minima in FAC rates appear at a pH of 9.5 [3,4]. Therefore, a raise in pH to close to 9.5–10.0 would help reduce the FAC drastically. However, caution has to be taken to consider the effect of this rise in pH on corrosion of other components. Especially that of any copper based alloys, the corrosion of which increases with rise in pH. Also the influence of this rise in pH has to be assessed for its possible influence on corrosion and cracking of SG tubing from the secondary side.

The Chexal–Horowitz model [3] predicts the FAC rates to drop from 3.2 to 0.89 mm/year as the dissolved oxygen content is increased from 10–30 ppb. The effect of DO level is related to the formation of haematite in preference to magnetite on carbon steel surfaces when the DO levels are high. The rate of dissolution of haematite is slower than that of magnetite in the feed water hence the drop in FAC rates. It has been reported [3,5] that in the secondary circuits of PWR, an injection of oxygen to obtain around 10 ppb is sufficient to achieve reduction in FAC rates. However, before any increase in DO levels in the secondary circuit to control FAC rates, its effect on (i) long term corrosion performance of SG tubing (especially corrosion of Monel 400 tubing and cracking of alloy 800 tubing) and (ii) any possibility of increase in crud levels has to be assessed.

3.2.6. Design improvements

The layout of piping system and its configuration is also understood to be a contributing factor for FAC. The efforts are being made to study these aspects in existing stations. However, it is felt that changing the existing layout will be difficult. In the future projects special efforts shall be made to design the piping system layout so as to minimize turbulent flow, direct pipe wall impingement, vortex flows which are the perceptible causes to increase FAC. The local flow velocities are important (e.g. downstream of flow disturbance). This is due to the turbulent (as against laminar) flow that is generated just after passing the flow-measuring device/flow restriction/change of flow direction forming a complex velocity pattern [4]. These can be two to three times the bulk velocities. For most feed water segments, modelling has shown [3] that the maximum FAC rates are at the temperature of ~150 °C.

3.2.7. Future Plans

The computer soft-wares/codes analyze and predict the susceptible FAC components and locations so that FAC management can be done on such locations in a more effective manner. Efforts will be made to develop such a soft ware.

4. Conclusions

The failure of the plain carbon steel feeder pipeline was established to be due to excessive thinning due to single phase FAC. Plain carbon steel is susceptible to FAC due to increase in corrosion rates under flowing conditions. The situation is aggravated whenever there is enhanced turbulence in the flow (e.g. downstream of flow meters causing flow restriction), which increases the flow rate at localized regions. Optimising operating parameters e.g. pH helps in minimizing the FAC. Steels containing Cr (and Mo) are expected to offer longer life under similar operating conditions. As detailed above, overall FAC management is being achieved in Indian NPP's by implementing an exhaustive and systematic, periodic inspection program, following uniform guide lines and procedures for inspection, repair/replacement, criteria for grid size and adopting a system for recording the inspection data and its residual life analysis. Already the FAC prone components/locations have been identified in all the operating plants and baseline data on thickness generated in upcoming projects. Actions are also taken for replacing the pipes and fittings at FAC prone locations in the systems with a better material in case of stations and projects. These actions are aiming to improve the healthiness of secondary cycle systems and to avoid failures.

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