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Review of License Renewal Application for Vermont Yankee Nuclear Power Station: Program for Management of Flow-Accelerated Corrosion

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U.S. NUCLEAR REGULATORY COMMISSION
In the Matter of Entergy Nuclear Vermont Yankee LLC
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I. Background

Flow Accelerated Corrosion (FAC) is a physical phenomenon in which metal dissolution is accelerated by fluid flow. In the present definition of FAC, no distinction is made between the processes where corrosion is governed by electrochemical reactions, and those involving abrasion of a protective oxide layer either by droplet impingement or shear forces.

Flow Accelerated Corrosion (FAC) is both a safety and a financial concern. Pipe ruptures from FAC resulted in casualties at the Surry nuclear plant in Virginia and at the Mihama nuclear plant in Japan. Leaks and severe wall thinning resulting in plant shutdowns and expensive repairs have also occurred. Following the pipe rupture at Surry in 1986, EPRI sponsored the development of a computer code called CHECWORKS to predict FAC in power plants. Vermont Yankee proposed in its LRA to rely on CHECWORKS as the main management tool to control FAC during the life extension period.[1]

An effective aging management plan for FAC would predict: (a) which components should be inspected, (b) what should be the scope of the inspection, (c) what should be the frequency of inspection and (d) what criteria should be used to decide whether a component should be replaced or allowed to remain in service. The following discussion measures the ability of CHECWORKS to define the above actions against its consistency with commonly accepted FAC theories, its ability to predict FAC in nuclear power plants, and Entergy's rationale for using CHECWORKS at the VY plant.

A. Historical Background

FAC (more commonly and more appropriately called erosion-corrosion) has been known for more than 100 years. FAC occurs in oil and water pipelines, refineries (Catalytic converters), offshore oil platforms (Christmas tree areas), and power plants. A combination of empiricism, on-line monitoring, inspection and component replacement are commonly employed to control FAC. For example, Sentry holes on the outer diameter of elbows were used for years as indicators of potential pipe ruptures. Coupons placed in flowing fluids are widely used to measure corrosion potential. Robots (Smart Pigs) are used to survey the inner surfaces of pipelines. Submersibles are used to visually inspect underwater pipelines and structures.

The nuclear industry adopted a different approach to managing FAC. Nuclear power plants rely primarily on in-service inspections during refueling outages. In April 1985, EPRI issued inspection guidelines for Erosion/Corrosion in nuclear power plants (EPRI NP-3944s). EPRI also initiated a program to develop a computer code to predict FAC rates.

On December 9, 1986, an 18-inch pipe elbow ruptured on the condensate feedwater system at the Surry nuclear plant in Virginia and caused several fatalities. The

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[1] License Renewal Application Table 3.4.1 ¶ 3.4.1-29, and Appendix B § B.1.13; FSER, NRC Staff Exhibit 1 at § 3.0.3.1.2.

rupture was caused by localized wall thinning at the pipe-to-elbow weld. Following this accident, the Government Accounting Office, GAO, at the request of Rep. E. J. Markey, identified 34 out of 109 plants as having some form of FAC damage. Reference 17. The oldest plant among the 34 plants was San Onofre Unit 1, which started operation in 1968. At the time of the accident, the Surry plant had operated for about 14 years. The NRC stated that the Surry pipe rupture and the wall thinning discoveries were "unexpected," Reference 17, and, in the wake of these incidents, limited its activities to issuing Information Notices on FAC events. References 10-15.

Prior to 1986, most of the FAC studies, both analytical and experimental, were conducted in the UK, France and Germany, and a small study was conducted at MIT. The nuclear industry trade organization, NUMARC, briefed the NRC about the "CHEC" code in May 1987, and released the code to the industry in July 1987. This was followed by a release of different versions of the code (CHECMATE April 1989, CHECWORKS August 1994).

Numerous wall thinning incidents have occurred following the release of the above codes. The continuing failure of these codes to predict pipe wall thinning has been blamed on factors such as operator error, unfamiliarity of users with plant operating conditions, exclusion of components from inspections, incorrect modeling, lack of visual inspections and lack of base line measurements. Apparently it has not occurred to either EPRI or the NRC that the code methodology itself could be flawed. I am not aware of any documentation to indicate that CHECWORKS and its predecessors have been assessed independently to ensure that CHECWORKS predictions are reliable and technically sound. Without providing any proof, the developers of CHEC stated at the American Power Conference in 1988 that the CHEC correlation of +/- 50% is "better than other known erosion-corrosion correlations." Reference 8.[2]

B. Theoretical Considerations

Any theoretical model that can reliably represent the FAC phenomena must take into account the following field observations: (a) FAC is component- and location-specific, (b) it varies with temperature and velocity, (c) it depends on material composition and oxygen content in the fluid, and (d) component surfaces typically exhibit a combination of holes, ridges and smooth areas. The model in Figure 1 accounts for the above observations; it consist of a metal (iron) which is exposed to flowing liquid containing oxygen. A protective oxide layer (magnetite) separates the bare metal from a liquid boundary layer where a velocity gradient exists. The dissolution of the iron takes place in two steps: (a) the oxidation of the iron at the metal iron interface and (b) the dissolution of the magnetite into the boundary layer. The overall loss of metal or the corrosion rate CR can be expressed by

$$1. \quad CR = C_{eq} / (1/K + 1/h) \qquad \text{For } C_{eq} \gg C_b$$

[2] Exhibit NEC-JH_37.

Ceq is the equilibrium concentration of the soluble iron within the magnetite, Cb is the bulk concentration of iron, K is the reaction rate constant, and h is the mass transfer coefficient of soluble iron across the boundary layer. Ceq depends on the pH or the oxygen concentration and the temperature. K depends on the temperature and h depends on the intensity of the local turbulence.

When the corrosion rate is not controlled by chemical kinetics, i.e. $K >> h$, it becomes solely dependent on turbulence. High turbulence increases the intensity of agitation in the boundary layer thereby accelerating the transfer of the soluble iron to the bulk fluid. Flow velocity, component geometry and surface topography control turbulence intensity. For example, the effect of the local geometry on turbulence can be illustrated by comparing the pressure drop of a flow through a rounded corner nozzle vs. the pressure drop of the flow through a sharp corner nozzle. The pressure drop in the latter case is more than 10 times as large as in the former case. In straight smooth pipes at distances larger than 30 diameters from the entrance, turbulence is fairly steady and is relatively small in comparison to curved pipes and non-streamlined bodies. In a straight pipe, h can be expected to vary with the velocity to the 0.8 power. The problem is more complex when one is interested in predicting the corrosion rate in curved pipes or nozzles.

As shown in Figure 2, the primary flow in curved pipes induces high intensity turbulence because the fluid particles near the pipe axis experience higher centrifugal forces than the slower moving particles near the wall. Reference 1.[3] The process of high velocity particles impacting the wall and slower velocity particles deflecting away from it creates high intensity turbulence due to the mixing between the fast and the slow fluid particles. The net result of such mixing is that the erosion rates vary widely both circumferentially and along the length of the pipe, the pipe radius, and the flow angle. The most severe wall thinning usually occurs on the extrados.

While there has been a very large amount of work on general wall thinning in pipes, elbows, and nozzles, there has been relatively little work on the effects of roughness on the corrosion rate. Understanding of the interaction of the flow with surface roughness is important because it leads to preferential material loss. To some degree, this is beneficial because preferential corrosion would favor a leak before a pipe break. On the other hand, the occurrence of seemingly randomly dispersed surface roughness islands requires considerable care in specifying grid size for FAC inspection and complicates the prediction of corrosion rates. Figure 3 illustrates the effect of roughness on the corrosion rate in flowing liquid; it depicts a small surface area consisting of a surface protrusion and a shallow cavity with a depth H and a width d. Due to the formation of relatively strong turbulence at the downstream side of the protrusion and the interior of the cavity, after some time t_1, the protrusion begins to dissolve and the cavity to deepen. Since it has been shown experimentally that the intensity of the turbulence increases with the depth of the cavity, Reference 1,[4] the rate at which the cavity would penetrate the wall would steadily increase at a faster and faster

[3] Exhibit NEC-JH_30.

[4] Id.

rate. For simplicity, the schematic in Figure 3 depicts a cavity of a constant width d. In actuality, d will vary with time. Since the turbulence intensity depends on H and d, both the local turbulence and the local geometry will also continuously change, causing the surface to assume irregular patterns. The above observations are important in the selection of grid sizes for Ultrasonic Inspection.

Field observations generally confirm the above theoretical concepts. Corrosion rates in straight pipes and 90-degree elbows are on the order of 5-14 and 15-38 mils/year respectively. Wall thinning takes place at the fastest rates at the outer surfaces of elbows. Corroded surfaces exhibit a wide spectrum of surface roughness, valleys, ridges, holes of any shape. Figure 3, for example, shows a photograph of a combination of a smooth surface and a cavity. The main point of these results is that wall thinning does not vary in time in a linear and predictable manner, especially in regions of high turbulence.

When the corrosion rate is controlled solely by the mass transfer coefficient h, it can be shown, Reference 2, that Ceq is proportional to the square of the mass transfer coefficient h^2, and therefore the corrosion rate CR (Eq.1) would depend on h^3. These predictions agree with experimental observations, as shown in Figure 4. Since the mass transfer coefficient varies with the 0.8^{th} power of the velocity for straight pipes and the square of the velocity for curved pipes, the variation of CR with the velocity V can be expressed as:

$$2. \quad CR \ \alpha \ V^n \qquad n = 2.4 \text{ to } 6$$

For a given flow velocity and temperature, CR also varies with the pH and the alloying element, especially Chromium, Figure 5, the temperature, Figure 6, and the oxygen content, Figure 7. The alloying elements inhibit the diffusion of the iron ion in the oxide layer. As shown in Figure 7, relatively high oxygen concentrations inhibit corrosion while low oxygen concentrations accelerate corrosion. Since oxygen enhances the formation of an oxide layer, the rate of oxygen diffusion to the surface may be controlled at a certain temperature on the mass transfer coefficient. In other words, the CR may be controlled by the rate at which oxygen can diffuse from the bulk fluid to the surface of the oxide layer. These observations imply that CR may vary locally not only with turbulence but also with the oxygen concentration in the fluid, which in turn would depend on upstream surfaces if they act as oxygen getters.

The mechanism of FAC in wet steam is somewhat different from the mechanism of corrosion in a single phase fluid. The commonly accepted concept is that FAC is controlled by the mechanical destruction of the oxide layer. In general, it depends on the temperature, the steam quality, the local geometry and the flow velocities.

The importance of the above theoretical discussion is the understanding that the corrosion rate is a system-dependent variable, because parameters such as velocity, geometry, pH, oxygen level, Chromium content, and temperature all may interact with each other. Small changes in velocity, for example, may change the controlling mechanism from mass transfer controlled to chemical kinetic controlled or vice versa. This is qualitatively described by Eq. 1. The practical implication here is that two reactors operating at the same power levels and oxygen levels will not necessarily experience the same component corrosion rate.

C. Corrosion Rate Prediction

The prevention of piping failure from FAC is essentially controlled by two parameters, the local wall thinning rate and overall inspection cost. As long as the local wall thickness exceeds the design thickness, the component can be considered safe. The local thickness is simply the initial wall thickness less the integrated product of the corrosion rate, CR, and the time interval between inspections. The other parameter is cost, which depends on the sample size, geometry, grid size, and accessibility (insulation and location).

The CR at any location can be in general expressed in terms of the variables that were discussed above:

$$3.\quad CR_l = \sum A_k (\, S^G \,)_k \; = A_1\, S_1^{G1} \; + \dots\dots\dots\dots + A_n\, S_n^{Gn}$$

Here A and G are experimental constants and S represents a variable such as velocity, oxygen content, time, material composition, grid size, etc.; k represents any given variable and constant; and n represents the total number of variables. Equation 3 is strictly experimental because it is devoid of any theoretical considerations. With adequate determination of all the empirical constants, Equation 3 can provide a reliable tool for predicting corrosion rates so long as the corrosion rate was measured under similar conditions to those that existed when the empirical constants A and G were determined. Equation 3 becomes unreliable when conditions change from those existing when CR was originally calibrated or benchmarked. There are three basic methods that can be employed to determine the empirical constants A and G: (a) laboratory tests, (b) periodic wall thickness measurements of plant piping, and (c) use of on-line monitoring devices to continuously measure corrosion rates.

Laboratory tests can conveniently be used to determine the empirical constants because the variables can be independently varied and accurately measured. On the other hand, laboratory tests may introduce scaling issues and the test duration is limited.

The relatively large amount of historical data permits each plant to generate correlation for CR for each component over long periods of time. Since the corrosion rate in a plant can vary by an order of magnitude between different components (a straight pipe and a valve for example), and between different component locations, it is apparent that a large number of components would have to be monitored for such calibration. In power plants, FAC monitoring must be conducted by sampling because of the large number of components and wetted surface area with difficult access. The difficulty of selecting a representative sample can be illustrated by the FAC experience with J–tubes in PWRs. In a typical Westinghouse steam generator, a number of J-shaped elbows are mounted on top of the feedring (header) to distribute the feed water. Because of high velocities (30 ft/sec) and poor material selection (A106 Grade steel), these J-tubes experienced severe wall thinning due to FAC. In approximately 1987, I had the opportunity to inspect J-tube degradation due to FAC at the Sequoyah plant in Tennessee. The degree of the damage was highly localized. Some tubes were severely damaged to the point that they were dislodged and fell to the bottom of the steam generator, other tubes exhibited large through-the-wall holes, while others were in almost perfect conditions showing no sign of wear. One could find two adjacent tubes where the velocity through each tube was almost the same, but one tube was severely damaged while the other tube was not affected. Plant data also shows that local corrosion is driven by differences in centrifugal and gravitational forces, as well as upstream disturbances such as welds or fittings. Differences in the heat-affected zone of welds can also result in different FAC.

The above observations point out the difficulties of benchmarking Equation 1 even under ideal conditions where the flow, coolant chemistry and temperatures remain constant. When these parameters deviate from such conditions, Equation 1 becomes unreliable and must be recalibrated.

The use of corrosion coupons together with periodic wall thickness measurements can be effective in benchmarking Equation 1. In this technique, the recalibration time of Equation 1 is reduced each time plant conditions change, compared to plants that do not use online corrosion rate measurements.

II. CHEC/CHECMATE/CHECWORKS Family of Codes

The CHEC/CHECMATE/CHECWORKS ("CCC") codes were developed by EPRI and have been used in many nuclear power plants. By early 1988, a little over a year after the Surry incident, CHEC was in the possession of 51 utilities.

CCCs are proprietary documents and Entergy provided the NEC only the user manual for CHECWORKS. I rely on the following sources regarding the ability of the CCC to manage FAC in nuclear power plants: (a) a paper presented to the American Power Conference in 1988, Reference 8,[5] (b) a number of discussions I have had over the years with plant operators about their experience with CCC, (c) EPRI NSAC-202L-R3,[6] (d) transcript of ACRS Thermal Hydraulic Phenomena Subcommittee (January 26, 2005),[7] (e) Literature references to CCC (Reference 7),[8] and (f) plant experience.[9]

[5] Exhibit NEC-JH_37.

[6] Exhibit NEC-JH_38.

[7] Exhibit NEC-JH_39.

[8] Exhibit NEC-JH_40.

[9] Exhibits NEC-JH_45 - NEC-JH_53.

The CCC codes provide plant operators a framework to rank plant components in accordance with their susceptibility to FAC. None of these codes and specifically CHECWORKS is in fact suitable to meet the requirements of 10 CFR 54.21(a)(3). The regulation requires a demonstration that "the effect of aging will be adequate managed" for each structure and component. This means that a management program must prevent component failure at any time in between service inspections. For this purpose, screening components alone by designating elbows as having higher propensity to FAC than straight sections is not sufficient. Nor is it sufficient to calculate ballpark numbers for the corrosion rate that may occur at a given location.

To maintain component integrity at any time during the extended period, any FAC tool must be able to accurately identify the components that must be inspected and predict where and at what rate FAC will occur. CHECWORKS cannot perform such predictions because the required correct inputs that account for local turbulence are not included in CHECWORKS. F.M. Ferng, Reference 7,[10] was first to observe that average component velocities instead of local velocities were used to benchmark CHEC. [redacted] See also, Reference 8.[12] As already discussed above, it is the local flow velocity that directly controls the local turbulence and not the average velocity.

The importance of local geometry variations (welds, flow angles at pipe entrance) was recognized by CHECWORKS, but the accounting for them is either left to "operator's judgment" or was arbitrarily selected. The selection of the correct grid size for UT measurements is one of the most critical inspection tasks. If the selected grid size is too large, local corrosion in a form of small pockets would escape detection. Such pockets have escaped detection in a plant that used 4x4 inch inspection grid on a 30-inch size component. Reference 16.[13] [redacted] I am aware of no published reports showing that failure probability is a function of component size. I believe that valid criteria for grid size selection must be based on the local turbulence intensity and not a grid matrix of an arbitrary size.

Component selection for inspection is also a very important element of effective FAC management. Proper methodology for component selection should be based on risk significance and component susceptibility to failure. Based on data on the failure of

[10] Exhibit NEC-JH_40.

[11] Exhibit NEC-JH_ 38 at 12-4.

[12] Exhibit NEC-JH_37.

[13] Exhibit NEC-JH_41.

[14] Exhibit NEC-JH_38 at Table 4-1.

similar components, small elbows for example, one can establish a distribution function for through-the-wall penetration time. Weibull or Poisson distributions can be used for this purpose. There is no indication that components to be included in the FAC program are selected on the basis of such criteria; instead, component selection is left to the judgment of plant operators.

Review of VY inspection records indicates that component selection for inspection is based on CHECWORKS rankings, review of FAC data from other plants, an increase in component velocity, and engineering judgment.[15] The Self Assessment Report, dated 10/22/04, indicates that components are not ranked by their risk consequences.[16] Instead they are ranked by their susceptibility to FAC, i.e. a valve is more susceptible to FAC than a straight pipe so it has a higher ranking. Although the FAC program at VY incorporates numerous guidelines regarding the selection of inputs to CHECWORKS,[17] all the inputs are, in essence, based on operator judgment. It is left to plant operators to decide how components should be inspected following changes in plant conditions such as increase in velocity or change in oxygen content.

Neither CHECWORKS nor the VY plant has a scientifically based methodology for the selection of components, grids and frequency of inspections. The only credible test for whether EPRI Guidelines /CHECWORKS can meet the requirements of 10CFR 54.21 (a) is to test EPRI Guidelines/CHECWORKS predictions against plant data.

III. Comparison of CCC Predictions With Plant Data

In early 1988, EPRI presented a paper entitled "Tackling the Single Phase Erosion-Corrosion Issue," Reference 8, showing that their computer code CHEC can correlate plant data wear within +/- 50% over a range of mass flow rates, plant age, oxygen content and pH, temperatures, and plant age between 6.3 and 11.4 years (see figure 8). The empirical equation that was used to correlate the data did not include factors which would account for individual plant time, local turbulence and average flow velocity. Material composition at the point of measurements and initial wall thickness was not known. The above not withstanding, if one uses the wear prediction, Figure 8 (solid line), and an exposure time of 6.3 years, CHEC would predict mean FAC corrosion rate of 0- 145 mils/year, Reference 8.[18] Such corrosion rates are not commonly observed in nuclear power plants.

In my estimation, the actual wear "predictions" are less certain than the +/- 50% indicated by the authors of the EPRI paper, Reference 8. It is more likely +60% and -70% because a significant number of data points fall out of the +/- 50%.

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[15] Exhibits NEC-JH_ 42 at 1; NEC-JH_43 at NEC020180.

[16] Exhibit NEC-JH_ 44 at 18.

[17] Exhibit NEC-JH_ 38.

[18] Exhibit NEC-JH_37.

[redacted]

According to NUREG/CR-6936, *Probabilities of Failure and Uncertainty Estimate Information for Passive Components – a Literature Review* (May 2007) at Table 5.15, there were 250 through-wall pipe failures from FAC in BWRs and PWRs between 1988 and 2005, compared to 183 failures that occurred between 1976 and 1987. On a yearly basis, this represents a reduction of 2 failures per year during the 1988-2005 period compared to the previous period, disregarding the number of reactors and their age. Since the CCC codes were introduced in 1987, one could attribute the 10% reduction to the CCC codes. Based on my observations, however, the reduction was due to increased awareness of FAC by all plants following the catastrophic Surry accident.

Many of the failures referenced in NUREG/CR-6936 were not risk-significant. The critical question that must be asked is can CHECWORKS in its present form, together with EPRI guidelines NSAC 202L, prevent major accidents. EPRI guidelines regarding FAC were available to the industry about two years before the Surry accident occurred. These guidelines were based on the same methodology as CHEC, i.e. reliance on empiricism and operator judgment. Since FAC inspection is very expensive, especially when the removal of insulation is required, one can see why leaving the choice to plant operators alone to decide which and how many components are to be inspected is not sufficient. Following the 2004 catastrophe at the Mihama plant, the NRC issued an Information Notice which attributed the accident to ineffective management and poor safety culture. No indication was provided whether CHECWORKS or a similar methodology was employed at Mihama.

Since there have been only two major FAC-related accidents, a better way of testing the adequacy of the CCC codes (and/or the EPRI guidelines) is to assess their ability to prevent precursors to incidents or near misses. The following list provides examples of incident precursors that EPRI guidelines/CCCs codes failed to detect.

A. Examples where EPRI Guidelines and the CCCs codes failed to detect Safety- Related Failures. Reference 18.[20]

1. May 1990 – Erosion and corrosion was discovered in the feed distribution piping of units 2 and 3 at San Onofre – IN 91-019.[21]

2. December 1990 – Two six inch pipes were damaged as a result of wall thinning at Millstone 3. The first pipe completely sheared off while the second was

[19] Exhibit NEC-JH_38.

[20] Exhibit NEC-JH_45.

[21] Exhibit NEC-JH_46.

sheared by 1/2 to ¾". The pipe eroded from its original thickness of 0.28 inches to 0.11 inches. IN 91-18.[22]

3. May 1992 – Unexpected high erosion rates in the feedwater piping at Susquehanna Unit 1 (BWR) in a section of piping that could not be isolated from the reactor vessel. IN 92-35.[23]

4. June 1993 – Through wall FAC of two J-tubes in Unit 2 Steam Generator at San Onofre. IN 93- 06.[24]

5. March 1993 – Wear in the feedwater nozzle at North Anna in the safety-related area of the plant.

6. November 1994 – 180-degree crack in a 14" condensate piping at Sequoyah. IN 95-11.[25]

7. April 1997 – 6 square foot rupture of a 12-inch elbow at Ft. Calhoun. IN 97-84.[26]

8. August 1999 – Double ended pipe break in a moisture separator at Callaway. IN 36015.[27]

9. April 2004 – A work order to inspect the elbow for wall-thinning at Kewaunee was cancelled after wall thickness in a nearby elbow was evaluated by the licensee and deemed acceptable. The extrapolation of inspection results from one elbow to the other elbow was inappropriate.[28]

10. August 9, 2004 – A secondary pipe ruptured, 5 workers were killed and 6 more were injured at the MIHAMA plant in Japan. Strictly speaking, MIHAMA did not use EPRI guidelines or CHECWORKS. They used their own Management Guidelines. From the information available to me, these guidelines were formulated following the Surry accident and they are based on projecting past experience to develop future inspection frequencies. In essence, EPRI guidelines are not that much different, with the exception that they use

[22] Exhibit NEC-JH_47.

[23] Exhibit NEC-JH_48.

[24] Exhibit NEC-JH_49.

[25] Exhibit NEC-JH_50.

[26] Exhibit NEC-JH_51.

[27] Exhibit NEC-JH_45 at 7.

[28] Exhibit NEC-JH_ 52 at 4.

CHECWORKS as a veil for somewhat formalizing such procedure. Reference 9.[29]

It should be noted that the Surry catastrophe was not included in the above list even though EPRI original guidelines were released two years prior the accident.

IV. Entergy's Rationale in ASLB Proceedings to Date for Not Requiring Recalibration of CHECWORKS for the Extended Period of Operation With Responsive Comment

Entergy: "As the testimony before the ACRS indicates, generally the increase in wear is less than the increase in velocity; and typically, from EPU studies, the maximum increase in projected wear rates is in proportion to the velocity increase."[30]

Comment: This statement has neither theoretical nor experimental support. As discussed on page 4 of this memorandum, the local corrosion rate varies exponentially with the velocity, the exponent varying between 2.4 and 6.0 depending on the geometry. A velocity increase of 20% would increase the corrosion rate by a factor of 1.5 to 4.2, depending upon whether the component is a straight pipe or an elbow. For geometries such as nozzles, the effect of velocity increase on corrosion may be higher.

Entergy:
Entergy has stated that it "will be looking at the highest length locations and the highest velocity locations in the next three outages," reflecting a belief that length and the highest velocities control corrosion.[31]

Comment:
Length-to-diameter ratio is a factor that may control corrosion, not maximum length. Maximum velocity is an important parameter but it is the local maximum velocity in a combination with the local geometry, as discussed above, not the average component velocity that controls corrosion rates. CHECWORKS has not been calibrated with respect to the local velocity within any given component.

Entergy
"CHECWORKS was designed, and has been shown, to handle large changes in chemistry, flow rate and or other operating conditions."[32]

Comment

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[29] Exhibit NEC-JH_53.

[30] Entergy's Answer to New England Coalition's Petition for Leave to Intervene, Request for Hearing, and Contentions (June 22, 2006) at 33.

[31] Id. at 35.

[32] Joint Declaration of Jeffrey S. Horowitz and James C. Fitzpatrick In Support of Entergy's Motion for Summary Disposition of NEC Contention 4 (May 31, 2007) at ¶ 38.

As already discussed above, CHECWORKS is not a mechanistic model and the empirical correlation does not include local turbulence and time. The correlation of CHECWORKS was performed in an unscientific manner. Commonly, empirical equations, such as Equation 1, are correlated with experimental data. The empirical constants, A and G, and their range of applicability are specified for each variable. Before one can determine the empirical constants one must know the interaction between all the relevant parameters. The developers of CHECWORKS did not follow this procedure because in a system as complex as a power plant one does not know what that interaction is, especially when some of the most critical parameters were not measured. Figure 8 does not support Entergy's statement that CHECWORKS can predict changes in chemistry, flow rate or other operating conditions.

The correlation of Figure 8 lumps data from all plants irrespective of the local conditions and the possible interactions between the various variables. For example, consider two identical plants with similar operating histories. Because of small differences in unknown parameters (weld procedure, material composition, local velocities, etc.) one elbow in one plant could be subjected to high corrosion rates while a seemingly identical elbow in the other plant, or even in the same plant, may not be affected by FAC at all. Such observations are consistent with plant experience.

Entergy has not provided data showing how CHECWORKS predictions compare with plant data at VY. At a 2005 ACRS meeting, following a comparison of CHECWORKS predictions at another plant, ACRS member Mr. Ford commented : "If you look at that data base, you don't have much confidence in CHECKWORKS."[33]

Entergy
Five years would be sufficient to benchmark CHECWORKS at VY.[34]

Comment
This is purely a conclusory statement, not supported by data.

Entergy
"Were Dr. Hopenfeld correct in his opinion that it takes 10-15 years of accumulated data before CHECWORKS can be used reliably, every plant that has been using CHECWORKS in the last ten to fifteen years has been in error in doing so."[35]

Comment
The numerous component failures since plants began using the EPRI guidelines and CHECWORKS demonstrates that both the EPRI NSAC-202L-R3 and CHECWORKS have not been effective in reducing the damage from FAC in nuclear plants.

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[33] Exhibit NEC-JH_39 at 201.

[34] Joint Declaration of Jeffrey S. Horowitz and James C. Fitzpatrick In Support of Entergy's Motion for Summary Disposition of NEC Contention 4 (May 31, 2007) at ¶ 39.

[35] Entergy's Answer to New England Coalition's Petition for Leave to Intervene, Request for Hearing, and Contentions (June 22, 2006) at 33.

V. NRC Requirements for Managing FAC During License Extension Period

Following the Surry accident in 1986, the NRC stated that the observed pipe thinning was "unexpected." As already mentioned above, NRC limited its activities to issuing Information Notices regarding some of the most significant incidents, documented in References 10- 15. In the essence, it relied on EPRI and individual plant operators to address FAC problems. For the life extension period, the NRC issued specific guidelines on how to control FAC. The FAC program consists of major elements and specific guidelines:

Major Elements

(1) Scope
(2) Preventative actions
(3) Parameters monitored or inspected
(4) Detection of aging effects
(5) Trending
(6) Acceptance criteria
(7) Corrective actions
(8) Confirmation processes
(9) Administrative processes

Guidelines

NUREG 1800, § A.1.2.3.4, The detection of wall thinning due to FAC should occur before there is a loss of the structure and the component intended function(s). Wall thinning must be monitored or inspected to ensure that the structure and component intended function(s) will be adequately maintained for license renewal under all CLB design conditions. Sample size and frequency of wall thinning measurements must be conducted in a timely manner so as not to exceed the minimum design thickness of a given component. The licensee must provide information that links the parameters to be monitored or inspected to wall thinning.

NUREG 1801 XI.MI7, The FAC program "Relies on implementation of the Electric Power Research Institute (EPRI) guidelines in the Nuclear Safety Analysis Center (NSAC)-202L-R2 for an effective flow-accelerated corrosion (FAC) program. The program includes performing (a) an analysis to determine critical locations, (b) limited baseline inspections to determine the extent of thinning at these locations, and (c) follow-up inspections to confirm the predictions, or repairing or replacing components as necessary.

The GALL Report further states that, "[t]o ensure that all the aging effects caused by FAC are properly managed, the program includes the use of a predictive code, such as CHECWORKS, that uses the implementation guidance of NSAC-202L-R2 to satisfy the criteria specified in 10 C.F.R. Part 50, Appendix B" concerning control of special processes. NUREG-1801 Vol.2, Rev. 1 at XI-M-61. "CHECWORKS or a similar predictive code is used to predict component degradation in the systems conducive to FAC, as indicated by specific plant data, including material, hydrodynamic, and operating conditions. CHECWORKS is acceptable because it provides a bounding analysis for FAC. CHECWORKS was developed and benchmarked by using data obtained from many plants. The inspection schedule developed by the licensee on the basis of the results of such a predictive code provides reasonable assurance that structural integrity will be maintained between inspections." Id. at XI-M-62.

The NRC also has guidelines for approving analytical codes. It requires that such codes be assessed and benchmarked against measured plant data. The benchmarking must be valid within the range in which the data was provided.[36]

The Gall report is silent about how one uses CHECWORKS when conditions at a given plant change. The observation that CHECWORKS can bound plant data between 100-200 mils/year, as can be concluded from wear predictions and the given operating times, Reference 8,[37] without specifying how each variable separately effects corrosion, does not address the issue of how the corrosion rate at a given location would be affected when the velocity changes by 20% at a given plant. When one uses corrosion data from a large number of plants, the number of variables that affect corrosion is unquantifiable. It would be impossible to predict specific corrosion rates from such correlation reliably, especially as the data was obtained under unknown conditions.

VI. Time Required to Establish FAC Database at Uprate Conditions

Fundamental FAC principles, together with plant experience, indicate that the root cause of EPRI guidelines/ CHECWORKS' inability to reduce FAC incidents in power plants is mainly caused by the following three factors: (a) lack of knowledge as to where high turbulence is located and the mechanism by which turbulence accelerates corrosion, (b) lack of knowledge of the interaction between exposure time and surface topography and (c) lack of scientific sampling procedures to include components in the CHECWORKS program.

Item (a) can be somewhat circumvented by selecting a small grid size. Item (b) is difficult to address, except that plant experience suggests that the time scale for wall penetration in large size components is on the order of 15 years. Item (c) can be addressed by inspecting all susceptible components until a scientifically based sampling method becomes available.

Item (a) does not relate to deficiencies in CHECWORKS; it relates to the adequacy of the current input to the code, i.e. grid size. The current grid size is arbitrary and must be considerably reduced. The degree of grid size reduction could be reduced by incorporating in CHECWORKS a mechanistic model that accounts for local turbulence.

[36] Exhibit NEC-JH_35.

[37] Exhibit NEC-JH_37.

The above discussion makes no distinction between plants that operate under constant conditions and those that operate under conditions where known parameters effecting FAC have been changed. The main difference between a plant that has operated continuously at the same power level and water chemistry, and a plant that begins operations under different conditions would be in the number of components that must be selected for monitoring. The former also may not require as large a reduction in the grid size, especially if the plant's data bank includes similar components with different grid sizes.

The Vermont Yankee plant represents a plant where a 20% increase in velocity resulting from a 20% power uprate may increase the local corrosion rates by factors ranging between of 1.5 and 4.2. In addition, VY also reduced the oxygen content in the plant in 2003,[38] further increasing the potential for FAC.

The following describes a procedure that accounts for the effects of local turbulence, the effect of time and lack of scientific sampling: The total number of all risk-significant susceptible components are divided into four groups, A, B, C, and D. Each group must operate at the minimum three inspection periods before a trend can be established. An "inspection period" is equal to the typical eighteen month fuel cycle. To account for local turbulence within each group, the grid should be kept to below 1"x 1" inch. The test matrix in Table 1 shows that eight inspection periods (12 years) would be required to obtain data on all components without resorting to sampling. Five inspection periods is the time interval between component inspection and the establishment of a corrosion rate for a given component at a given location. This allows for the determination of the corrosion rate of all components after 8 inspection periods.

Inspection	A	B	C	D
1	x			
2		x		
3			x	
4	y			x
5	x	y		
6		x	y	
7			x	y
8			)	x

[38] Exhibit NEC-JH_18 at 3.2.

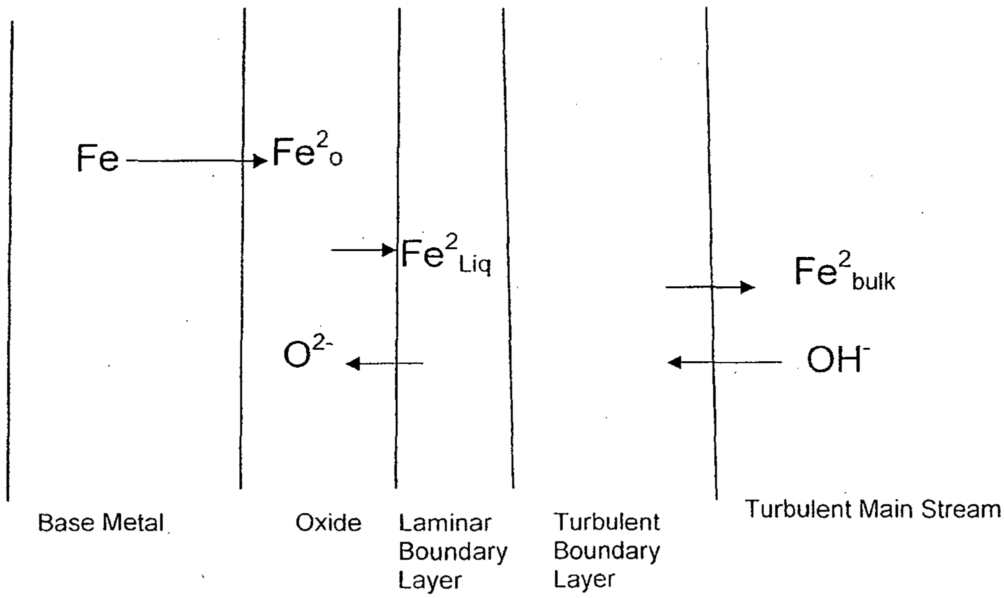
Table 1- Eight inspection periods would be required to establish a sufficient data base to account for local corrosion using a 1"x1" grid. X designates that the entire grid is inspected, Y designates that only selected points on the grid are inspected. If instead of dividing the susceptible components into four groups, they were divided into three groups, the required number of inspections would be 6 (12 years). If all the susceptible components are inspected, at the minimum three inspection periods would be required to account for the variation of FAC with time.

Another way of assessing the minimum time that would be required to benchmark a code is to look at historic plant data in terms of the time scale for the occurrence of large, risk-significant wall thinning events. Table 2 indicates that on the average it takes about 16 years for a major FAC failure to occur if FAC degradation goes undetected. Something inherent in the present inspection methodology allows serious wall thinning to continue without detection. Using 1x1 grid size and collecting data for all susceptible components over a period of 15- 20 years would provide the required data base to calibrate a computer code like CHECWORKS.

Plant	Time to Failure (Years)
Surry	14
Trojan	15
San Onofre	8 and 11
Clinton	16
Fort Calhoun	26
Mihama	28

Table 2 – Time Scale for the Occurrence of Risk Significant Events at several power plants

Figure 1 – Schematic of Basic Metal Dissolution



Transfer Rate of Iron From Oxide Layer to Bulk Stream = (Transfer Function) x (Concentration of Iron at oxide/liquid Interface – Concentration of Metal in the Main Stream)

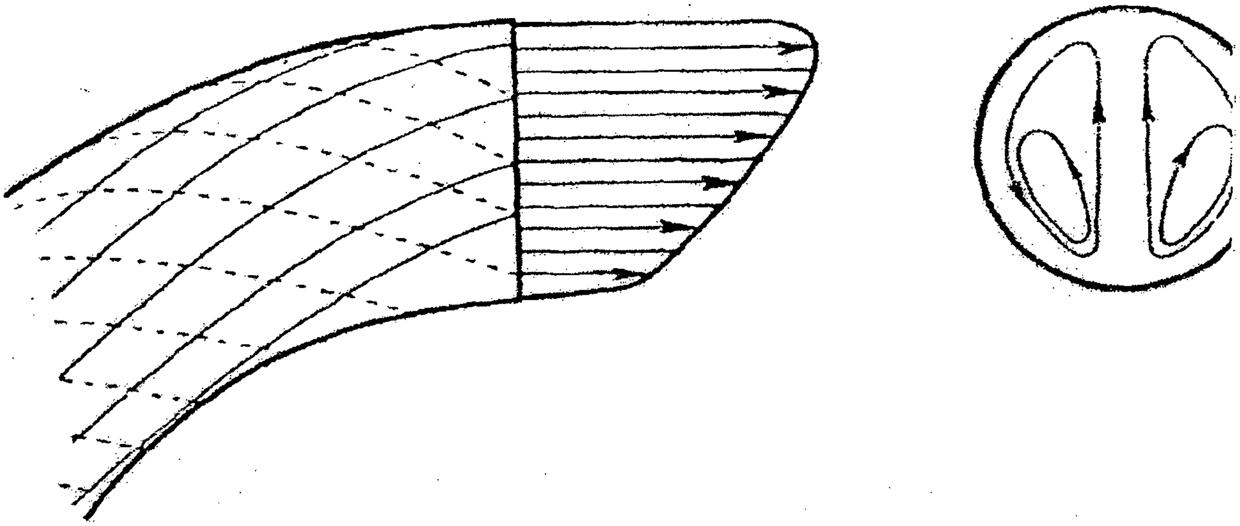
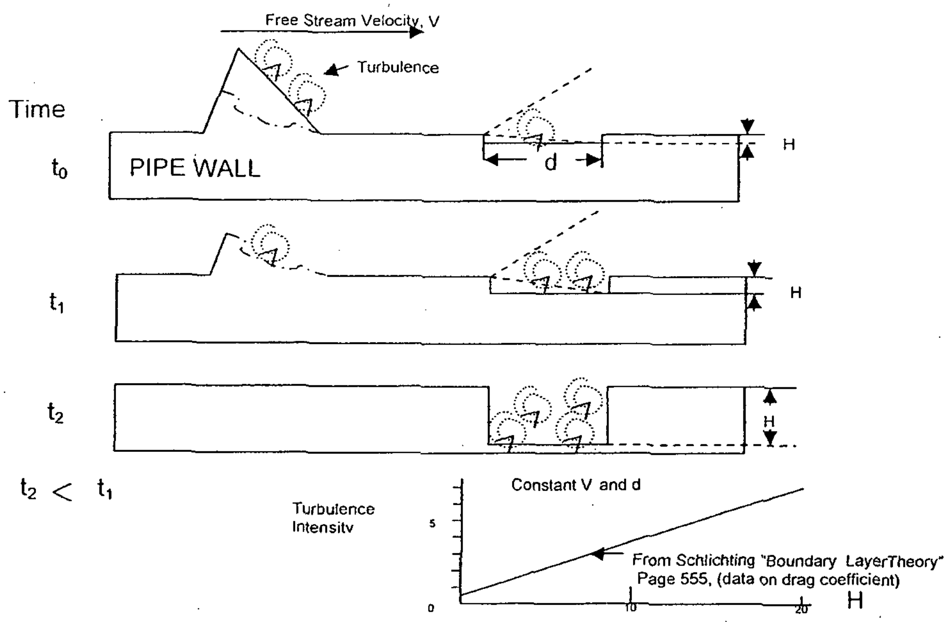


Figure 2 – Flow in curved pipes varies with location. Turbulence intensity increases with the centrifugal force, outer surfaces experience the highest turbulence.

Figure 3- Schematic of roughness formation; showing that the local wall thinning is not linear with time and that FAC is a local phenomenon



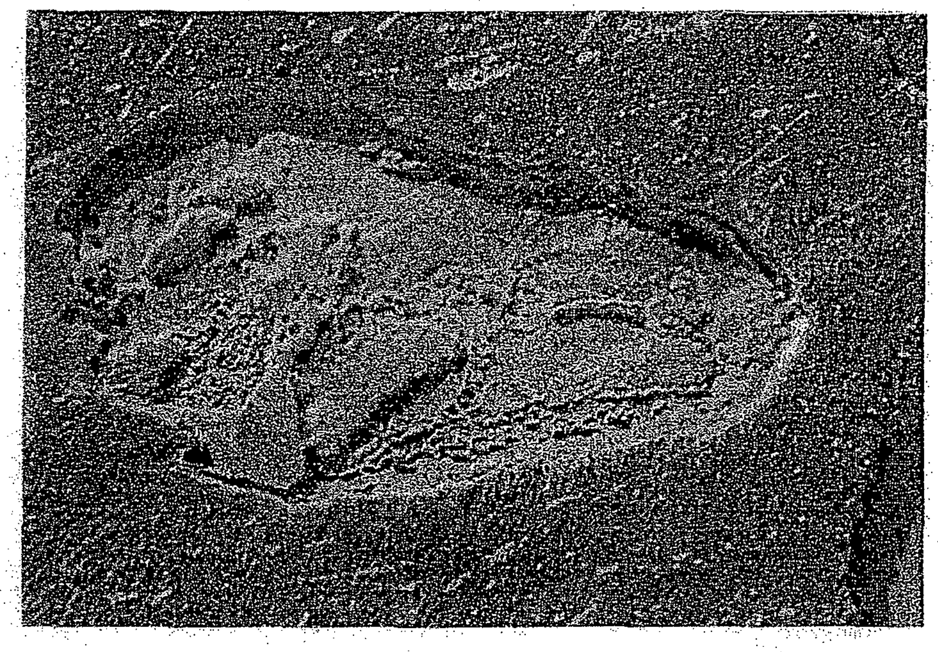


Figure 3 – showing a cavity surrounded by a smooth surface

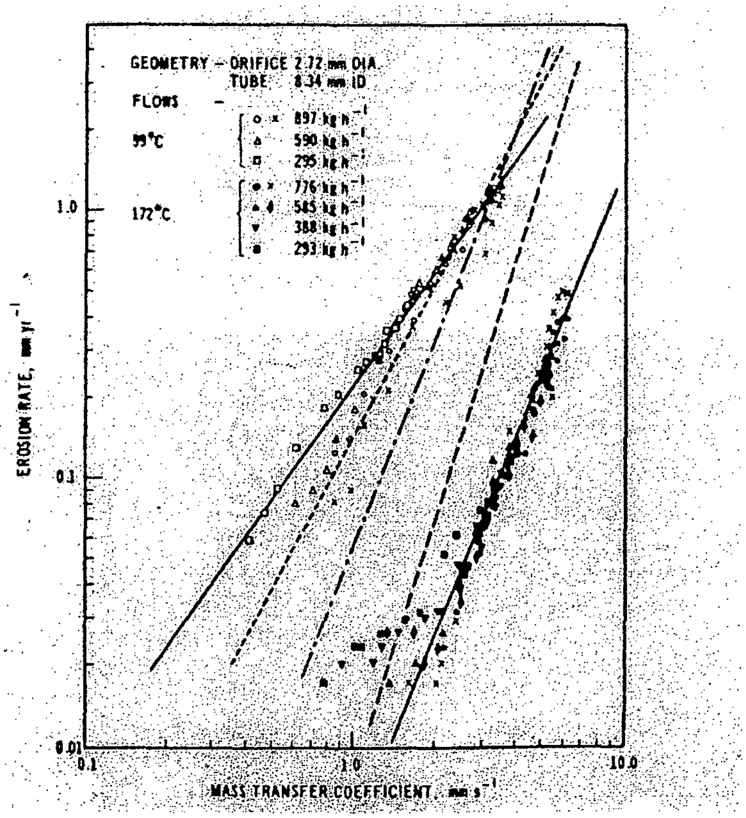
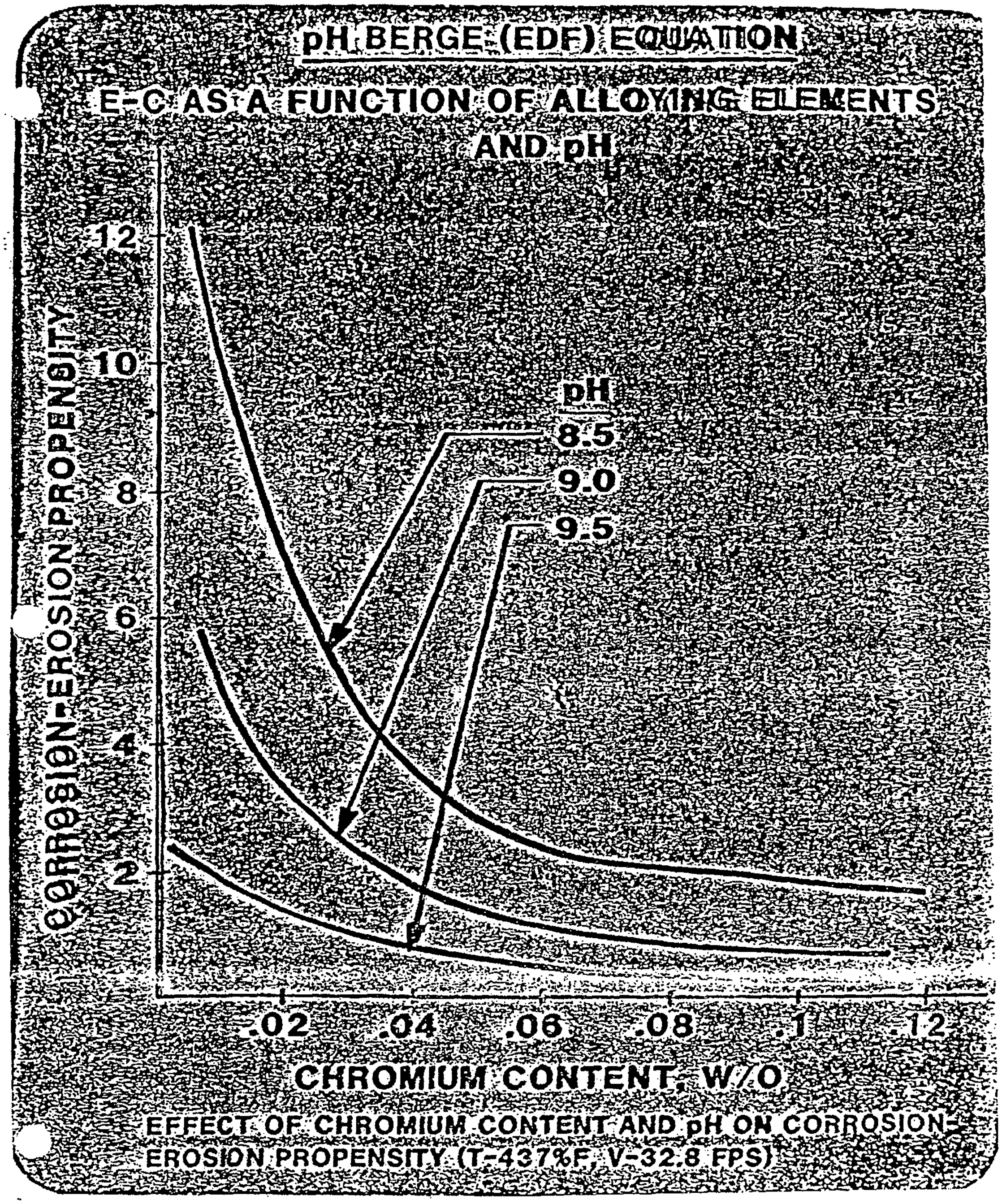


Figure 4 – Showing that the corrosion rate varies as the mass transfer coefficient cube

Figure 5 - Variation of the corrosion rate with pH and material composition



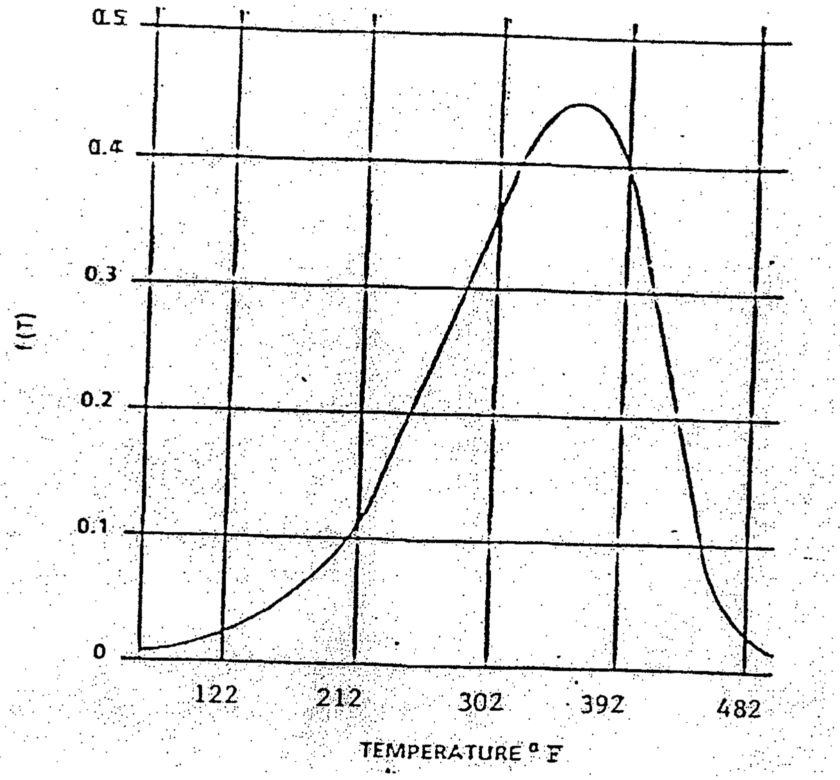


Figure 6 – Variation of corrosion rate with temperature for wet steam

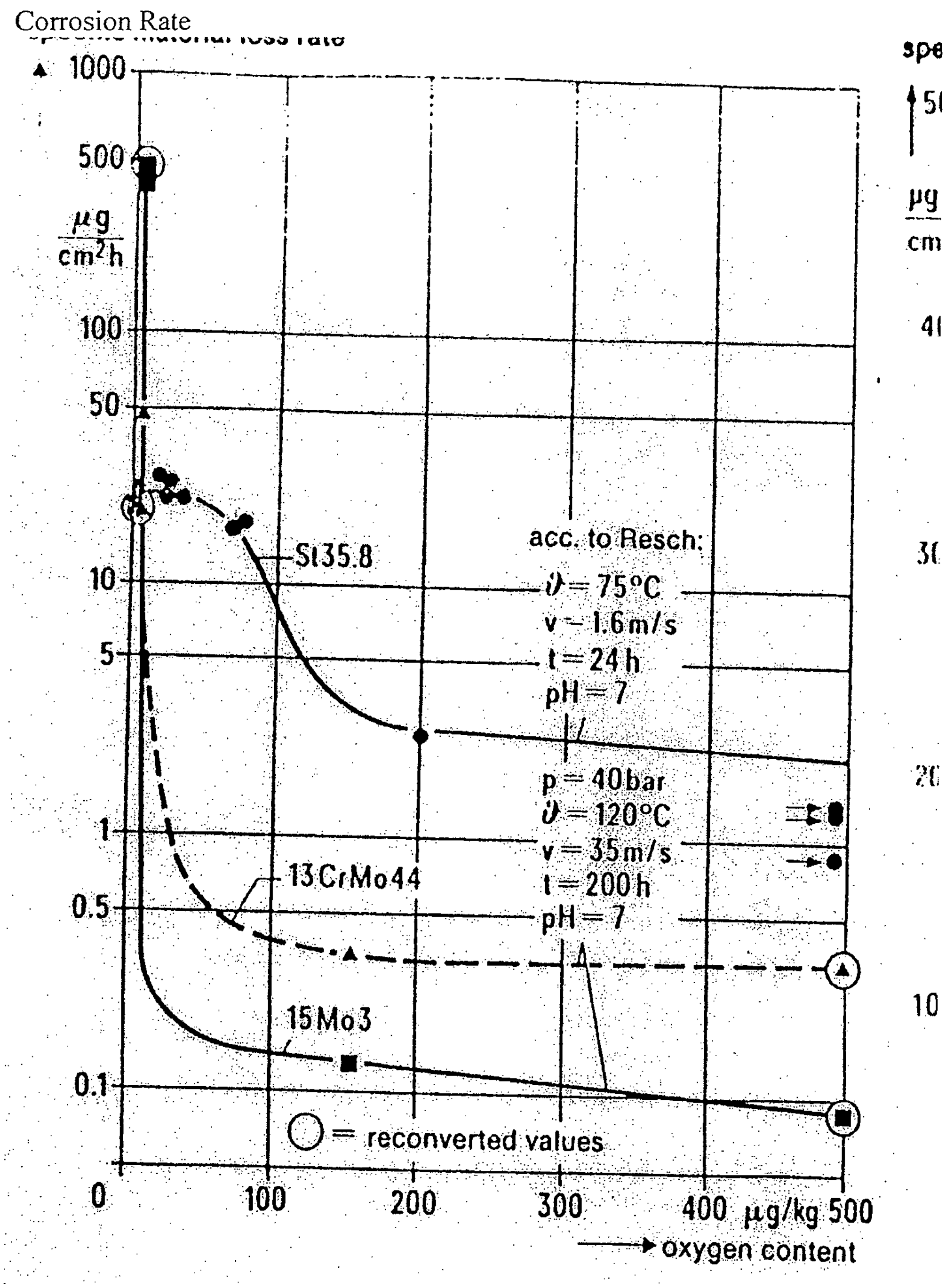


Figure 7 - Effect of Oxygen Content on the Corrosion Rate (W. Kastner et.al. Experimental Investigation of Material Loss due to Erosion/Corrosion. VGB KRAFTWERKSTECHNIK 64, May 1984).

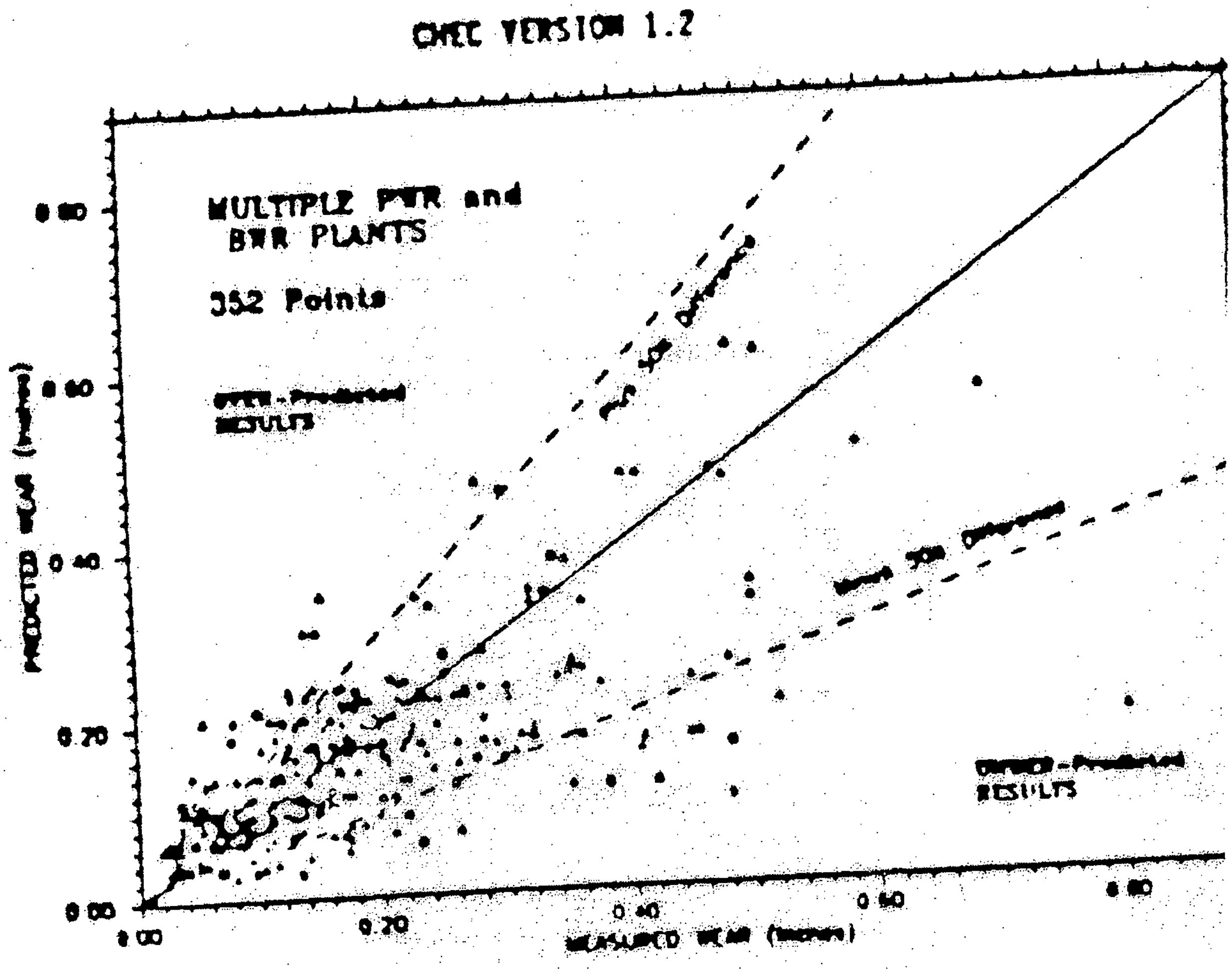


Figure 8- Measured Wear vs. Predicted Wear including data from both BWR and PWR's. Reference 8.

VII. Summary

FAC is a phenomenon with serious safety consequences that increases in severity as plants get older, beyond 30 years of age. It is expected that the number of wall thinning incidents at VY would increase during the life extension period. Based on past experience with FAC, the VY program to combat damage from FAC during the next 25 years is inadequate.

Entergy's program to manage FAC at the Vermont Yankee, VY, plant is based on EPRI guidelines NSAC-202L-R3 and the accompanying computer code called CHECWORKS. Plant experience shows that the EPRI Guidelines, NSAC-202L- R3 and the several previous versions of these guidelines, did not prevent the catastrophe at Surry in December 1986, nor did the EPRI guidelines prevent hundreds of equipment failures following that accident. CHECWORKS, which is used to rank components in the order of their susceptibility to FAC and predict the frequency of inspection of a given component, also has not prevented hundreds of failures, some with high-risk significance.

In my opinion, several factors contribute to the inability of the EPRI Guidelines/ CHECWORKS methodology to prevent pipe ruptures from unpredicted wall thinning: (a) incorrect local inspection procedures, i.e. selection of grid size, (b) unscientific sampling of components, (c) inability to reliably predict corrosion rates between inspections, (d) no online instrumentation to monitor the potential for corrosion, and (e) insufficient independent competent assessment.

Setting the issue of CHECWORKS' general reliability aside, because of the 20% increase in flow velocity and reduction in oxygen concentration at VY in the past few years, CHECWORKS must be recalibrated. Entergy claims that the recalibration would take only 3 inspection periods, and CHECWORKS will be ready for use at VY during the extended period of operations. My assessment indicates that it would take at least 10 to 15 years to benchmark CHECKWORKS after the grid size is reduced and the code is appropriately modified to properly account for local turbulence.

In order to comply with 10 CFR 54.21(a), Entergy must formulate a new plan to manage FAC before entering the extended period of operation that does not rely on CHECWORKS predictions. The new plan must specify a scientifically based component sampling and an inspection grid size that is determined by turbulence intensity and not only by component size. The new plan must be reviewed by an independent, competent third party with no financial ties to Entergy.

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