DEGRADATION OF AGED PLANTS BY CORROSION: “LONG-CELL ACTION” IN UNRESOLVED CORROSION ISSUES

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1. Introduction
In conventional corrosion science it is well established that ‘long cell action’ can seriously accelerate or suppress the local cell corrosion activities. Although it is another fundamental mechanism of corrosion, especially in an underground corrosion arena, potential involvement of this corrosion process has never been studied for the nuclear and fossil power plants. The author believes that the omission of this mechanism is the root cause of practically all un-resolved corrosion issues for LWR plants.

2. ‘Long cell action’ corrosion in NPPs
In the current local cell action hypothesis, the effect of cell action is assumed limited only to its proximity considering the high purity and low conductivity of coolant water used in NPPs. However, the author believes that this intuitive assumption can be false for the following reasons:
(1) Circulation of water as a coolant
Ions can be transported easily through the hydraulic circulation of coolant, while the structure itself act as an electric conductor.
(2) Cathodic counter-cell action
A closed circuit can be established, due to the counter cell cathodic activities (e.g., reduction of dissolved $O_2$ into $OH^-$ ions, reduction of hydrogen ions into dissolved $H_2$ and deposition of $M^{+}$ ions often with $OH^-$ ions) that consume corrosion-induced electrons generated at the remote anode, while metallic ions deposit at cathodic sites or are removed by purification systems. The local cell action corrosion hypothesis is a practical application of the more fundamental theory of corrosion mechanism (called cathodic de-polarization theory) developed by a Russian academician Akimov as early as 1945 [1].
(3) Several mechanisms for potential differences
There exist several mechanisms that induce potential differences (e.g., temperature, aeration, flow velocity, concentration, radiation and corrosion potential) at different components that are electrically connected to each other through piping (ICONE14-89350).
(4) A large cathode to anode area ratio
The anodic corrosion activities are enhanced by a large cathode to anode surface area ratio that gathers the small cathodic current from the large surface area into a significant current which is then focused onto the small anodic area in the long cell action corrosion mechanism (e.g. localized corrosion) [1].

3. Assessment of unresolved issues
In a series of previous papers already published (including ICONE14-89350, 89651, ICONE12-49432, and 49433), the author has identified that ‘long cell action’ corrosion plays a pivotal role in practically all unresolved corrosion issues such as IGSCC, PWSCC, AOA, FAC (Erosion-Corrosion). In this paper, the author further deployed this assessment to other key corrosion issues, e.g. steam generator and turbine corrosion issues.

4. Conclusions
In the long cell action hypothesis, additional efforts should be directed towards the electrical insulation of components that have large heat transfer areas, including both heat exchangers and fuel assemblies. As early as in 1953, the remarkable effectiveness of electrical insulation towards the mitigation of corrosion issues in power plants had been demonstrated in three fossil power plants [2]. The author is calling for institutional review activities and further verification experiments as a joint international project.

References
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ABSTRACT

In a series of previous papers already published (includingicone14-89350, 89651, icone12-49432, and 49433), the author has identified that ‘long cell action’ corrosion plays a pivotal role in practically all unresolved corrosion issues for all types of nuclear power plants (e.g. PWR/VVER, BWR/RBMK and CANDU). Some of these unresolved issues are IGSCC, PWSCC, AOA, FAC (erosion-corrosion) and various corrosion issues in steam generators and steam turbines.

In conventional corrosion science it is well established that ‘long cell action’ can seriously accelerate or suppress the local cell corrosion activities. Although long cell action is another fundamental mechanism of corrosion, especially in an underground corrosion (also called ‘soil corrosion’) arena, potential involvement of this corrosion process has never been studied for the nuclear and fossil power plants as far as the author has been able to establish. The author believes that the omission of this basic corrosion mechanism is the root cause of practically all unresolved corrosion issues for light water reactor plants worldwide.

In this paper, the author further deployed this assessment, without going into details about electrochemistry, to other key corrosion issues, e.g. steam generator and turbine corrosion issues, while briefly summarizing previous discussions for completeness, as well as introducing additional experimental and theoretical evidence of this basic corrosion mechanism. Due to the importance of this potential mechanism the author is calling for institutional review activities and further verification experiments as a joint international project.

1. INTRODUCTION

In spite of industry’s effort over the last 40 years, corrosion-related issues continue to be one of the largest un-resolved problems for nuclear power plants (NPPs) worldwide. As an example, according to the recent statistics covering a five year period from 2000 to 2004, it indicates that 75% of the total 115 cases of incidents, malfunctions and troubles reported by to the Japanese regulatory agency have been identified as being due to mechanical problems [1]. These mechanical problems break down as follows: 44% consist of stress corrosion cracking (SCC), 19% of component degradation due to ageing (mostly in corrosive environment), 8% of fatigue cracking and 6% of wear of seals.

In addition, since some of the corrosion cracks grow after a period of incubation these un-resolved issues began to overlap with ageing issues. The ageing of nuclear power plants is also becoming an issue of increasing concern throughout the world, with
operational plant life of most NPPs approaching their original design life, ageing issues are beginning to appear. The list of unresolved issues is very long and there needs to be a reappraisal of the current operational systems and approaches taken to ameliorate problems in order to understand and mitigate them. These unresolved issues include:

• Steam generator degradation issues;
  - Primary water stress corrosion cracking (PWSCC)
  - Intergranular Attack (IGA) and Outside diameter stress corrosion cracking (ODSCC)
  - Corrosion degradation at the tube/tube sheet and tube support plate
• PWSCC cracking in upper and lower head penetrations of PWRs
• Stress corrosion cracking (SCC) of reactor coolant piping in BWRs and RBMKs
• SCC in core shrouds and core internals in BWRs
• Sticking and cracking of control rod assemblies and control rod drive mechanisms (CRDM)
• Axial offset anomaly (AOA) in PWRs and crud deposition anomaly (CDA) in VVERs
• Flow-accelerated corrosion (FAC) and erosion-corrosion (E-C)
• Cracking of turbine rotors, corrosion-fatigue failure of turbine blades

These corrosion-related issues are one of the biggest concerns for the management of aging structures in the current-generation of nuclear power plants. Due to the economic impact but more importantly structural safety concerns, finding solutions to avoid and mitigate corrosion issues are a high priority for the industry worldwide. Still scientific mechanisms and root causes for these phenomena have yet to be well clarified, although industry has appropriated billions of dollars towards the mitigation of these issues.

At first sight, these issues appear to be independent and occur under special environmental conditions specific to each type of nuclear power plant. Through studying and coping with diverse corrosion phenomena, the author has searched for possible fundamental mechanisms that may have been overlooked during the early stages of investigation when the current focus of corrosion study was first developed. The author noticed that the current studies on these corrosion phenomena share a common basis with respect to the assumed corrosion mechanism (e.g., ‘local cell action’ hypothesis). The ‘local cell’ action corrosion has been considered as a tacit agreement among scientists and engineers in nuclear communities.

However, the ‘long cell action’ that transports electrons through structures far beyond the region of local cell corrosion activities has been established as a basic mechanism in soil corrosion. Before the author’s most recent study, this mechanism had never been investigated seriously as far as the author has been able to ascertain. For this reason, the author has investigated potential involvement of the long cell action corrosion mechanism in water-cooled nuclear and fossil power plants. The author’s study has been published in six conference papers [2-7]. A review paper which is written from an electrochemical corrosion mechanism point of view has been submitted for possible publication in another journal [8].

In the author’s previous papers, an assessment has been made and reported to clarify the role of ‘long cell action’ for typical corrosion-related issues commonly observed (e.g., FAC (EC), SCC and AOA). In this paper, the author further deployed this assessment, without going into details about electrochemistry, to other key corrosion issues, e.g. steam generator and turbine corrosion issues, while briefly summarizing previous discussions for completeness, as well as introducing additional experimental and theoretical evidence of this basic corrosion mechanism.

If the long cell action corrosion mechanism is assumed in nuclear power plants, the structure becomes anodic in the area where the electrochemical potential is less positive, while cathodic where this potential is more positive. Metallic ions generated at anodic corrosion sites are transported to remote cathodic sites through the circulation of water and deposits as corrosion products. Very often the excess electrons generated at the anodic sites are neutralized at the counter-cell cathodic sites through a cathodic polarization with dissolved hydrogen or oxygen. The SCC, FAC (E-C) and PWSCC occur in the anodic sites as the structure itself acts as a short-circuiting conductor between the two sites, the action is similar to a galvanic cell but on a very large scale. The corrosion attack under long cell action tends to be more
hazardous because of its localized nature compared to local cell action corrosion. Electrical insulation becomes more important in the engineering culture of the long cell action hypothesis, whereas material/welding improvement, water chemistry control and corrosion inhibitors are the basic strategy for mitigation of corrosion phenomena in local cell action.

Due to the significance of corrosion issues for NPPs world wide, the author’s papers were written to invite comments and studies either supporting or contradicting this thesis of a new potential mechanism of corrosion based on the long cell action hypothesis. The author is aware of the insufficient substantiation for this mechanism since it is only based on a few pieces of supporting experimental data at this stage in the investigation. Yet the author is searching for any information explaining why long cell action has been deemed technically insignificant in regards to the unresolved corrosion issues in the nuclear reactor environment. In spite of many unknowns it is fortunate that good insight into these issues can be made from electrochemistry, which is one of the very well established fields of science, combined with information obtained from corrosion science and water radiolysis.

2. HISTORY OF CORROSION ISSUES IN EARLY NPPs

The history of strange corrosion issues in NPPs dates back to a military endeavor which began post World War II and was established to develop the nuclear propulsion technology for battle ships under the leadership of Admiral Rickover. It must be noted that at that time little was known about the long cell action corrosion mechanism since the theory was developed several years later. The current reactor technology evolved from this project without changing the fundamental approach for corrosion control; hence there is no electrical insulation of components in the heat transport systems.

(1) Selection of water as the reactor coolant

Though water was chosen partially because it was a familiar fluid for power engineers this choice nearly caused the demise of the nuclear submarine program. Laboratory testing of the pumps, bearings, valves and piping demonstrated to Rickover's team that the simple familiar fluid was not so simple at high temperatures and pressures, particularly when exposed to neutron radiation. There were a number of unexpected reactions that make water almost unworkable as a reactor coolant. The in-pile test of the fuel element, using the NRX reactor in Canada, revealed that the fuel element became covered with a significant amount of a black deposit that came to be known as CRUD, an acronym for Chalk River Unidentified Deposit [9].

(2) Dissemination of corrosion issues in Naval Reactors Handbook

The ‘reactor’ corrosion issues were first disclosed in a historical report at the time of Atoms for Peace\(^1\). Some of the previous military secrets were declassified to the world’s scientific community as a gift of the United States of America for the peaceful use of atomic energy. These former military secrets first appeared in a series of historical Naval Reactors Handbooks, the first volume was published in June 1950 under the title ‘Liquid Metals Handbook.’

Among this collection of Naval Reactors volumes there is one entitled the Corrosion and Wear Handbook for Water-Cooled Reactors [10]. It is amazing to find that practically all the corrosion problems currently being faced had already identified in this handbook. Morphologies of those corrosion problems introduced in the handbook are not much different from what is often discussed in current journals and conference papers throughout the world.

3. LONG CELL ACTION CORROSION IN NPPs

3.1 Local Cell vs. Long Cell

The reason that little attention has been paid to this mechanism appears to be due to the fact that the long cell action corrosion is a specific mechanism that was believed only to occur in soil corrosion, which appearance wise is a much different corrosive environment compared to that of the water chemistry of NPPs. The long cell action in soil corrosion occurs due

\(^{1}\text{This address was given by Dwight D. Eisenhower before the General Assembly of the United Nations on Peaceful Uses of Atomic Energy, New York City, December 8, 1953.}\)
to a difference in aeration of oxygen in underground corrosion. Similarly, significant differences in the concentration of oxidants have been known to exist in NPPs, especially in Boiling Water Reactors (BWRs). In this situation, the difference occurs between the reactor core area and out-of-core piping area which is induced by water radiolysis [6, 7].

In the current local cell action hypothesis, the effect of cell action is assumed limited only to the local corrosion area considering the high purity and low conductivity of coolant water used in NPPs. Therefore, corrosion tests are usually performed by paying attention only to the surface chemical reactions of the specimens by simulating the local corrosion environment. In general, local cell action is rarely severe since it produces a fairly uniform corrosion.

However, the author believes that this intuitive assumption can be false for the following reasons:

1. **Circulation of water as a coolant**
   Metallic ions can be transported easily through the hydraulic circulation of coolant.

2. **Cathodic counter-cell action**
   A closed circuit can be established, due to the counter cell cathodic activities (e.g., reduction of dissolved oxygen into hydroxyl ions, reduction of hydrogen ions into dissolved hydrogen and deposition of metallic ions often with hydroxyl ions) that consume corrosion-induced electrons generated at the anode and transported to the cathodic sites through the structure, while metallic ions deposit at cathodic sites or are removed by water purification systems.

3. **Several mechanisms for potential differences**
   There exist several mechanisms that induce potential differences (e.g., temperature, aeration, flow velocity, concentration, radiation and corrosion potential) at different components that are electrically connected to each other through piping [7].

4. **A large cathode to anode area ratio**
   There exists a mechanism for enhancement of the anodic corrosion activities due to a large cathode to anode surface area ratio that gathers the small cathodic current from the large surface area into a significant current which is then focused onto the small anodic area in the long cell action corrosion mechanism (e.g. localized corrosion).

A detailed explanation of these mechanisms from an electrochemistry point of view has been provided in the author’s review paper and will not be repeated here [8]. In addition to these points, within the long cell action corrosion the anodic corrosion (oxidation) reactions (e.g. dissolution of metals by losing electrons) are visible and are manifested by SCC, FAC (E-C) and PWSCC. However, the counter cell cathodic reactions are usually not visible as they occur inside the high temperature/pressure cooling systems of NPPs. Typical cathodic reactions include an increase in the concentration of dissolved hydrogen, or either reductions of dissolved oxygen into the water or hydroxyl ions. Within the long cell action corrosion this ‘invisible’ cathodic activity often controls the anodic corrosion activities, which has both scientists and engineers pay more attention to the latter than trying to locate the long cell cathodic sites.

### 3.2 Different Culture for Engineering Mitigation

If we start with the long cell action corrosion mechanism, a new approach is necessary for mitigation of corrosion issues, since basic strategies for the mitigation of corrosion are significantly different between the technology spheres within the hypothesis of the local cell action only and that considering the long cell action corrosion mechanism. In the former, more focus is directed towards the improvement of materials and welding technologies, management of water chemistry and corrosion inhibitors, and the amelioration of residual stresses. In the latter, additional efforts should be directed towards the electrical insulation of components that have large heat transfer areas, including both heat exchangers and fuel assemblies, as well more effort should be placed on the mitigation of cathodic depolarization processes. In pipelines buried underground, it is a common sense to apply electrical insulation around the steel piping to cope with the surrounding corrosion environment. In water-cooled nuclear power plants, a corrosive environment occurs inside of the piping. Why is it believed that electrical insulation unnecessary in power plants?

Even before the theory of long cell action corrosion was developed, the remarkable effectiveness of
electrical insulation towards the mitigation of corrosion issues in power plants had been demonstrated in three fossil power plants through research performed by H. W. Wahlquist in 1952 [11]. He was an electrical engineer who visualized the corrosion problems encountered in steam-electric power plants as being in effect a huge short-circuited battery with current discharging to the cooling water from the interior surfaces of the water-box, and then collecting on the tube-sheet and tube ends. The closed circuit being completed through the flange bolts of the water-box. Three surface condensers constructed for a new steam-electric station were provided with electrical insulation between the cast-iron water-box flange bolts, and also the flanges for the auxiliary piping. This made it possible to measure the open-circuit voltages and short-circuit currents of the galvanic cells. Condenser No. 1 was operated with the flange insulation short-circuited, No. 2 had the flange insulation open-circuited and No. 3 was initially operated with open-circuited flange insulation and was later changed to being cathodically protected with magnesium sacrificial anodes. Severe corrosion occurred only in No. 1. Although Wahlquist concluded that it is due to a galvanic corrosion between the brass tubing and the water-box, this author thinks that the cathodic current had been apparently accumulated through the large surface area of the condenser tubing.

4. HISTORY OF THE DEVELOPMENT OF THE LONG CELL ACTION CORROSION THEORY

Localized corrosion in long underground structures was the focal point of the research performed by the US based National Bureau of Standard (NBS), which was entrusted to them by the US Congress in 1910. Through 45 years of NBS research, the field data carried out consisted of nearly 37,000 specimens representing 330 varieties of material. The NBS found that most underground corrosion is the result of electrochemical reactions. For such reactions to occur there must be a potential difference between two points of the metal in contact with an electrolyte. Current flows from the anodic area through the electrolyte to the cathode which is located more or less remote from the anodic area, then it returns through the metal structure itself to complete the circuit. The differential aeration cell developed by I. A. Denison and his colleagues was used to compare the corrosivities of different soils and of different metals in the same soil [12].

From 1955 to 1956, the question of the causes for corrosion on long structures was brought up at meetings of a technical committee of National Association of Corrosion Engineers (NACE) headed by R. Pope, then Chairman of NACE. One of the main points considered was whether corrosion was being caused by local cells or long cells (i.e., long line currents). He published a paper explaining the relative effects of long cells on local cells by using the polarization diagrams. According to his theory, long cell action occurs on long structures where the corrosion environment is anodic in one area of the structure with respect to another area. The structure becomes anodic in the area where the potential is less positive and cathodic where it is more positive. Long cell action was found to alleviate or aggravate corrosion caused by local cells depending on their location. Corrosion activities are aggravated in the anodic area of the long cell whereas those in the cathodic area are alleviated. [13].

In 1963, E. Schaschl and G.A. Marsh presented a comprehensive view of long cell action arising from differential aeration [14]. In their view, oxygen plays the dominant role as a cathodic reactant as illustrated in Figure 1. Isolated steel corroded through local cell action in a well aerated soil of low resistivity for example, is a potential cathode for long cell action. Should this steel be connected to steel in a poorly aerated soil, long cell action will occur with the anodic steel supplying electrons to the cathodic steel. With long cell action, water on the surface of the cathode becomes alkaline whereas that on the anode turns acidic with the suppression of the molecular hydrogen generation reaction \(2H^+ + 2e^- \rightarrow H_2\) between hydrogen ions, where electrons are supplied from corrosion activities at the anodic sites. The findings of E. Schaschl and G.A. Marsh provided the foundation for cathodic protection against soil corrosion and can be considered a well-established mechanism. Figure 1, as well as the short explanation provided in the caption illustrates this corrosion process.
Fig. 1: Illustration of Soil Corrosion with Long Cell Action
Note: Soil corrosion with long cell action has the following characteristics: (1) the electrochemical potential difference is induced by the availability of oxygen in relatively pure water; (2) local cell corrosion activity is suppressed at the cathodic area, whereas local cell anodic corrosion activity is accelerated; (3) electrons are easily transported long distances, whereas ferric ions are not transported to the cathode but removed locally by cementing with the soil; (4) a counter cell reaction occurs at the cathode, which neutralize the excess electrons by reducing oxygen into water; A closed electrical circuit is thus formed between the two physically separated electrodes; and (5) The anodic corrosion activities are intensified when there is a large cathode to anode surface area ratio.

5. ELECTROCHEMICAL CORROSION BY DEPOLARIZATION

Almost independent of this development in soil corrosion theories from American scientists, a Russian scientist G.V. Akimov made an in-depth study of the cathodic reactions and published a compendium of the processes for electrochemical corrosion. R. Pope’s assumptions regarding the equalization of anodic and cathodic potentials by the long structure is included in G.V. Akimov’s depolarization theory published in 1945 [15]. This article provides a theoretical basis for long cell action corrosion in a more comprehensive manner. Akimov visualized that the deviation of the potential from its equilibrium value (e.g. the over-voltage) is some measure of corrosion rate, indicating that some process at the electrode is in a non-steady state of electrochemical reaction. If the functional dependence between the rate of process and the over-voltage is known then the rate of process at the electrode can be determined from the value of the over-voltage because the rate of process is proportional to the current through the electrode. Since the original paper is very comprehensive, only those discussions directly relevant to the long cell action corrosion hypothesis have been extracted below. In the following explanation, the hydrogen depolarization at the cathode is closely related with most of the steam generator corrosion issues and FAC (E-C) in the secondary cooling systems of PWR/VVER, whereas the oxygen depolarization at the cathode is closely related with SCC in BWR/RBMK.

(1) Corrosion by hydrogen depolarization

Akimov tried to correlate the over-voltage to the Nernst equation. For a hydrogen over-voltage,

$$\eta = E_K - E^o_K = \frac{RT}{F} \ln \frac{C_{H^+}(cathode)}{C_{H^+}(solution)}$$  \hspace{1cm} (1)

where $\eta$ is the hydrogen over-voltage at the cathode, $E_K$ is the potential of the polarized cathode, $E^o_K$ is the equilibrium hydrogen potential at the cathode, $R$ is the gas constant, $T$ is the absolute temperature, $F$ is the Faraday constant and finally, $C_{H^+}(cathode)$ and $C_{H^+}(liquid)$ are the hydrogen ion concentration at the cathode and in the liquid. He estimated that the current through the cathode $I_K$ by applying a diffusion coefficient for hydrogen. In analyzing the behavior of a cell with hydrogen depolarization, he discussed the influence of changes in electrical resistance on the current and therefore, on the rate of corrosion. He observed that, when the area of the electrolyte is 15 times larger than that of electrode, the resistance-distance curve is essentially flat, deviating from Ohm’s law.

(2) Corrosion by oxygen depolarization

In a similar approach, Akimov discusses the electrochemical cell with oxygen depolarization theory, which includes important processes such as corrosion...
of iron in neutral solutions, often encountered in practical engineering fields. An over-voltage is connected with the corrosion process similar to a hydrogen discharge at the cathode. If in the chain of interconnected processes, the oxygen supply to the cathode is the slowest process then the total rate of corrosion is determined essentially by its slowest link. Thus, the rate of oxygen supply to the cathode through the solution limits the total rate of corrosion.

Experiments with models indicate that the large increase of the anodic area does not affect the total corrosion current, which demonstrates the result of an insufficient oxygen supply at the cathode. The situation is different when the cathodic area is increased. In this case the amount of oxygen arriving at the cathode per time unit is proportionally increased; therefore there would be an increase of current when the cathodic area is increased. Experiments confirm this expectation, showing that the current increases roughly in a linear fashion with the cathodic area.

Concerning the influence of the cathodic material on the current in the cell, the following can be said. When there is a deficiency in oxygen in the solution and the oxygen supply to the cathode is the limiting factor, the cathodic material should not affect the current of the corrosion cell, and therefore the total rate of the corrosion process.

Akimov also discusses the formation of a differential aeration cell in an iron pipe laid in the ground with sections exposed to different levels of permeability to the air, which was later proposed by Evans [13]. If a pipe is laid partly in an easily aerated soil, and partly in non-porous soil such as clay, a differential aeration cell is created; thereby the pipe placed in the clay soil will be attacked. The pipe located in the sand will suffer very little corrosion. This observation is identical with the soil corrosion theory developed by the American scientists E. Schaschl and G.A. Marsh [14].

6. MECHANISM OF POTENTIAL DIFFERENCES IN WATER

The long cell action, such as established in the soil corrosion theory, occurs when there is a potential difference between an anodic site and a cathodic site. One of the important features of the electrified interface between the electrode and the electrolyte is the appearance of a potential difference in the system where the corrosion is taking place. Various mechanisms exist (i.e., electrochemical cell configurations) that induce such potential differences, including ionic concentration, aeration, temperature, flow velocity, radiation and corrosion potentials.

Most of these phenomena have been established by electrochemistry and are well documented in the Pourbaix diagram [16], which graphically expresses the thermodynamic relationships of metal/water systems and demonstrates at a glance the regions of the thermodynamic stability of various phases that can exist in the system. Since the original E-pH diagram was developed at ambient temperature, it was necessary to develop corresponding diagrams at temperatures and pressures relevant to nuclear power applications. This has been attempted by EPRI in 1982 [17, 18] as well as a few other scientists. This author’s study uses some of the high-temperature chemical thermodynamics data from the EPRI reports, as well as those from Barner and Scheuerman [19]. A detailed analysis has already been reported in previous papers by the author and will not be repeated here [2, 4]. In this paper, only the results related to cathodic depolarization processes due to oxygen and hydrogen are shown in Figures 2 and 3.

The potentials corresponding to the differential concentration of dissolved hydrogen (line a) and oxygen (line b) can be determined starting with the Nernst equation for the activities expressed in the dissolved molecular concentrations, \([\text{H}_2]\) and \([\text{O}_2]\) (expressed in g-mol/kg of water) as well as the high temperature thermodynamics data taken from references [18, 19]. At 300 °C, the equilibrium potentials \(E_0\) are:

\[
E_0 = -0.15 - 0.114pH - 0.57\log[\text{H}_2] \quad \text{for H}_2 \quad \text{………(2)}
\]

and

\[
E_0 = 1.08 - 0.114pH - 0.028\log[\text{O}_2] \quad \text{for O}_2 \quad \text{………(3)}
\]

These lines are illustrated in Figure 2 with a set of parallel lines as parameters of concentrations. As a rule of thumb, one order of increase in hydrogen/oxygen concentration will result in a potential shift of -0.057/+0.028 volts, for the case when either \(\text{H}_2\) or \(\text{O}_2\) is respectively dominant in the water at a temperature of 300 °C.
7. ASSESSMENT OF CORROSION ISSUES IN NPPS

In the author’s previous paper [3, 5-7], an assessment has been made and reported to clarify potential corrosion mechanisms for typical corrosion-related issues commonly observed (e.g., FAC (EC), SCC and AOA). In this paper, the author further deployed this assessment to other key corrosion issues, e.g. steam generator and turbine corrosion issues, while briefly summarizing previous discussions for completeness.

7.1 Inter-Granular Stress Corrosion Cracking [6, 7]

Inter-granular stress corrosion cracking (IGSCC) is still frequently reported in Western-type boiling water reactors (BWR), specifically in the recirculation piping, reactor shrouds, etc. [6, 7]. Similarly, severe IGSCC has also been reported in some of the RBMK plants. For this reason in 1999 the IAEA launched a special program, i.e., IAEA-SPB-IGSCC, to better understand the mechanism and find mitigation measures [20].

In a review of the recent stress corrosion cracking (SCC) findings in Japanese BWRs and Russian RBMKs, the author searched for possible mechanisms that may have been overlooked, judged insignificant or dismissed during the early stages of investigation when the current focus of SCC work was first developed. The pivotal mechanism identified was ‘long cell action.’

By extending the SCC theory developed by Evans and Uhlig [21, 22], the author proposes a hypothetical mechanism that states; ‘radiation-induced ‘long cell action’ causes electrolytic corrosion.’ This mechanism has been explained in detail in previous papers by the author [6, 7]. The ‘long cell action’ enhances ‘autocatalytic growth of cracks in crevice water chemistry’ by keeping it acidic and preventing the neutralization of hydrogen ions into molecular hydrogen within the crevice. This hypothetical mechanism does not appear to have ever been
investigated by the nuclear community to the extent surveyed by the author. The ‘long cell action’ corrosion mechanism leads us to visualize that the SCC in the reactor environment is similar to a radiation-induced stray current corrosion phenomenon.

In addition to the theory by Evans and Uhlig, T. P. Hoar presented evidence that ‘stress-corrosion cracking’ is not a rupture of brittle material but rather cracks that propagate from a rapid dissolution of their mechanically yielding advancing edges. It is an exceptionally deep and narrow fissure, while the static sides dissolve extremely slowly. Either of the mechno-chemical mechanism or film-rupture at the crack tip mechanisms requires not brittle, but ductile metal at the advancing edge of a crack to propagate. Hoar pointed out the equally critical importance of the chemical nature of the environment. This must be such that static metal dissolves very slowly, either because it becomes passivated or has an inherently very slow rate of active dissolution at the anode potential that operates, whereas yielding metal dissolves very rapidly, either by rupture of a passive film at the crack tip or by the mechno-chemical effect. In fact, stress-corrosion cracking can occur only when both the metal has very particular properties and the solution a very specific composition. Further, the metal/solution interface must operate in particular properties and a solution with a very particular composition [23]. However, Hoar’s mechno-chemical effect should be revised to reflect our recent experience with IGSCC in BWR shrouds where the cracks are propagating far beyond the surface region of high residual stress into the region of essentially zero stress [6, 7]. The author believes that by applying an external potential due to the long cell action, the system is no longer in a state of equilibrium resulting in a rapid dissolution at the crack tip.

7.2 Flow Accelerated Corrosion and Erosion-Corrosion [3]

FAC (E-C) phenomena are often observed in both nuclear and fossil power plants. Such phenomena are often experienced in high speed, two-phase steam-water flow lines constructed with carbon steel in both BWR and PWR power plants. For PWRs, thinning due to FAC (E-C) occurred in some plants in the latter half of the 1970s and investigations were carried out on pipe thinning. After that, pipe rupture accidents occurred in the secondary cooling systems in both the US and Japan, for instance a secondary pipe rupture of an 18-inch diameter elbow occurred in the feedwater pipe leading to the main feed pump “A” of Virginia Power Surry Unit #2 in the US in 1986.

In 2004, a terrible accident occurred at the Mihama Power Station Unit 3 in Japan. As workers in the turbine building were preparing for maintenance for the scheduled shutdown a pipe ruptured and high-temperature secondary cooling water flushed out. The accident resulted in a serious consequence that was unprecedented at a nuclear power plant as five people were killed and six were injured [24].

Since the author has recently presented a paper on the FAC (E-C) issue at the Ninth Conference in St. Petersburg [3], only some of the essential points are included here for completeness. The relative movement between the corrosive fluid and the metal surface essentially causes a removal - erosion - of the protective surface (oxide) layer (i.e., passive film). This removal of the protective surface layer is followed by a complete (though somewhat localized) depassivation. After this removal the bare metal is exposed to the corrosive fluid which will cause a rapid attack.

In this regard, as early as in 1949 the Italian scientist G. Petracchi demonstrated that electrochemical effects significantly influence erosion rates [25]. He investigated whether a primary influence of corrosion from ‘cavitation’ could be attributed to anodic reaction currents either from external (e.g., stray currents or galvanic couplings) or internal causes, including the development of micro-pits originating from localized mechanical stress. (Although Petracchi used the word ‘cavitation,’ his experiment was a FAC (E-C) test.) He constructed a flow nozzle with two specimens kept under external electrical potential. Upon inducing as low as 0.1 mA/cm² of positive current, the erosion rates reported were drastically increased. In fact, this was the estimated current level in the recent Mihama Unit 3 pipe rupture accident. This phenomenon is consistent with Akimov’s theory of cathodic depolarization due to hydrogen. These electrochemical factors appear to have been overlooked in FAC (E-C) studies performed to date.

7.3 AOA (PWR) and CDA (VVER) [5]
Axial Offset Anomaly (AOA) is a phenomenon where corrosion products (CRUD) as thick as 100 microns co-deposit or absorb boron in the corrosion products on the upper half of fuel rods, causing the power distribution (axial offset) to be skewed. So far, AOA has reportedly affected 16 U.S. PWRs during 30 operating cycles. AOA eroded the shutdown margins at one plant to the extent that it forced the unit to operate at reduced power for the final 6 months of the operating cycle.

Several VVER plants have also experienced similar anomalous crud deposition (CDA) phenomena, including a coolant channel blockage accident which was the worst case scenario for at least two plants. In CDA, the deposited corrosion products are mostly magnetite, coming from the stainless steel steam generator tubes with no indication of boron deposition, nor with sub-cooled boiling.

Corrosion products that deposit in cores with appreciable AOA are almost entirely nickel-based (as NiO or elemental nickel) as opposed to nickel ferrite deposits common to non-boiling cores. Significant quantities of meta-ZrO₂ and nickel iron oxyborates (bonaccordite), notably Ni₃FeBO₅ have also been found in deposits on cores with AOA. Characteristics of fuel deposits from an AOA core were discovered at the AECL Chalk River Laboratories by examining deposit samples taken from the Callaway Cycle 9 fuel. The cross-sectional X-ray analysis of a typical 100 micron thick flake disclosed a peculiar layered structure, starting first with a bonaccordite rich layer near the crud surface of approximately 30 microns, which is covered with a zirconium rich layer as thick as 30 microns, overlaid by a NiO rich layer up the outer surface [26]. These layered structures may suggest a change in the electrochemical configuration and/or ion concentration in the primary water. Since a considerable weight fraction of long slender needles of the boron-rich nickel-bonaccordite were observed in the Cycle 9 fuel deposit sample, these needles are obviously growing as boron-bearing mineral crystals on top of the clad from the ions in the cooling water. On the basis of these general characteristics, the author has constructed a potential-pH diagram relevant to Ni₃FeB(OH)₁₀, which is a hydrated state of FeNi₂(BO₃)O₂ [3]. This confirms that AOA results from cathodic reaction activities.

The concentration of both nickel and iron ions and particulates must have been unusually high during the AOA cycle for deposition of a significant amount of crud and Bonaccordite. The author believes that such an acceleration of anodic dissolution of metal cations is due to the effect of the long cell action corrosion mechanism. Similar phenomena are also taking place in the erosion-corrosion processes as discussed in a previous section. The author suspects that the initial local depassivation is somehow related with organic leakage from the ion exchange resin or decontamination activities with insufficient repassivation.

Without taking into account the electrochemical configuration, it is not surprising to see some pure 'thermo-mechanical' experiments being unsuccessful in reproducing the AOA phenomena in laboratories. For example, one of the most important experiments on the root cause of AOA, carried out since 2001 as part of the EPRI RFP (Robust Fuel Program), failed in two fundamental ways [27]:

• They have not been capable of producing laboratory precipitation of the "typical" deposits observed in plants with AOA (achieving neither the quantity nor similar characteristics), and;
• In experiments with existent deposited crud (thick and porous), they have not been capable of precipitating the boron compounds.

7.4 PWSCC [4]

Control rod drive mechanism nozzles and other vessel head penetration nozzles welded to the upper reactor vessel head are subject to another phenomenon - primary water stress corrosion cracking (PWSCC). The issue is a potential safety concern since a nozzle with sufficient cracking could break off during operation. This would adversely affect the integrity of the reactor coolant system pressure boundary. The break may also result in the ejection of a control rod, which could cause a combined depressurization and reactivity accident, not to mention a potential threat to the containment integrity. Recently, the issues highlighted the importance of PWSCC associated with the extensive degradation of the pressure boundary material. This was the case for the reactor pressure vessel (RPV) head at the Davis-Besse Nuclear Power Station reactor.
pressure vessel RPV head. The VHP nozzles, which are made from a nickel based alloy, are part of the reactor coolant pressure boundary in PWR plants. The VHP nozzles are highly resistant to general corrosion, but can be susceptible to PWSCC. The discovery of the cavity occurred following a plant shutdown for a refueling outage, during which the licensee was conducting inspections for reactor pressure vessel head penetration (VHP) nozzle cracking due PWSCC. The boron bearing primary water flushes on top of the hot VHP concentrating the boric acid containing the appropriate amount of moisture. The resultant corrosive liquid attacked the low alloy steel vessel head base metal as in the case of molten salt corrosion, making a cavity around the VHP. The licensee discovered a cavity with a surface area of approximately 20-30 square inches. Upon further examination, the licensee identified that the cavity extended completely through the 6.63 inch thick carbon steel RPV head down to a thin internal liner of stainless steel cladding.

The PWSCC is also known to occur on the lower head penetrations, which is more troublesome due the difficulties of replacing or repairing it. In 2003, the licensee for South Texas Project Unit 1 (STP 1) discovered small boron deposits around two of the unit’s bottom mounted instrumentation penetration nozzles during a bare metal visual examination of the reactor pressure vessel (RPV) bottom head. Subsequent nondestructive examination of all 58 nozzles at the South Texas nuclear power plant confirmed the existence of leaking and axially-oriented flaws in the two nozzles [28].

The author thinks that the long cell action corrosion process is taking an important role in the PWSCC process due to a potential difference. Although the potentials of the water out of the flux zone are determined by the dissolved hydrogen concentration, the potential in the flux region (e.g., in the core region) is reported to be approximately 0.4 V higher than that on the outside, according to a recent in-pile loop experiment and model calculations for radiolysis of PWR primary coolant\(^2\) [29]. This means that the cathodic reactions are enhanced in the flux region, which therefore means that it is surrounded by anodic zones outside the core region. The anodic reactions, such as the dissolution of metals or stress corrosion cracking are enhanced out of the core region. Electrons released by anodic activities are transported to the core region and neutralized there. The metallic ions are transported through the circulation of water to deposit as crud mostly on the fuel surface or removed from the stream through its water purification system. Such anodic activity often occurs first in the stagnant region of the primary water system as observed in SCC in BWR [5].

It is important to note that PWSCC per se does not seem to be occurring in VVER plants. There has been no tube failures detected in VVER SGs due to corrosion attack on the primary side during 40 years of VVER plants operation [30]. The corrosion cracks in the steam generator tubes are reported to always be initiated from the secondary side in VVERs, whereas both PWSCC as well as secondary side (or outer-diameter) corrosion cracking (ODSCC) are reported in PWRs. This issue will be discussed in the next section of this paper. It is not known why this mode of corrosion cracking has not been observed in VVER plants, with its unique potassium hydroxide and ammonia/hydrazine water chemistry.

Since the surface area ratio of the long cell anode (primary side of steam generator) and cathode (reactor fuels) is not much different, therefore if we extend the Akimov’s cathodic depolarization theory there can possibly be a mitigation of the cathodic depolarization process due to water radiolysis. As a matter of fact, some findings from the primary water chemistry and component design at modern VVER plants were taken into account for the EPR design [31-33]. The composition of chemical species in the water radiolysis process is well known to drastically change by adding appropriate scavengers into the water. Substances that have been used as positive ion scavengers include those that accept a proton from the primary radical to form a stable ion, for example, ammonia, amines, water, alcohols and others that possess a low ionization potential [34]. The idea of mitigation of the corrosive environment of primary water by adding a small amount alcohol into the coolant of boiling water reactor
7.5 Steam Generator Corrosion Issues

Steam generator corrosion is undoubtedly the field that has the largest amount of resources dedicated to its operational amelioration, maintenance and replacement, as well research and development efforts have been going on throughout the world. This industry effort has enabled the existence of a vast amount of references, perhaps as many as several hundreds. Due to the concerns in relation to a potential tube failure for mainly safety reasons as well as economic issues, good review papers have been published in the recent years [36-38].

However, in spite of industry’s effort over the past 40 years, the exact mechanisms that are responsible for steam generator corrosion issues ‘remain elusive’ [36]. Although substantial mitigation has been achieved by improving tubing alloys, water chemistry and designs, this category of corrosion issue is far from under control. According to R. Staehle “there is ample precedent for aggressive corrosion to arise after some delay, as with the delay of the onset of the low potential SCC in Alloy 600 in operating SGs” [37]. Similarly in Russia with their unique experience of horizontal steam generators with stainless steel tubes, it is well recognized that their actual service life is determined by their tubes’ ability to withstand corrosion [38].

With diverse manufacturers, materials and operational histories, the actual corrosion phenomenon is indeed very complicated in its manifestation. Some of the differences are in basic design configuration (e.g. U-tube/recycling type, once through type and horizontal type), tube materials (Alloy 600, 690, 800 and 08X1810Ti) under different heat treatment, tube support type design (drilled hole, quatrefoil, egg crate and trefoil), tube expansion geometries (e.g. part-depth expansion, full-depth expansion and fully expanded with top ‘kiss’ roll), tube support material (carbon steel and stainless steel), primary water chemistry (hydrogen doped with lithium in the Western countries and ammonia doped with hydrazine in Eastern countries), secondary water treatment (initially phosphates, later changed to AVT and w/o boric acid additions), addition of corrosion inhibitors, condenser tube materials (copper alloys and titanium), ingress of Pb contaminant in some cases and leakage of salty water due to condenser leakage. In particular, earlier troublesome operation with additions of phosphates introduced complex deposit on ‘heat transfer crevices’ condensing aggressive chemicals, such as chloride and SO₄, making it difficult to isolate the effect of particular amelioration from the after effects (e.g., so-called hideout return) of previous history of operational water chemistry.

Since failures in steam generators have been extensive, numerous descriptions about various arrays of failures have been published. There are many modes of corrosion and failures at various locations and each combination of failure mode and its location is called “mode-location case.” To date there have been a total of 25 different combinations experienced mainly in the U-tube/re-circulating steam generators [38]. S. Majumdar has summarized that most of the cracking currently suffered by Alloy 600 tubes of PWR steam generators is intergranular and that three main types of intergranular attacks have been identified. Intergranular stress corrosion cracking/PWSCC occurs in the primary side mainly in the roll transition zones of the expanded tubes. On the secondary side, IGSCC known as outer-diameter SCC (ODSCC) occurs typically in the crevices at the junctions of tubes with tube supports and tube support plates and under sludge piles. The inter-granular attack (IGA) has been observed under sludge piles as well as at the tube to TSP junctions. Outer-diameter-initiated cracking also occurs from scratches or abrasion in free spans.

From the point of view of the long cell action hypothesis, these complex issues can be greatly simplified and classified into 6 essential modes correlated with a different manifestation of this corrosion process: (1) PWSCC occurring at the high residual stress areas, especially tube expansion and tight U-bend; (2) pitting, ding, IGA and ODSCC occurring under sludge piles or heat transfer crevices filled with sludge located at tube and tube support crevices; (3) pressure buildup due to expanding corrosion products, inducing denting, ODSCC; (4) Free-span ODSCC; (5) Secondary side wastage -general erosion-corrosion; and (6) Corrosion fatigue at wide and loose U-bend.
In horizontal steam generators of Russian design, different morphologies are reported [38]. The corrosion cracks in this type of SGs are initiated on the secondary side. Cracks are induced both on free spans, and in slot-hole crevices under tube spacers. In the U-tube/recirculating SGs with reactors such as the PWR, the majority of corrosion defects in tubes occur at the location of sludge buildup near where the slots connecting the tube with the tube sheets. In the horizontal type SGs, defects are distributed more uniformly. At the same time in both types of SGs, there are some defects that are basically concentrated on plugged tubes while the other defects which are mainly located under the spacer grids. The morphologies observed in the horizontal steam generators are summarized as below [38].

(i) The defects in the free span of empty tubes (i.e. between the spacer grids) are most frequently located at the bottom part of SG tube bundles next to the "hot" collector.

(ii) Defects under the spacer grids are located in the bottom parts of tube bundles, but are distributed more evenly along their length.

(iii) General wall-thinning of the middle and top part of tubes is observed only as general corrosion, and at the particular level of the two-phase steam-water mixture in the SG.

In the long cell action corrosion mechanism, anodic local cell action corrosion activities are enhanced. This acceleration of corrosion is caused by the effect of long cells that are induced by the cathodic depolarization effect of dissolved hydrogen or oxygen, according to the theory by Akimov [15]. In the steam generator corrosion issues, the radiation-induced depolarization plays the key role on the primary side and the depolarization due to hydrogen, on the secondary side. In the primary cooling system, the reactor core appears to be taking on the role of a cathode with a large surface area of the fuels under the effect of water radiolysis. On the other hand, steam generators should be anodic, especially on the hot side, due to lower potential with higher temperature as illustrated in Figure 3. [4]. This generally explains the PWSHDE phenomena as listed in Point (1) above. On the secondary side, the steam generator should be anodic especially in the hot section, whereas condensers and some of the low-pressure heat exchangers must be cathodic due to their lower temperature. This is not contradictory to the various corrosion activities on the secondary side of the steam generators. This generally explains points (4), (5), (6) and (iii).

In addition, the cathodic depolarization due to dissolved hydrogen can occur on a smaller scale or more locally. The deposition of dense sludge induces a decrease in dissolved hydrogen concentration, resulting in a local potential difference as illustrated in Figure 2. Also deep inside the crevice, the hydrogen concentration is reduced due to the crevice chemistry. The local anodic corrosion activities under the sludge or deep inside the crevices are enhanced, with the removal of excess electrons from the anode which are consumed by the cathodic reactions. The reactions include reduction of hydrogen ions by $2e^- + 2H^+ \rightarrow H_2$ and local deposition of metallic ions near the crevices to further impede the diffusion of hydrogen to the anode. If the tube support material was carbon steel, the resultant corrosion products expand in volume. This generally explains points (2), (3) and (ii). The anodic corrosion activities are well known to be aggravated with chemical impurities such as chloride and sulfate ions, which are often found condensed in the sludge deposited on the heat transfer crevices.

For the local anodic corrosion activities under the sludge to occur, the deposit should be non-permeable to water. As a matter of fact, the analysis of morphology and compositions of deposits generally have three layers of deposits inside heat-transfer crevices. The inside layer seems to contain metallic species or their oxides of impurities and alloying elements. The second layer in some cases composed of silica gels. The outside layers tend to contain various compounds of metals that seem to have crystallized from ions in solutions. The occurrence of SCC is indeed related to the formation of almino-silicate compounds. Little or no SCC occurs where the alumino-silicates are absent [37]. It appears that the second layer is non-permeable to water. The permeability determines the extent of long cell action corrosion. This phenomenon is similar to the case of soil corrosion (called 'cementing'), although it is due to the permeation of dissolved oxygen. The soil corrosion by long cell action occurs even without ions being transported to the cathodic sites. Ferrous ions on the surface of the soil grains of low permeability are quickly converted to hydrous...
ferric oxide, which cements the soil grains at the surface of the metal, therefore further restricting the diffusion of oxygen through the soil grains. The anodic area under the soil develops more intensely with time as the cementing process continues. In the soil corrosion anodic corrosion activities are enhanced in clay soil when the cathodic portion are in the permeable soil like sand in the long cell action corrosion mechanism [14, 15]. How this phenomenon is related with the corrosion under the sludge in the steam generator is not known.

Some remarks are necessary to be made about the observation that there are some defects that are basically concentrated on plugged tubes. In the empty tube, the wall temperature should be lower without having primary flow. This should make such a tube cathodic and there must be an accelerated build up of deposits of metallic ions with hydroxyl ions. When the thickness of the deposits increases, the metallic surface seems to become anodic through the depletion of hydrogen. Further studies are required although this process seems to be consistent with the observations that severe corrosion damage always occurs in the case of violation of Russian requirement which specifies decontamination before the thickness of deposits exceed a recommended level [38].

Since the long cell action hypothesis does not seem to contradict the various corrosion activities inside the steam generators, the author invites further study on the potential involvement of this mechanism, although he intends to investigate this in more detail in the near future.

7.6 Corrosion Issues in Turbines

Since there is no direct water flow to the turbine from the nuclear steam supply system (NSSS) and efficient moisture separators are always installed, it is likely that only a small fraction of the metallic ions and suspended particulate corrosion products in the cooling water are carried over to the turbine. Therefore, the intuitive assessment of the long cell action corrosion mechanism was that its effect does not influence the turbine. However, a closed circuit configuration can be established by consuming the excess electrons generated at the anodic corrosion sites in the NSSS, which can be consumed by the counter-cell cathodic action. This involves the turbine with its large surface area and with decreasing steam temperature towards the low pressure stages, resulting in higher potentials as sown in Figure 3. The dissolved hydrogen and its ions (in case of PWR/VVER) or oxygen and its hydroxyl ions can be easily carried over to the turbine. Sometimes deposits of magnetite or hematite are observed on top of the turbine blades even with very strict water chemistry control. In addition to this global potential difference, there are cases of local closed circuit configuration involving individual turbine blades.

The corrosion related degradation in steam turbines occurs both on the turbine blades as well as on the turbine rotors [39-41]. In this regards, a careful assessment is necessary in the fitting mechanism between blades and rotors of the last several stages of low pressure turbine blades where the centrifugal force will be large with long wings. Combined with the corrosive environment and high stress, SCC and fatigue corrosion cracking are often observed both on the female side (usually in the turbine rotor) as well as on the male counterpart on the root of blades. In addition, corrosion related degradation by corrosion fatigue of the blades occurs often in the last few stages where a dry to wet transition precipitates water droplets from the supersaturated steam.

The author would like to introduce a remarkable experimental demonstration of a decrease in high cycle fatigue strength, as observed in a rotational fatigue test while applying positive current to the specimen. As early as in 1949, an Italian scientist G. Petracchi demonstrated that electrochemical effects significantly influence the fatigue strength in sea water. He used a rotary bending machine with a cantilever test piece. Using samples of gunmetal he found a decisive destructive effect with an anodic corrosion environment. When the polarity was reversed, the fatigue strength was restored to the test results in the air [25]. Similar phenomena are very likely taking place in various fatigue processes of steam turbines under the potential induced by the long cell action.

CONCLUSIONS

Although well established in conventional corrosion science, potential involvement of long cell action mechanism in the unresolved corrosion issues
does not appear to have ever been investigated by the nuclear community to date, based on the author’s examination of the available information on the topic. The long cell action is known to suppress local cell anodic corrosion activities at the long cell cathode while increasing the local cell anodic corrosion processes. In particular, the anodic corrosion activities can be significantly aggravated when the long cell cathodic reaction occurs at a component with a large surface area (e.g., heat exchangers and reactor cores). The long cell cathodic reaction seems to be rate limiting for the anodic corrosion activities in the nuclear reactor environment, using high purity and low conductivity water as a coolant. The author invites independent study and verification tests, since introduction of this hypothesis provides new insight into many of the unresolved corrosion issues as explained in this paper.

In view of this significance, the author proposed an urgent international joint initiative to prove or disprove this mechanism’s existence in nuclear power systems. Once this mechanism is confirmed, there are a variety of ‘engineering’ counter measures to mitigate the problem including, application of electrical insulation between fuel assemblies and reactor core support plate, as well as between tube bundles and cells of heat exchangers, although this requires the development of a new culture for structural integrity. Nonetheless, the author strongly insists that scientific verification experiments be performed first before discussing mitigation measures since so many hypotheses for immediate engineering amelioration without going into the science behind have been proposed in the past often resulting in misleading the nuclear industry.

**ACKNOWLEDGEMENTS**

This is a companion paper of the author’s study on component degradation of aged plants also presented at this conference [42]. A portion of this work has been performed when the author was a Technical Counselor of Nuclear Safety Commission (NSC) of Japan; however the views described here represent those of author and do not in any way represent those of the NSC. At this stage of the investigation, this study is the result of the author’s private initiative and has not been authorized, nor supported by official research funding.

The author is looking for lead institutions somewhere in the world that can further investigate the proposed mechanism.

This paper is written by compiling a series of lectures given last year at the Ninth Conference by ‘Prometey’ in St. Petersburg, at VNIIAES in Moscow, University of Florida, Texas A. M. University and at the ICONE-14 also in Florida, while adding the author’s responses to some of the questions received during his visits to these institutions. In particular, the assessment of steam generator corrosion issues has been added in view of strong interest expressed both in Russia and the United States.

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