Erosion/Corrosion in Power Plants Single- and Two-Phase Flow Experience, Prediction, NDE Management

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ABSTRACT

Based on experimental and theoretical investigations started in 1973, an empirical model was developed to calculate erosion corrosion (EC) wall thinning as a function of geometry, material thermohydraulic and chemistry parameters. The model, available as a PC code named WATHEC, yields reasonable results under both single- and two-phase flow conditions. It can be used to streamline non-destructive examination (NDE) efforts and to quantify parameters for system/operational improvements as well. A data management program interfaced to WATHEC provides processing and storing of wall thickness reading files and enables follow-up of component life history. Application of these EC analysis tools to power plant components is in progress. As an example, evaluations for an extraction steam line of the Rancho Seco Nuclear Station are presented.

INTRODUCTION

According to (1), EC is a flow-induced material degradation process affecting metallic materials, the corrosion resistance of which is based on the formation of protective oxide films. Wear-off destruction of such films by turbulent flow of water or wet steam causes dissolution of the unprotected metal. Besides EC, another erosive mechanism, associated with the liquid phase, but known to occur in two-phase flow systems only, is destructive oxide fatigue caused by droplet impingement Thus, before reliable wear predictions can be made, it has to be determined first which of these mechanisms will dominate in a given steam-water system. (Under single-phase flow conditions, there is no question, since only the dissolution mechanism exists). As described in (2), this assessment is possible e.g. by using a graph as schematically demonstrated in Figure 1. This paper deals with a predictive model which can be applied only when EC is the prevailing mechanism.

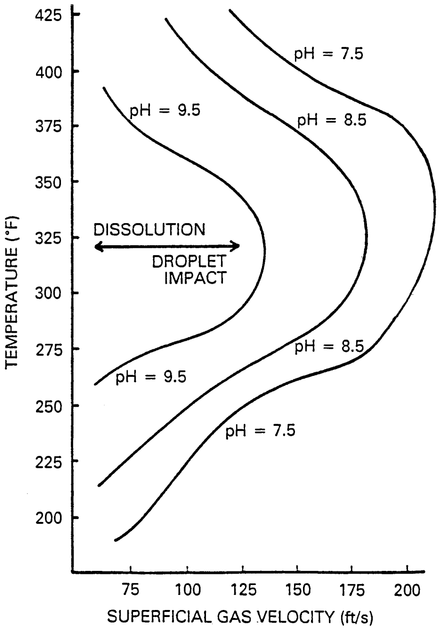


Figure 1: Diagram for Determining whether Dissolution or Droplet Impact Wear (Left or Right of pH Line) Will Dominate in Two-Phase Steam-Water Flow, as a Function of Temperature, pH and Superficial Gas Velocity

EMPIRICAL MODEL AND PREDICTIVE CODE DEVELOPED BY SIEMENS/KWU

The parameters influencing EC are well known, e.g. from experimental investigations described in (3),(4),(5). As a result of these tests performed in a single-phase water flow, the EC wear rate producing wall thinning in components such as piping can be calculated by an empirical equation given in (6),(7):

$$r = kc * f(w, T, pH, O2, h, t) \qquad [1]$$

with r = wall thinning, kc = geometry factor, w = fluid velocity, T = fluid temperature, pH = pH value, O2 = dissolved oxygen concentration, h = Cr+Mo content of the material, t = operating time.

The resulting impact of the individual parameters on wall thinning is shown in Figures 2, 3, 4 and 5 in summary.

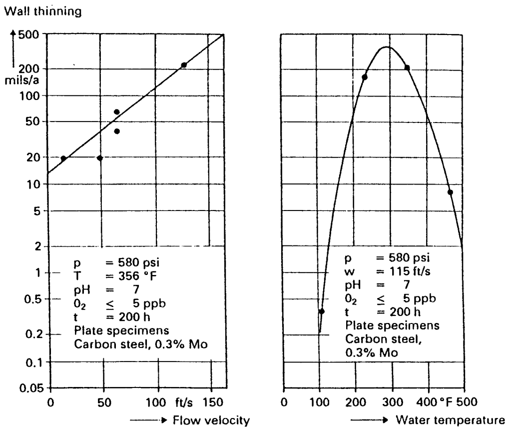


Figure 2: Effect of Water Velocity and Temperature on Wall Thinning due to Erosion Corrosion in Single-Phase Water Flow

KWU Experiments with Plate Specimens of Carbon Steel, 0.3% Mo

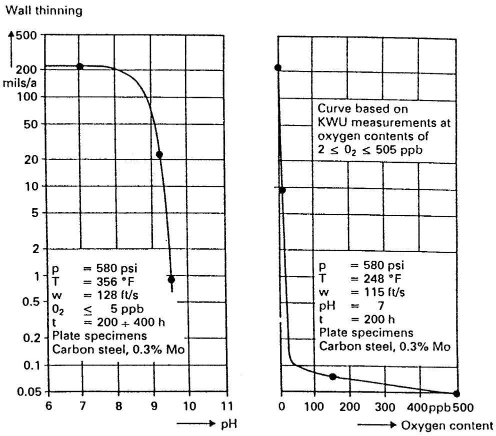


Figure 3: Effect of pH Value and Oxygen Content on Wall Thinning due to Erosion Corrosion in Single-Phase Water Flow

KWU Experiments with Plate Specimens of Carbon Steel, 0.3% Mo

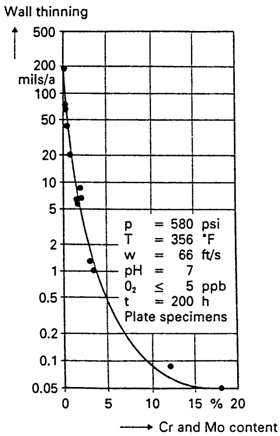
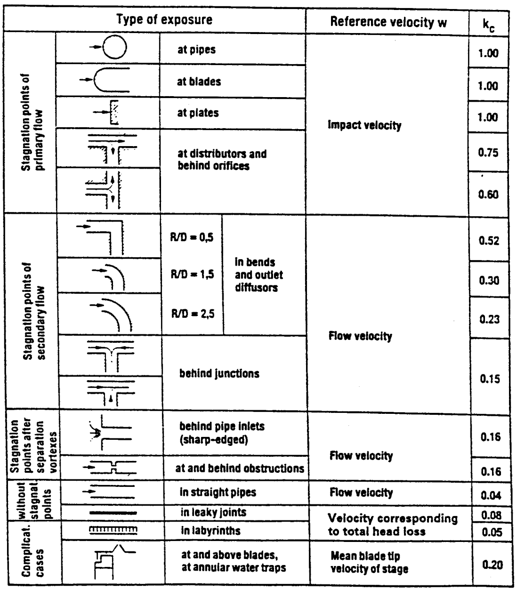


Figure 4: Effect of Cr and Mo Content on Wall Thinning due to Erosion Corrosion in Single-Phase Water Flow

KWU Experiments with Plate Specimens



Type of exposure				Reference velocity w	k_c
Stagnation points of primary flow		at pipes		Impact velocity	1.00
		at blades			1.00
		at plates			1.00
		at distributors and behind orifices			0.75
					0.60
Stagnation points of secondary flow		R/D = 0,5	in bends and outlet diffusors	Flow velocity	0.52
		R/D = 1,5			0.30
		R/D = 2,5			0.23
		behind junctions			0.15
Stagnation points after separation vortexes		behind pipe inlets (sharp-edged)		Flow velocity	0.16
		at and behind obstructions			0.16
without stagnat. points		in straight pipes		Flow velocity	0.04
		in leaky joints		Velocity corresponding to total head loss	0.08
Complicat. cases		in labyrinths			0.05
		at and above blades, at annular water traps		Mean blade tip velocity of stage	0.20

Figure 5: Geometry Factors According to Keller (8), (9), (10)

Based on the results of this parameter study, an empirical model was developed which allows material loss due to EC to be predicted in single- and in two-phase flow as well (Figure 6). This model is available as a menu-driven PC code named WATHEC (= Wall Thinning caused by Erosion Corrosion). It is structured such that only input data is used which can be taken from the operating records of power plants or from design documents of the system considered. WATHEC is restricted to carbon and low-alloy steels with Cr+Mo contents up to 5 o/w and component operating times of at least 200 hr. Verification by checking against laboratory and field data proved WATHEC to yield reasonable (and in tendency conservative) results: Calculated wall thinning values were equal to or greater than measured data in 85 % of all cases.

EC wall thinning as a function of geometry is evidently related to local flow turbulence. Thus, the close consecutive arrangement of flow obstacles such as junctions and bends in piping systems will induce synergistic effects, i.e. some downstream superimposition of geometry factors. Turbulence decay characteristics as derived from (11),(12),(13) are shown in Figure 7 and 8.

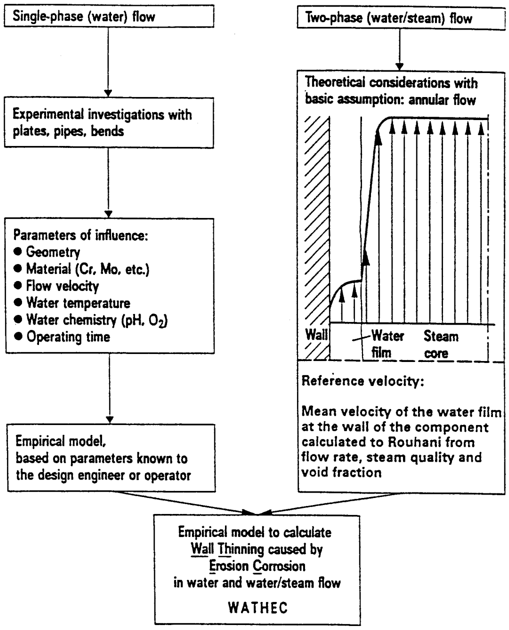


Figure 6: Development of the Predictive Code to Calculate Wall Thinning due to Erosion Corrosion

They lead to "die-away function corrected" total geometry factors, e.g.

$$kc(B)total = kc(B) + kc(A) * \exp(C * z/D) \qquad [2]$$

with kc(A) and kc(B) = geometry factors of components A and B, respectively, C = constant (C = -0.231), z = downstream distance from obstacle A, D = pipe diameter, which are taken into account by an upgraded, recent version of WATHEC.

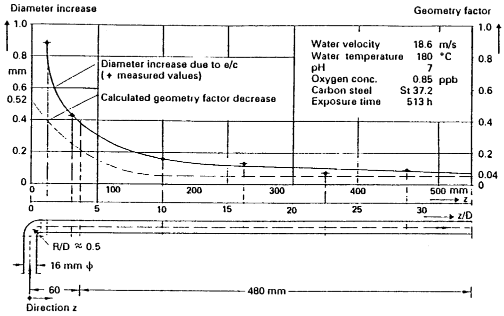


Figure 7: Wall Thinning due to Erosion Corrosion (Measured as an Increase in Pipe Diameter) and Calculated Geometry Factor Decrease in a Pipe Downstream of a Sharp Bend in Single-Phase Water Flow

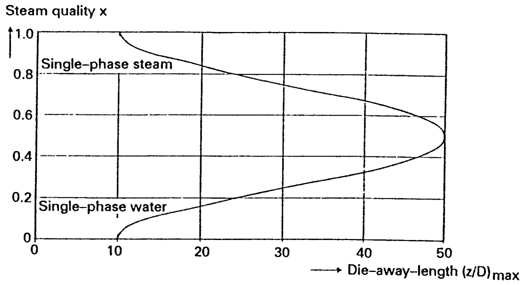


Figure 8: Effect of Steam Quality on Die-Away Length of Local Turbulence in Two-Phase Steam-Water Flow

Since using such improved geometry factors, WATHEC yields satisfactory wear rates even for complex configurations. This could be shown e.g. by re-evaluating actual cases such as Surry 2 (as far as available plant information on design/operating and inspection data allowed). Frequently, the initial wall thickness of piping is not known accurately, so that the residual wall thickness can be correlated to the design code wall thickness only; consequently, the obtained wall thinning values are subject to the tolerances of the respective standard nominal wall thickness.

Of course, a predictive model is not primarily aimed at retrospectively quantifying earlier damage. Its more important purpose is its use in "preventive diagnostics", i.e. to determine the anticipated material loss of a component and, conversely, the residual life of the component under the given stress conditions. On the other hand, WATHEC can be used as a "design tool", i.e. to quantify the impact of parameter changes on the EC wear rate. This is demonstrated in Table 1 for changes in geometry, velocity, and, more practical, in material and chemistry.

Table 1: Impact of Parameter Changes on EC Wear Rate per Year (8,760 hr) under PWR and BWR Conditions at 300 F

a) PWR Conditions:			b) BWR Conditions:		
Parameters	EC Wear Rate		Parameters	EC Wear Rate	
	mil/yr	%		mil/yr	%
h = 0.3 %			h = 0.3 %		
w = 20 ft/s			w = 20 ft/s		
pH = 8.7			pH = 7.0		
O2 = 3 ppb			O2 = 3 ppb		
kc = 0.75	69.2	100	kc = 0.75	138	100
kc = 0.30	27.7	40	kc = 0.30	55.2	40
h = 0.3 %			h = 0.3 %		
kc = 0.75			kc = 0.75		
pH = 8,7			pH = 8.7		
O2 = 3 ppb			O2 = 3 ppb		
w = 20 ft/s	69.2	100	w = 20 ft/s	138	100
w = 10 ft/s	51.2	74	w = 10 ft/s	101	73
w = 20 ft/s			w = 20 ft/s		
kc = 0.75			kc = 0.75		
pH = 8.7			pH = 8.7		
O2 = 3 ppb			O2 = 3 ppb		
h = 0.3 %	69.2	100	h = 0.3 %	138	100
h = 2.5 %	14.8	21	h = 2.5 %	27.9	20
h = 0.3 %			h = 0.3 %		
w = 20 ft/s			w = 20 ft/s		
kc = 0.75			kc = 0.75		
O2 = 3 ppb			pH = 7.0		
pH = 8.7	69.2	100	O2 = 3 ppb	138	100
pH = 9.2	22.8	33	O2 = 20 ppb	20.3	15

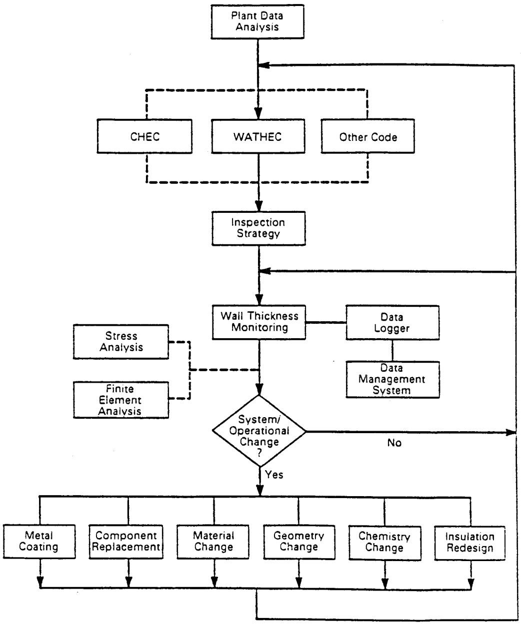


Figure 9: Bechtel-KWU Alliance's Erosion Corrosion Management Program

As outlined in Figure 9, WATHEC is one of the elements of an EC management program: Together with a continuously updated EC data base, the predictive code serves to perform, as the first step, a susceptibility analysis aimed at screening the systems of a power plant and selecting a small number of components (Tees, elbows etc.) as a representative sample to determine the EC susceptibility of the plant, quantifying the EC wear rates of those components, and developing an inspection strategy, i.e. focusing NDE efforts on areas of major concern.

Actual wall thickness measurements constitute the second step of the program. According to the state of the art, an accurate wall thickness evaluation can only be accomplished by taking measurements, e.g. UT readings, on a grid pattern. This implies a large number of measurements. Typical grid sizes and number of readings required are given in Table 2.

Table 2: Typical Grid Sizes and Number of Readings for Wall Thickness Measurements

Pipe Size/Sched.	Approx. Grid Size	Approx. # of Points for Tee or Elbow
2"/40	1"	35
6"/40	1.8"	60
12"/40	3.2"	90
24"/40	6"	150

A variety of currently available data logging equipment and data evaluation software can significantly reduce time and manpower required for inspection and data processing/documentation. Such a data management system is linked to WATHEC as a subroutine.

By subsequent feedback of measured data, the accuracy of calculated wear rates can be enhanced. Once weak points have been identified and confirmed, it can be decided if and when corrective action is necessary, the most promising option for which can be selected with the aid of a parameter study (see Table 1).

PROGRAM IMPLEMENTATION AT RANCHO SECO NUCLEAR STATION, UNIT 1

An EC analysis with WATHEC recently was performed on the Rancho Seco Nuclear Station, Unit 1, owned and operated by Sacramento Municipal Utility District (SMUD), Sacramento, CA. The intended use of WATHEC was to augment previous methods to select piping components for inspection and wall thickness measurement which SMUD had performed in the past in response to industry guidelines (14),(15) and NRC Bulletin 87-01. The total scope of piping systems was over 200 single- and two-phase flow lines in the balance of plant, i.e. the condensate, feedwater and steam systems. The lines were reviewed to determine potential EC candidates, then lines with similar operating conditions were grouped together, and the worst case piping layout was chosen for entering into WATHEC. This resulted in reducing the input from over 200 to 105 lines.

Prior to performing the WATHEC analysis, the following information was gathered to assemble separate input packages for each line:

- Piping isometrics with all dimensions shown (or piping layout drawings)
- Piping, fitting, and valve materials, sizes, and design wall thicknesses
- Piping system design and operating temperatures and pressures (including those downstream of pressure reducing devices)
- Piping system flow rates (or velocities)
- Piping fluid chemistry (dissolved oxygen, conductivity, pH, and chemical additives) during operating history
- Piping system total hours of operation.

With this input data, the program computed each component and indicated

- the predicted wear rate per operating year
- the predicted remaining wall thickness
- a recommended wall thickness inspection date
- a wear rate code based on remaining wall thickness compared to nominal wall thickness.

The following figures, which present the graphic display features of WATHEC, are from a HP turbine extraction system (line from HP turbine exhaust to HP feedwater heater) containing wet steam (steam quality x= 0.94) with a velocity of 152 ft/s at 388 F and 215 psig.

In Figure 10, the components of this system are depicted and their wear rate contributions are delineated, thus quantifying the EC wear rate for each component and allowing the user to understand the synergistic effects of the system configuration.

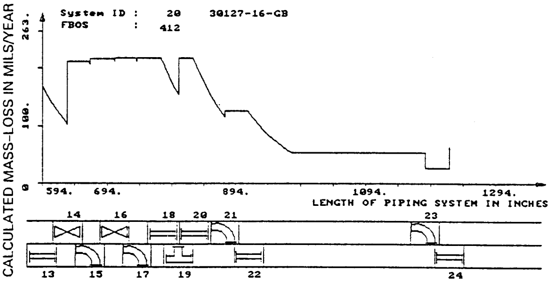


Figure 10: System Wear Rate Contribution Curve as Displayed by WATHEC — Rancho Seco Nuclear Station, Extraction Steam Line to HP Feedwater Heater

Figure 11 demonstrates, as an example, a wear rate boundary curve for component # 15. Similar curves which can be developed for each evaluated component, quantify the predicted wall thickness in relation to piping characteristics such as T_{MIN}, $T_{YT,}T_{UT}$ as a function of operating time.

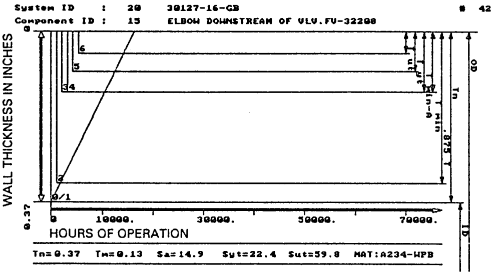


Figure 11: Component Wear Rate Boundary Curve as Displayed by WATHEC — Rancho Seco Nuclear Plant, 16" Elbow (Component # 15) in HP Steam Extraction System

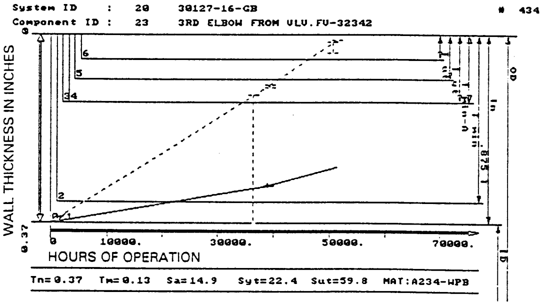


Figure 12: Component Wear Rate Boundary Curve as Displayed by WATHEC — Rancho Seco Nuclear Station, 16" Elbow (Component # 23) in HP Steam Extraction System

-- = predicted ____ = adjusted for UT measurement

Figure 12 is the wear rate boundary curve for component # 23 which normally would not have been chosen for inspection, which, however, had wall thickness measurement performed in the past. The graph shows the original predicted wear rate (dotted line) and the adjusted wear rate based on actual wall thickness measurement input (solid line), i.e. the wear rate from time zero to cross at 40,000 hours (time of measurement) and then a new predicted wear rate from 40,000 to 50,000 hours.

CONCLUSIONS

Developing and implementing a viable and economic EC program for any plant still requires a combination of engineering judgement and operating experience. EC computer models such as the WATHEC Code are at a stage where, properly implemented, they can significantly reduce plant downtime, maintenance costs and personnel safety hazards. In addition, the use of such programs as a design evaluation tool has the advantage of cost-effectively optimizing (re)designs to reduce the impact of EC.

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