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Light Water Reactor Sustainability Program

Flow-Assisted Corrosion in Nuclear Power Plants

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Flow-Assisted Corrosion in Nuclear Power Plants

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ABSTRACT

Flow-assisted corrosion, or flow-accelerated corrosion, is one of the major piping-degradation mechanisms in nuclear power plants, and is being investigated as one of the mechanisms that affect structural health of secondary systems in nuclear power plants under the Light Water Reactor Sustainability Program at Idaho National Laboratory. While every nuclear power plant in the United States has a dedicated flow-assisted corrosion management program, opportunities exist to improve the management of flow-assisted corrosion. . One such opportunity is online corrosion monitoring, which may reduce maintenance inspections and contribute to improved economic efficiency of nuclear power plants. The proliferation of low-cost sensor modalities, such as strain fiber optics sensors and noninvasive concentration sensors, allowed development of online nonintrusive monitoring techniques, which can complement or replace existing evaluation techniques. This report presents a literature review of the current state of the art in flow-assisted corrosion management and a research framework to study online monitoring techniques. The report addresses the problem of online monitoring of flow-assisted corrosion in nuclear power plants.

EXECUTIVE SUMMARY

The U.S. Department of Energy's Office of Nuclear Energy funds the Light Water Reactor Sustainability Program to develop the scientific and technical basis for extending the operation of commercial light water reactors beyond the current 60-year license period. One of the major areas of this effort is to develop and demonstrate the potential of online monitoring techniques for passive nuclear reactor assets, such as piping, concrete, and cabling. The current periodic and condition-based maintenance practices at nuclear power plants result in high maintenance costs and an increased likelihood of human error. Switching to online monitoring would reduce maintenance costs, enhance plant safety and reliability, and reduce hazardous exposures for personnel.

Efforts led by the Electric Power Research Institute resulted in all U.S. nuclear and fossil-fuel power plants having a mandatory flow-assisted corrosion (or flow-accelerated corrosion) management program, which contributed significantly to the reduction of FAC-related events. Difficulties remain, because the offline inspection process, an integral part of the management program, is complicated due to several factors, that according to [1] include:

- Uncertainty in the measurements of wall thickness provided to the predictive model (if baseline data were not taken)
- Variations in wall thickness along the axis and around the circumference of the piping components due to manufacturing variations
- Bias and variance in nondestructive evaluation measurements
- Possible presence of pipe-to-component misalignment and backing rings, or the use of counterbore to match two surfaces
- Data recording, transfer and storage errors
- Obstructions that complicates or prevent complete gridding of piping components for subsequent inspections (e.g., a welded attachment)
- Discrepancies in statistical interpretation of the inspection data.

These factors complicate the production of accurate forecasts for the remaining useful life of a pipe. The proposed online monitoring approach aims to alter this situation with continuous monitoring of degradation modes (i.e., corrosion processes) on three levels: system-wide, component-wide, and local. System-wide monitoring is proposed to be performed with clamp-on acoustical iron concentration sensors. This monitoring produces an overview of the general corrosion situation in the secondary circuit. If an elevated iron concentration is detected, the component-wide system scans are performed on substantial portions of a pipe with the aim to approximately locate the portion of the pipe wall that is thinning. This analysis can be performed either with guided waves, vibration or strain sensors. Finally, highly localized inspection techniques, such as ultrasonic phased array, will be used to pinpoint the exact location of the flaw. The proposed online monitoring approach will be developed and studied using either a flow-assisted corrosion flow loop or a rotating electrode test rig.

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ACRONYMS

BBL	break-before-leak
BWR	boiling water reactor
CODAP	Component Operational Experience, Degradation & Ageing Programme
ECP	electrochemical corrosion potential
FAC	flow-assisted corrosion
FY	fiscal year
HWC	hydrogen water chemistry
ICPMS	
IEEE	Institute of Electrical and Electronics Engineer
INL	Idaho National Laboratory
LWR	light water reactor
LWRS	Light Water Reactor Sustainability (Program)
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OCP	
PEC	pulsed-eddy current (testing)
PHWR	pressurized heavy water reactor
PWR	pressurized water reactor
REC	rotating cylinder electrode
RT	radiography technique
UT	ultrasonic technique
VT	visual testing

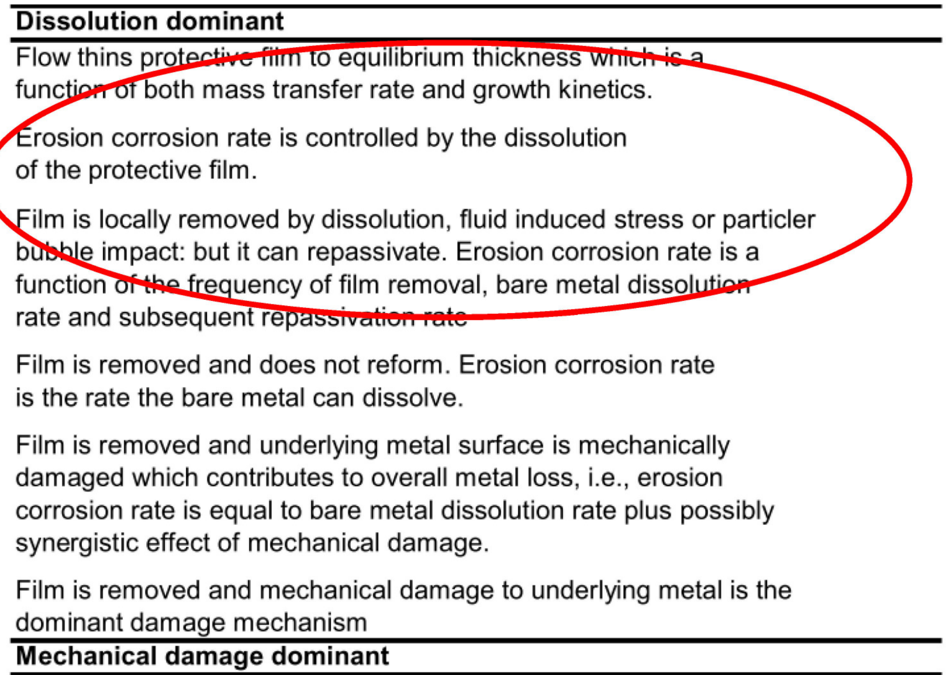
Flow-Assisted Corrosion in Nuclear Power Plants

1. INTRODUCTION

The structural health monitoring (SHM) of aging nuclear power plants is one of the most pressing problems facing industry, research community, and regulators. While a number of monitoring and managements programs are currently implemented, they all rely on periodic inspections through nondestructive evaluation techniques. On the other hand, in recent years a number of online monitoring techniques reached the level of maturity which allows them to be tested and validated in nuclear industry. Such techniques include online concentration sensors, fiber optics strain sensors and others. These sensor modalities can be used to monitor piping degradation in secondary circuits. There are a number of erosion-corrosion mechanisms which affect secondary piping and result in wall thinning. While some of these mechanisms, such as flow-assisted corrosion, is well understood and managed, others received less attention. However, even for the flow-assisted corrosion, all current management programs rely on periodic inspections and software forecasting without any online monitoring. The primary objective of this report is to provide an overview of the extant knowledge of flow-accelerated corrosion, or flow-assisted corrosion (FAC), and propose on-line monitoring techniques which can be used to continuously monitor the piping degradation in nuclear power plants. FAC is one of several corrosion mechanisms affecting secondary piping in nuclear power plants (NPPs). In this report, the FAC serves as a test bed to develop our research approach to SHM of secondary systems and to develop our parteneship with EPRI. The Light Water Reactor Sustainability (LWRS) Program, funded by the U.S. Department of Energy, Office of Nuclear Energy, aims to provide scientific and engineering foundations to extend the life of operating light water reactors (LWRs). This program involves several goals, one of which is ensuring safe operation of NPPs' passive components, such as concrete, piping, and cabling. Piping degradation due to corrosion is one of the major concerns for the U.S. Nuclear Regulatory Commission (NRC), as well as for utilities. Currently, all utilities implement a rigorous FAC management program that is based on a periodic maintenance strategy. Under the FAC management program, plant maintenance personnel inspect the piping during every outage using a localized technique (ultrasound, for example) to study corrosion and thinning of pipe walls. This approach is labor intensive, time consuming, and puts utilities at an economic disadvantage in comparison to other energy producing technologies, such as gas, for example. In high radiation exposure areas, it puts personnel at greater risk for radiological dosage. In addition, plant maintenance staff members have no means to monitor or estimate the increase in the rate of change in pipe corrosion on an online basis while plant is operational. Between two consecutive outages, the internal pipe wall thickness might degrade below the acceptable threshold limit and might result in pipe failure that forces an outage.

Current practices used by the nuclear industry to manage FAC have technical gaps that could be addressed by taking advantage of advancements in sensing, monitoring, and data analytics. These techniques may enable online monitoring of corrosion to support safe operation of current LWRs in the future. An online corrosion monitoring framework such as the one that is being considered for research in this report could enhance corrosion monitoring and reduce offline inspections during outages, thus reducing some of the operating costs associated with these types of inspections.

FAC is one of many corrosion mechanisms affecting piping in aging NPPs. As shown in Figure 1, FAC is a dissolution-dominated phenomenon with moderate flow rate contribution. It should be noted that all corrosion mechanisms in NPPs' piping are "flow-assisted", however the flow contribution to the corrosion differs, as shown in Fig. 1.



Dissolution dominant

Flow thins protective film to equilibrium thickness which is a function of both mass transfer rate and growth kinetics.

Erosion corrosion rate is controlled by the dissolution of the protective film.

Film is locally removed by dissolution, fluid induced stress or particler bubble impact: but it can repassivate. Erosion corrosion rate is a function of the frequency of film removal, bare metal dissolution rate and subsequent repassivation rate

Film is removed and does not reform. Erosion corrosion rate is the rate the bare metal can dissolve.

Film is removed and underlying metal surface is mechanically damaged which contributes to overall metal loss, i.e., erosion corrosion rate is equal to bare metal dissolution rate plus possibly synergistic effect of mechanical damage.

Film is removed and mechanical damage to underlying metal is the dominant damage mechanism

Mechanical damage dominant

Figure 1. The spectra of erosion-corrosion mechanisms with FAC region marked with red ellipse. Source [2].

FAC is primarily a corrosion process aided by chemical dissolution and mass transfer, as shown in Figure 2. FAC is overtaken by erosion processes at higher flow rates. FAC normally starts at flow rates of 3 meters per second (m/s), although lower flow rates are reported in the literature, and is replaced by shear stress corrosion processes at around 10 m/s in single-phase flows. Two-phase flows have slightly different mechanism are described later in this report. Specifically, the FAC region can extend up to a flow velocity of 30 m/s for two-phase flows.

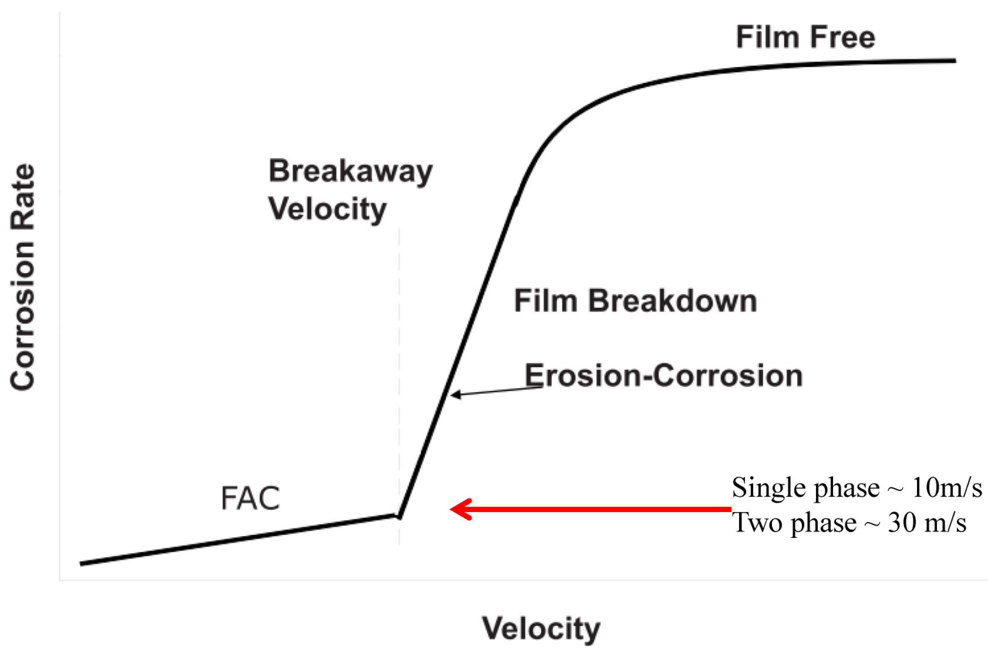


Figure 2. A schematic diagram of corrosion dependence on flow velocity. Source [2].

2. ELECTROCHEMISTRY OF FLOW-ACCELERATED CORROSION

FAC of carbon or low-alloyed steel piping occurs when the rate of dissolution of the protective magnetite oxide film (Fe_3O_4) that forms on the internal piping surface in a stream of flowing water or wet steam is enhanced, leading to an increased wall thinning rate [1–6]. The thickness of the magnetite protective oxide layer is normally less than 30 micrometers (µm). FAC is currently a primary concern, because more than 60% of all utilities have reported finding it in their piping components [1].

In general, the FAC process consists of two steps: (1) production of soluble iron species at the oxide/water interface by anaerobic iron oxidation and (2) mass transfer of the soluble and particulate iron species to the bulk flow across the porous diffusion boundary layer. Though FAC is characterized by a general reduction in pipe wall thickness for a given plant component, FAC frequently occurs over a limited area, such as a pipe elbow, due to a local, high area of turbulence. The rate of the wall metal thinning due to FAC depends on a complex interaction of a number of parameters, such as material composition, feedwater chemistry, geometry, and hydrodynamics. Rates up to 3 millimeters per year (mm/year) have been reported [3].

The hydrodynamic parameters affect the mass transfer rate of the corrosion products to the bulk water and, as a result, the FAC rate through concentration gradient changes. These hydrodynamic parameters are the flow velocity, geometry, Reynolds number, pipe roughness, piping geometry, and steam quality or void fraction for two-phase flows. Numerous inspections of power plants around the world have shown that piping and tubing components located downstream of flow singularities, such as expansion/contractions, orifices, valves, and elbows, are most susceptible to FAC. This vulnerability is attributed to the severe changes in flow direction and pressure, as well as the development of secondary flow turbulence downstream of such singularities, which causes higher removal rates for iron. Several parameters impact the extent of FAC degradation, including the geometrical configuration of the components, piping geometry, flow Reynolds (Re) number, water chemistry, water temperature, piping material, and the flow turbulence structure, which affect the surface shear stress and mass transfer coefficients.

A review by Poulson [1] of FAC in power plant piping systems established that the single- and two-phase flow conditions produce two very different wear patterns. Recently, Schmitt and Bakalli [7] suggested that FAC is initiated when the flow dynamic kinetic forces surpass the fracture energy of the protective oxide layers. FAC is considered an extension of the general corrosion process of carbon steel in stagnant water. The major difference is the effect of water flow on the oxide-water interface. FAC degradation mechanisms consists of a number of processes that occur at the interface of iron-magnetite, in the oxide layer, and at the interface of oxide-water [1–7]. These FAC processes are depicted in Figure 3 [8–10]. Notice that the turbulence of the flow expressed as Re number increases with the distance from the wall surface “y”, while ferrous ions concentration $c = f(y)$ decreases.

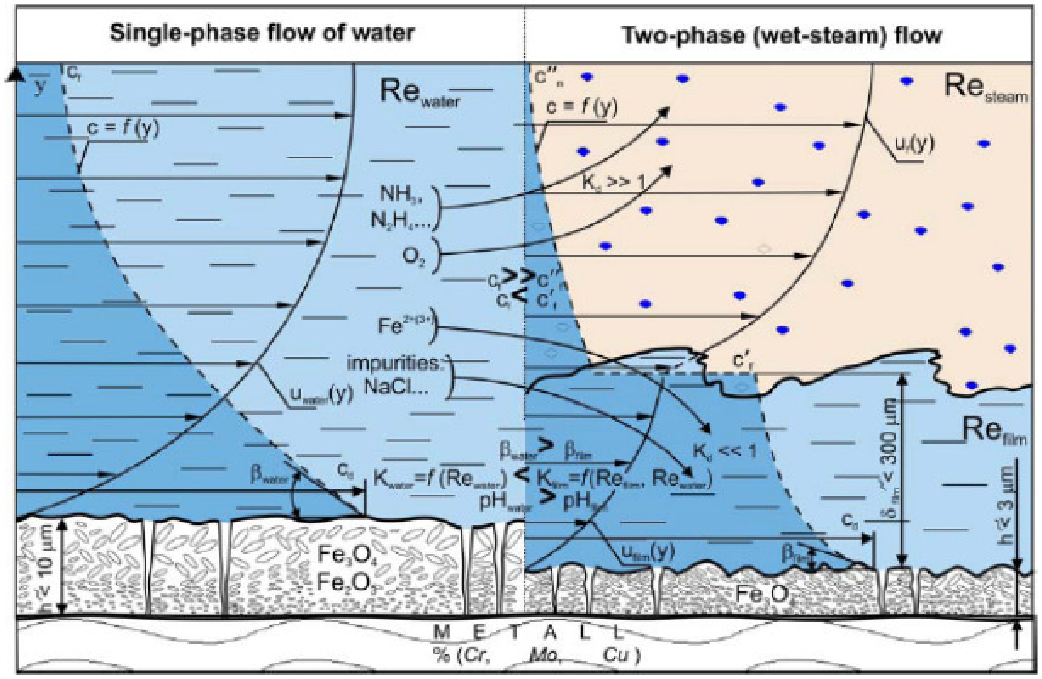


Figure 3. Mechanisms of FAC in single- and two-phase flows. Source [10].

According to References 8–10, fundamental differences exist between FAC in single- and two-phase flows. Specifically, in a single-phase water flow, it can be assumed with sufficient confidence that the parameters determining the nature and intensity of the corrosion factor (pH, conductivity, concentration of oxygen, iron-containing compounds, water treatment additives, impurities, etc.) change only slightly over a section of pipe and along the pipe.

As a result, when modeling processes of FAC degradation in single-phase water flow, use of averaged values of the water chemistry parameters is acceptable. For the single-phase flow, the electrochemistry involved in FAC is better understood (Figure 4) [11]. Conversely, under two-phase flow conditions, the FAC mechanism is determined by local values of the physical-chemical parameters and characteristics of corrosion processes (the pH, conductivity, temperature, etc.) and hydrodynamic conditions (Re_{film}, Re_{steam}, for instance) in the liquid film and in the two-phase boundary layer near the wall. As a consequence of the non-uniform interphase redistribution of the gases, contaminants, and impurities, the local values of the pH of the liquid film and other parameters may considerably differ from the mean value of the pH/parameters for the flow.

Thus, the methods for calculating the mass transfer coefficient in the liquid film are not entirely equivalent to those in a single-phase flow [9]. This results in nonlinear, time-dependent nature of the two-phase FAC, which is not captures by currently existing models.

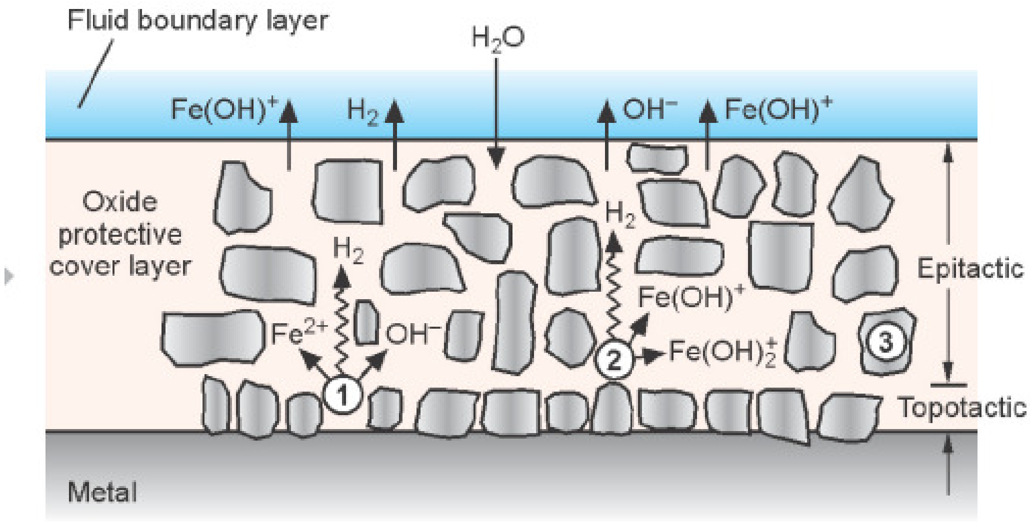


Figure 4. The schematics of electrochemistry processes involved in single-flow FAC. Source [11].

The chemical reactions involved into FAC process are as follows:

$Fe+2H2O \rightarrow Fe2++2OH-+H2\uparrow$ (1)

$Fe^{+2}+2OH^- \leftrightarrow Fe\,(OH)_2\downarrow$ (2)

$3Fe(OH)_2 \leftrightarrow Fe_3O_4\downarrow + 2H_2O + H_2\uparrow$ (3)

Equation (1) is the reaction of iron oxidation under anaerobic conditions. It should be stressed that FAC is largely an anaerobic process, and water oxygenation may significantly reduce the FAC rates. Equation (2) is formation of ferrous hydroxide, which penetrates into bulk fluid, and Equation (3) is formation of magnetite (Fe_3O_4) through the Schikorr reaction. Equation (2) is considered to be the rate-setting reaction and thus determines the rate of the magnetite formation.

Iron reacts with water to form a surface oxide layer. This oxide dissolves in the water to form ferrous ions, Fe^{+2}, and the rate of iron removal (the FAC rate) is controlled by the rate of diffusion of dissolved iron species through the boundary layer of water near the surface in the bulk water. The fluid boundary layer is an interface between magnetite and bulk water and is characterized by an elevated concentration of corrosion products in comparison to bulk water. $FeOH^+$ is the hydrolyzed Fe^{+2} species in solution. This diffusion rate (or mass transport of iron away from the surface) depends directly on the concentration of soluble iron species at the oxide layer surface and inversely on the thickness of the fluid boundary layer. Most importantly, it creates concentration gradient for iron species and directly affects the FAC rates. At equilibrium conditions, the concentration gradient is small and the diffusion of iron species is negligible. Thus, a decrease of the boundary layer thickness due to increased water flow rate or because of local turbulence and concentration gradient causes an increase in the corrosion rate, thus increasing the FAC rate [12]. The main electrochemical steps leading to FAC are listed below [12]:

- Fe (metal) → Fe^{+2} (oxide-metal interface)
- Fe^{+2} (oxide) diffuses through oxide to water interface
- Fe^{+2} (oxide-water interface) → FeOH + (dissolved in boundary layer)
- $FeOH^+$ (dissolved) diffuses through boundary layer to bulk water
- $FeOH^+$ may get carried away by bulk water

- $FeOH^+$ (Bulk water) → Fe_2O_3 (particles, suspended in flowing water).

The most important effect of flow velocity on FAC rates is related, however to the solubility limit of the dissolving ionic species in the bulk water. The bulk water of a given specific chemistry has a solubility limit for ionic species at the given (operating) pH level and temperature. Once the dissolving ions reach the bulk water solution and approach the solubility limit, further dissolution is reduced due to saturation. This is where the flow acceleration of corrosion rate occurs. The flow velocity provides a fresh liquid solution (bulk water) to the metal surface and has a large dissolving capacity to take in the soluble ions, thereby increasing the corrosion rate with velocity. Therefore, FAC is mainly governed by the flow velocity/turbulence affecting the boundary layer on the inside of the pipeline/component and also by the solubility limit of the dissolving ions at the operating parameters [12].

Under operating conditions with laminar flow, the magnetite is protective where its growth is usually exactly balanced by its dissolution of mainly ferrous ions in the flowing water or steam/water mixture. Depending on the temperature and water chemistry, the magnetite thickness may reach 15–25 µm, but it can be very thin at temperatures below about 150°C (302°F). Magnetite growth is controlled by the local cycle chemistries. Wherever turbulent flow conditions exist as a result of local geometries, the dissolved ferrous ions are more rapidly removed from the surface creating concentration gradient.

The process of magnetite removal is balanced by the growth of more magnetite on the inner carbon steel surface. This faster oxide removal means a faster overall corrosion process (i.e., FAC) and thinner remaining magnetite on the surface. FAC only occurs in water and water/steam mixtures and not in dry steam, because the magnetite is not dissolvable in steam and there is also no mechanical damage to the metal as in liquid droplet erosion and cavitation.

As early as the 1980s, the influences of the following factors on FAC had already been identified and, in some cases, experimentally quantified: pH, dissolved oxygen, reducing agents, temperature, mass transfer, and alloying steel composition. FAC in carbon-steel pipe systems is characterized by the simultaneous dissolution of iron from the iron-oxide/fluid interface and the formation of an iron oxide film at the oxide-metal interface. Bulk liquid flow plays a vital role in providing a sink for dissolution. Under stagnant conditions, corrosion products would concentrate in the aqueous solution, reducing the concentration gradient's driving force for the corrosion process. Flow inhibits this concentration process and enhances the concentration gradient.

Major FAC-induced structural pipe failures are dramatic and sudden. The FAC failures have break-before-leak (BBL) rather than leak-before-break characteristics. FAC-susceptible piping poses an occupational safety hazard and can result in power reduction, manual or automatic reactor shutdown, and economic losses. The overall effects of FAC-induced pipe failure, including collateral equipment damage and area spraying/flooding, can be considerable. Even a small steam leak can adversely affect the fire protection system and electrical equipment adjacent, or relatively close, to the leak. Therefore, consideration of FAC is an integrated part of the current internal flooding probabilistic safety assessment practice and modeling of high-energy line breaks.

Significance determination process assessments are concerned with determining the risk significance of degraded/failed piping, including FAC-induced failures. Risk-informed, high-energy line break analyses can be used to strengthen an existing FAC program. Despite led efforts led by the Electric Power Research Institute and the progress with implementation and maintenance of comprehensive inspection programs, FAC-induced pipe failures continue to cause power reductions and forced outages. These failures can be indicative of programmatic weaknesses, as well as the challenges in identifying vulnerable locations. Also, plant modernization and power uprate projects involving piping design changes may result in new regions being susceptible to FAC.

In the 1990s, a new FAC wear effect was discovered and documented. This effect has been called the "leading edge effect" or the "entrance effect." This effect occurs when water flow passes from a

FAC-resistant material to a nonresistant (susceptible) material, which causes a highly localized increase in the corrosion rate. This effect is generally manifested by a groove upstream or downstream of the attachment weld between the FAC-vulnerable and the resistant material. In one relatively recent example, significant wear was detected in an expander. The area in question consisted of a valve followed by a 150- × 200-mm expander attached to another 200- × 400-mm expander. A number of FAC inspections had been performed before and after replacement of the upstream expander that had resistant material due high FAC wall thinning. A very energetic thinning rate of 1.77 mm per cycle was noted over the subsequent refueling cycles; this prompted replacement of the downstream expander during an outage.

FAC mainly affects the secondary circuit of pressurized water reactors, but boiling water reactor (BWR) feedwater piping is also susceptible to single-phase, FAC-induced damage. In BWRs, several main steam line subsystems, including the high-pressure turbine exhaust piping, the turbine crossover piping, the extraction steam lines, and certain straight portions of the steam lines, are susceptible to two-phase FAC.

3. STATISTICS OF FAC IN NUCLEAR POWER PLANTS

The statistics on FAC-related accidents and incidents are maintained for both nuclear and fossil-fuel power plants.

On December 9, 1986, for example, an elbow in the condensate system ruptured at the Surry Nuclear Power Station. The failure caused four fatalities and millions of dollars in repair costs and lost revenue. FAC was found to be the cause of the failure. Because of the deaths involved and the high degree of oversight applied to nuclear power plants, a comprehensive overall approach was deemed to be necessary to address the causes and prevent further recurrences. An intensive international cooperative effort was initiated to understand the parameters that affect FAC.

Table 1 lists the failures in NPPs since 1982 that were caused by FAC and resulted in bursts, extensive plant damage, or fatalities. The continuing occurrence of FAC failures is evidence that utilities programs to mitigate FAC are needed and could potentially be augmented with other sensor modalities as industry knowledge evolves and more operating experience and plant data become available [1]. One such improvements could be the introduction of FAC on-line monitoring techniques, that rely on additional sensor modalities to improve the response time and sensitivity of the FAC monitoring programs.

The most comprehensive database on FAC-related failures in NPPs is maintained by the Nuclear Energy Agency, which is a specialized agency within the Organization for Economic Cooperation and Development. The database is part of the agency’s Component Operational Experience, Degradation, and Ageing Programme (CODAP) [13]. The CODAP project exchanges data between members on passive NPP component degradation and failure, including service-induced wall thinning, non-through-wall cracks, leaking through-wall cracks, pinhole leaks, leaks, ruptures, and pipe severance. For non-through-wall cracks, the CODAP scope encompasses degradation exceeding the design code for wall thickness or crack depth, as well as such degradation that could have general implications regarding the reliability of in-service non-destructive evaluation techniques (NDE).

Table 1. Summary of the most serious FAC accidents in NPPs since 1982. Source [13].

Plant	Type	Date	Phase	System
Oconee	PWR	6/82	Two-phase	Extraction
Navajo	Fossil	11/82	Single-phase	Feedwater
Surry	PWR	12/86	Single-phase	Condensate
Trojan	PWR	6/87	Single-phase	Feedwater
Arkansas Nuclear One	PWR	4/89	Two-phase	Extraction
Santa Maria de Garona, Spain	BWR	12/89	Single-phase	Feedwater
Loviisa, Finland	PWR	5/90	Single-phase	Feedwater
Millstone 3	PWR	12/90	Single-phase	Separator drain
Millstone 2	PWR	11/91	Single-phase	Reheater drain
Sequoyah	PWR	3/93	Two-phase	Extraction
Sequoyah	PWR	11/94	Single-phase	Condensate
Pleasent Prairie Power Plant	Fossil	2/95	Single-phase	Feedwater
Millstone 2	PWR	8/95	Single-phase	Heater drain
Fort Calhoun	PWR	4/97	Two-phase	Extraction
Point Beach 1	PWR	5/99	Two-phase	Feedwater heater
Callaway	PWR	8/99	Two-phase	Reheater drain
H.A. Wagner 3 Power Plant	Fossil	7/02		Feedwater heater line
Mihama 3, Japan	PWR	8/04	Single-phase	Feedwater
Edwards Power Plant	Fossil	3/05	Single-phase	Feedwater
South Ukraine 2	VVER	7/05		Feedwater heater line
South Ukraine 2	VVER	8/05		Reheater drain

The available service experiences and in-service inspection data show that piping components with complex geometries are most susceptible to FAC. Typical components that have been frequently susceptible include [13]:

- Tees and branch connections
- Expanders and reducers
- Long- and short-radius elbows
- Steam traps
- Exit nozzles
- Orifices
- Valve bodies with flow changes
- Significant inner surface discontinuity (if present).

Piping systems that are susceptible include safety-related as well as balance-of-plant (BOP) systems. Balance-of-plant piping systems, i.e., piping outside the reactor coolant pressure boundary, are not included in the nuclear steam supply system. The following are examples of carbon-steel piping structures that are typically monitored for FAC in NPPs:

- Feedwater piping (in BWR plants, this consists of piping outside the containment, and in pressurized water reactor [PWR] plants, this consists of piping inside and outside the containment)

- Feedwater heater drains and vents
- Moisture separator drains
- Moisture separator reheater drains
- Steam generator blowdown (in pressurized heavy water reactor [PHWR] and PWR plants)
- Feeder lines that are an integral part of the primary heat transport system in PHWRs
- High-pressure coolant injection pump steam supply and drain (BWR)
- Main steam system (this consists of piping outside the containment and includes turbine bypass piping)
- Auxiliary steam system
- Auxiliary feedwater system
- Auxiliary feedwater pump steam supply system
- Cross around (large-diameter wet steam piping between the high-pressure turbine and moisture-separator reheater and the relatively dry steam between the moisture-separator reheater and low-pressure turbine).

The total FAC event population in the CODAP Event Database consists of 1,987 records involving the thinning of pipe walls below the minimum allowable thickness, through-wall leaks, and ruptures for the period of 1970–2012 (Figure 5). Records on wall thinning have resulted in corrective actions, including temporary repairs (e.g., weld buildup, welded patch, and engineered clamp), volunteer pipe replacement, or replacement with FAC-resistant material. Of the total event population collected in CODAP database, 80% represents U.S. operating experience.

Non-U.S. data are limited to selected representative events. As a result, the FAC event population is inhomogeneous, reflecting different raw data screening criteria, as well as different maintenance and inspection practices. The participants of the CODAP project exchange data on passive component degradation and failure, including service-induced wall thinning, non-through-wall cracks, leaking through-wall cracks, pinhole leaks, leaks, ruptures, and severance (pipe breakage caused by external impact).

For non-through-wall cracks, the CODAP scope encompasses degradation exceeding the accepted thresholds on such parameters as wall thickness or crack depth, as well as such degradation that could have wide spread implications regarding the reliability of in-service inspection techniques. In other words, the CODAP Event Database collects data on the full range of degraded conditions, from precursors to major structural failures. The structural integrity of a pressure boundary is determined by multiple and interrelated reliability attributes and influence factors. Depending on the conjoint requirements for damage and degradation, certain combinations of piping materials, operating conditions, loading conditions together with applicable design codes, standard, and thresholds certain passive components are substantially more resistant to damage and degradation than others [13].

Region	Plant Type	Failure Mode	CODAP Event Database FAC Event Records					
			Total No. of Records	1970-79	1980-89	1990-99	2000-09	2010-12
North America	BWR	Wall Thinning	138	3	72	17	44	2
		Through-Wall Leak	183	30	43	45	52	12
		Rupture	10	1	5	2	2	0
	PHWR	Wall Thinning	57	0	24	5	27	1
		Through-Wall Leak	11	0	2	6	2	1
		Rupture	1	1	0	0	0	0
	PWR	Wall Thinning	1060	0	783	78	192	7
		Through-Wall Leak	160	10	52	49	39	10
		Rupture	35	0	19	12	4	0
Asia	BWR	Wall Thinning	18	0	0	7	10	1
		Through-Wall Leak	11	1	2	2	6	0
		Rupture	1	0	0	1	0	0
	PHWR	Wall Thinning	6	0	0	0	6	0
		Through-Wall Leak	3	0	0	0	3	0
		Rupture	1	0	0	0	1	0
	PWR	Wall Thinning	32	0	0	15	15	2
		Through-Wall Leak	7	0	3	1	3	0
		Rupture	2	0	0	1	1	0

Region	Plant Type	Failure Mode	CODAP Event Database FAC Event Records					
			Total No. of Records	1970-79	1980-89	1990-99	2000-09	2010-12
Europe	BWR	Wall Thinning	62	2	10	38	11	1
		Through-Wall Leak	48	1	22	7	17	1
		Rupture	3	1	2	0	0	0
	PWR	Wall Thinning	30	0	8	7	14	1
		Through-Wall Leak	86	0	24	42	19	1
		Rupture	22	2	2	10	8	0
		Totals:	1987	52	1073	345	476	40

Figure 5. FAC event population. Source [13].

Figure 5 shows a relatively stable number of FAC-related accidents over the years regardless of implementation of FAC management programs. This can be explained by the fact that the FAC management programs are not keeping up with pipe degradation or by more rapid degradation of the piping components as plants age. It should be noted though that the 2010-2012 data are only available for two years.

The total number of failures during 2000-2009 period is higher than the number of failures during 1990-1999. Figure 6 shows the distribution of FAC-related events by plant components. Wall thinning is the leading pipe degradation phenomenon in practically all components. The largest contributors to this event population are FAC in extraction steam piping (two-phase flow) and FAC in feedwater piping (single-phase flow). The primary heat transport system event population consists of small-bore (diameter $\leq$ 100mm) reactor outlet feed pipes of cold-drawn carbon steel. This event population is unique to PHWR plants. Also, the dominant degradation is wall thinning.

In Figure 7, the total FAC event population is organized by pipe size (small-bore versus large-bore piping) and failure mode (wall thinning, through-wall leak, and rupture). FAC programs typically define "small-bore" as piping having a diameter of 100 mm or less, for US plants small bore are 3 inches or less. The currently available version of CHECWORKS software does not address FAC in small bore pipes. However, out of 88 inspections performed at US nuclear power plants, 18 are performed on small bore pipes.

Figure 8 represents the number of FAC events as a function of reactor type and calendar year. Notice that the number of FAC events as a function of the calendar year is not monotonic, but rather cyclic. Figure 9 shows an interesting statistic on FAC events as a function of component age. Notice that the majority of the events are occurring when the components are between 9 and 15 years of age and that there is a significant drop after that time. This can be explained by "the burning out" effect when components that are "destined" to fail due to manufacturing defects, local conditions, etc., do fail, and the ones that survived do not fail.

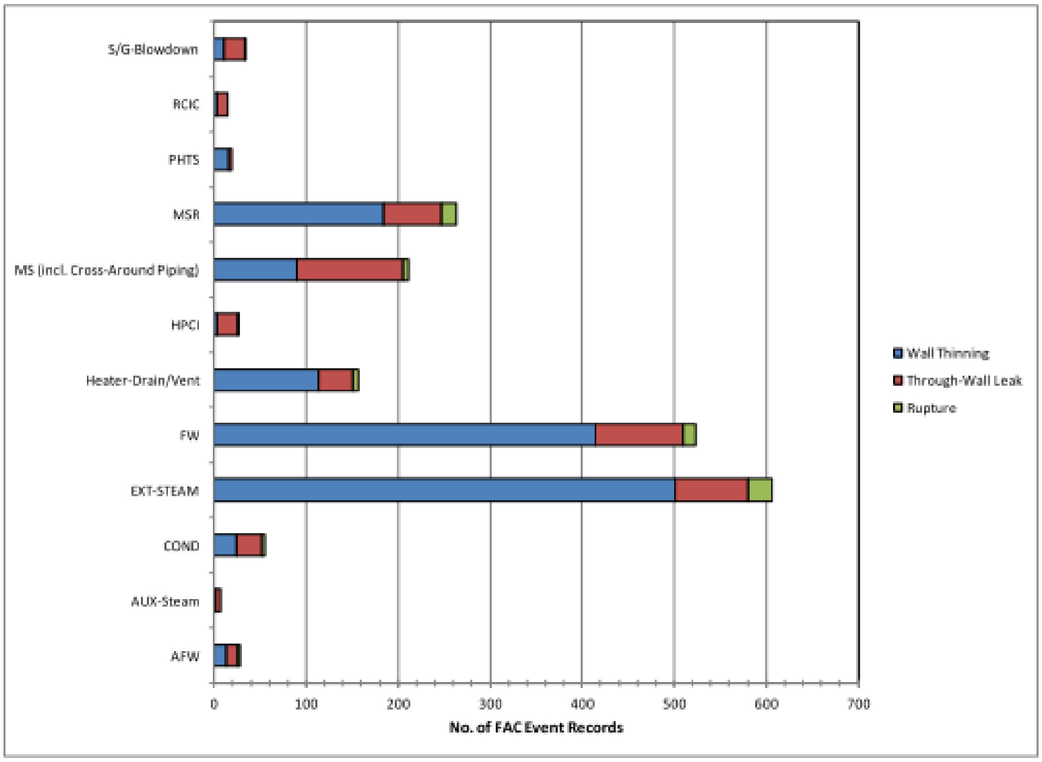
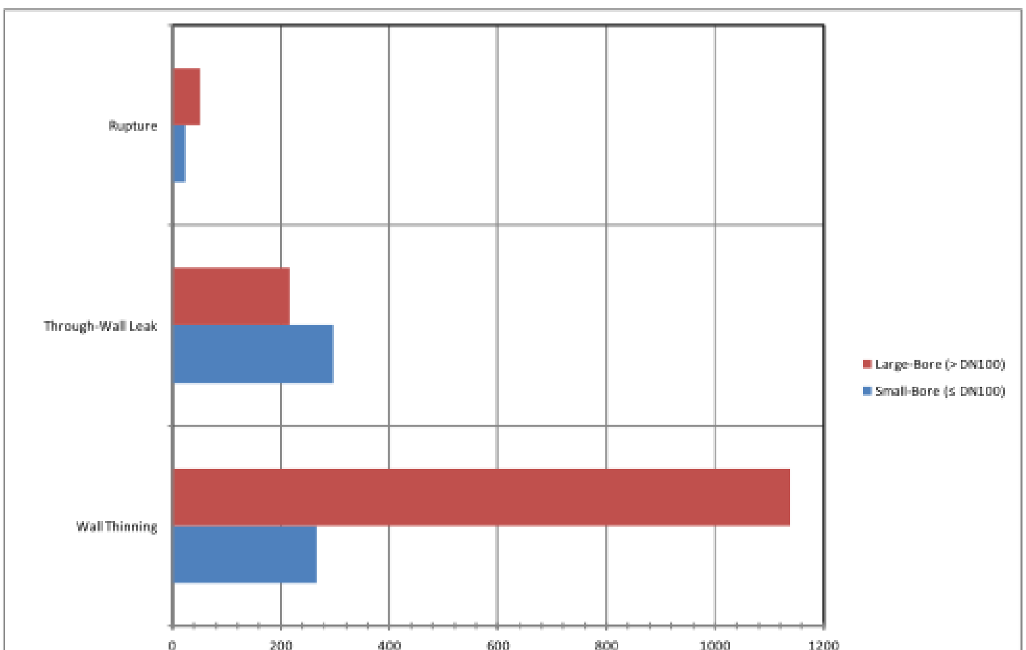
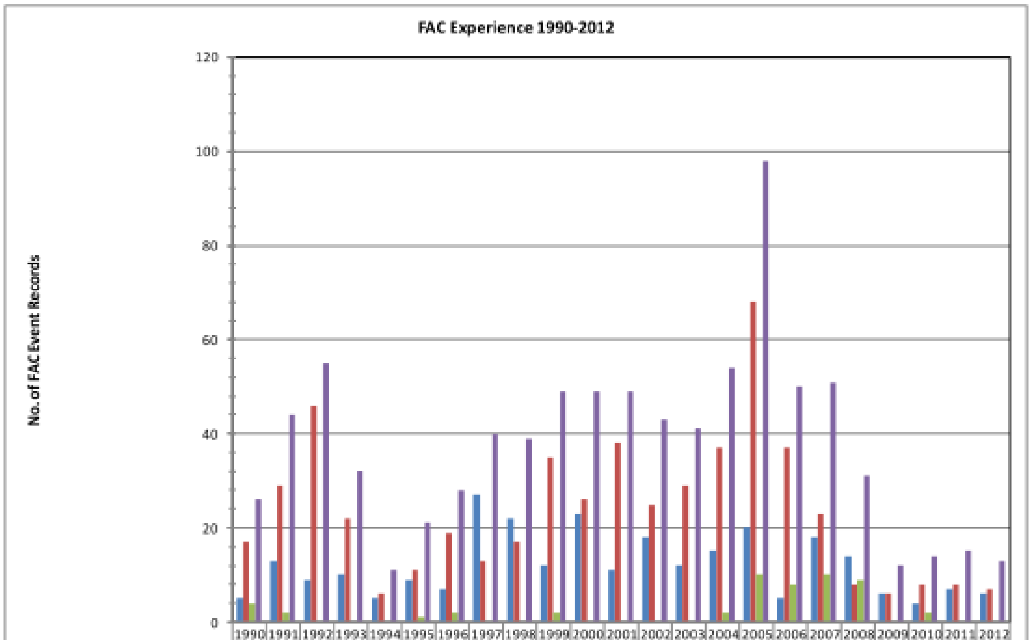


Figure 6. FAC events by plant component. Source [13].



	Wall Thinning	Through-Wall Leak	Rupture
Large-Bore (> DN100)	1138	217	50
Small-Bore (≤ DN100)	265	296	25

Figure 7. FAC events by pipe size. Source [13].



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
BWR (278 Records)	5	13	9	10	5	9	7	27	22	12	23	11	18	12	15	20	5	18	14	6	4	7	6
PWR (535 Records)	17	29	46	22	6	11	19	13	17	35	26	38	25	29	37	68	37	23	8	6	8	8	7
PHWR/CANDU (52 Records)	4	2				1	2			2					2	10	8	10	9		2		
All Plant Types (865) Records)	26	44	55	32	11	21	28	40	39	49	49	49	43	41	54	98	50	51	31	12	14	15	13

Figure 8. Number of FAC events by plant type and calendar year. Source [13].

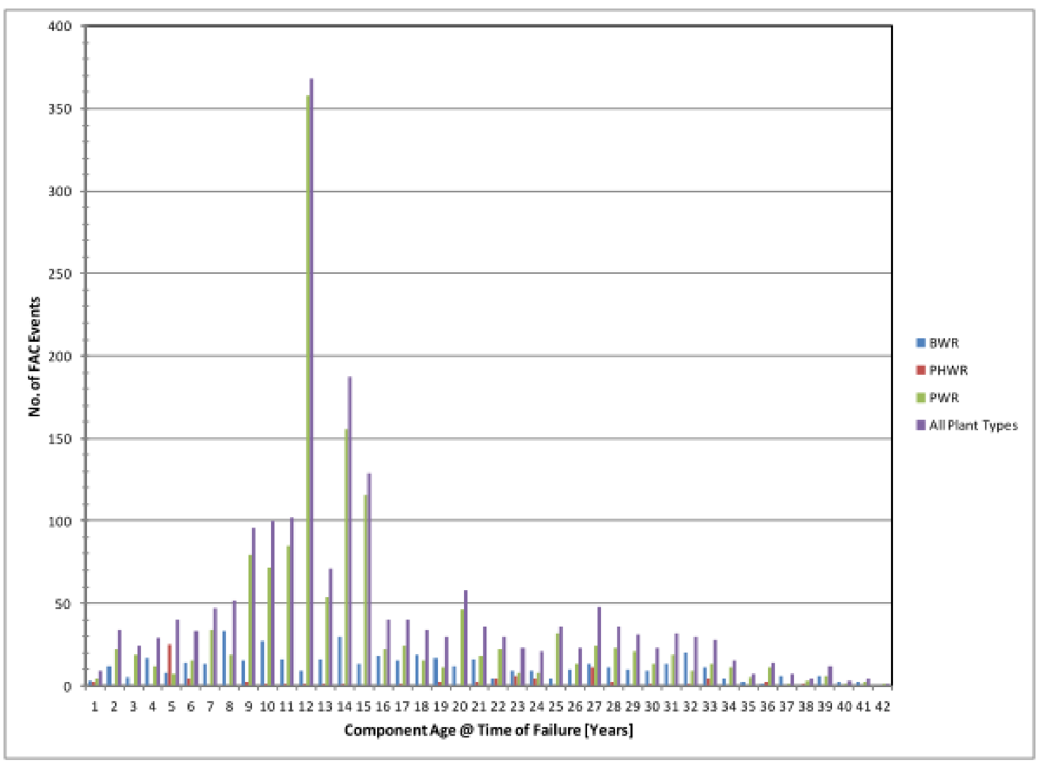


Figure 9. FAC events as a function of component age at the time of failure. Source [13].

The objective of any FAC program is to predict wear rates and prevent through-wall failures/ruptures or BBL-events from occurring. Despite the committed efforts to comprehensively manage FAC, pipe failures occur due to inadequate implementation of inspection plans and inaccurate wall-thinning forecasts. The CODAP database contains numerous examples of programmatic deficiencies. The following are examples of recent FAC events that can be attributed to programmatic deficiencies as described in [13]:

- *"Through-wall leak develops prior to next scheduled inspection*: This is usually an indication of higher-than-forecasted wall-thinning rates. It also includes instances where pipe routing has been modified or replaced without corresponding changes to the FAC monitoring program. An example of the latter type of monitoring deficiency is the failed extraction steam drain line in a Japanese BWR plant in 2010. The turbine rotors had been replaced in 2009 to improve thermal efficiency. This design change involved rerouting the drain piping, which in turn resulted in an increased drain flow and higher-than-predicted wear rate.
- *Failure occurs in a location identified by predictive program as susceptible*: This failure happens when the vulnerable location has not been transferred to the inspection plan in a timely manner. An example of this type of failure is the ruptured first stage extraction steam line at a U.S. PWR plant. The event occurred during the first quarter of 2009. The failed line was listed in the FAC program documentation as susceptible but was not monitored at the failed location. This type of deficiency can also be caused when the piping is replaced, but the replacement is not identified in the FAC-monitoring software.
- *Failure occurs due to FAC software model input errors*: During the third quarter of 2006, a moisture separator reheater drain line failed at a U.S PWR plant. The FAC monitoring program included inaccurate wear prediction due to a computer software modeling error that resulted from a lack of verification efforts by the utility. In addition, the FAC management personnel did not recognize that a formal second level of verification was needed to ensure a quality software model was in place to guarantee the safety of plant personnel and plant's availability.
- *Inadequate FAC program implementation*. In 1999, a U.S. PWR plant experienced a rupture of a moisture separator reheater drain line. The failure occurred in a straight section of pipe immediately downstream from a 45-degree elbow in the pipe. All FAC management programs recognize that such elbows are vulnerable to FAC. The first reason for this failure was identified as the manner in which the FAC inspection program provided guidance for inspecting downstream piping when performing fitting gridding inspections. The program did not consider downstream piping inspections as mandatory, although such piping is known to be a vulnerable location. Nevertheless, this downstream piping was not inspected when the upstream 45-degree elbow was inspected during previous refueling outages. Had this piping been previously inspected, an abnormal wear rate likely would have been detected through software forecast. The second reason involved the correct perception that the upstream 45-degree elbow would be the most susceptible component for failure due to FAC. However, this causal factor contributed to the decision made during previous refueling outages to not inspect the downstream piping associated with this elbow."

The above analysis shows that there are a number of areas where the FAC management programs may potentially benefit from on-line monitoring. Specifically, the higher than forecasted wall-thinning rates may have been detected by online monitoring techniques and the forecast could have been adjusted to reflect the increase in wear rates. Notice that the higher than inspected wear rates cannot be addressed by currently implemented FAC management programs, since they rely on off-line inspections. Also the online monitoring could help to alleviate the second deficiency on the list by continuously monitoring the corrosion situation. The failures due to input errors and inadequate program implementation could also be alleviated by implementing the on-line monitoring tool, since it would always be on, and can provide continuous surveillance of piping degradation.

4. FACTORS AFFECTING FLOW-ASSISTED CORROSION RATES

FAC is a complex multi-parameter phenomenon. The interplay of different FAC parameter is shown in Figure 10 [14].

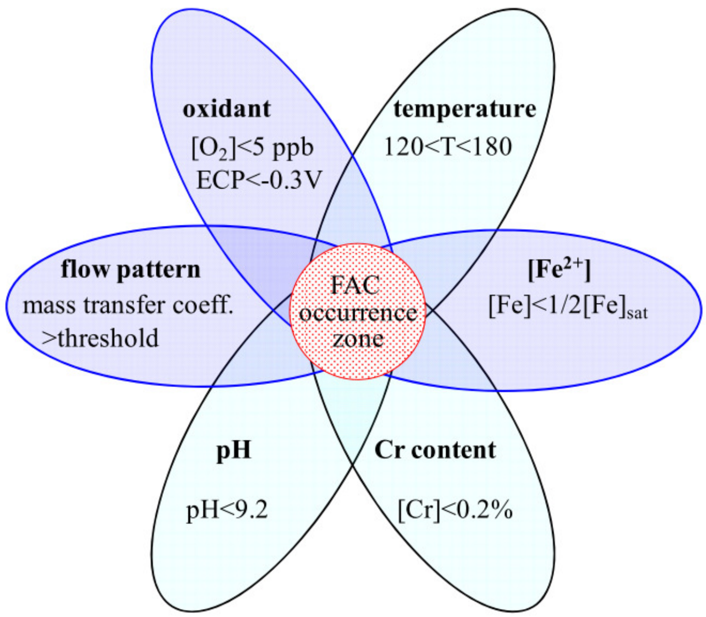


Figure 10. Major parameters influencing FAC. Source [14].

Several parameters affect the extent of degradation due to FAC, including the geometric configuration of the piping components, piping orientation, flow Re number, water chemistry, fluid temperature, piping material, and the flow turbulence structure that affect the surface shear stress and mass transfer coefficients [6]. The most important parameters of FAC are described in this section.

4.1 Oxidation-Reduction Potential

Redox-potential or oxidation-reduction potential and, more generally, the corrosion or mixed potential (ECP) are indicators of the balance between the reducing and oxidizing agents during the corrosion process. The major contributors to the ECP values in NPP water systems are dissolved oxygen, hydrazine, and dissolved iron. While ECP has been recognized as the most important parameter influencing the single-phase FAC, its measurement is infeasible in the bulk water. Concerning two-phase FAC conditions, oxygen partitions to the steam phase, and therefore the possible positive effect of oxygen on the FAC rate, do not apply to such conditions [15]. There is a decrease of more than four orders of magnitude in the FAC rate of carbon and low-alloy steel in water at 120°C when the oxygen concentration is 150–500 micro-gallons per liter (µg/L) as compared to deoxygenated conditions. This is due to the fact that FAC reactions are largely anaerobic. Furthermore, significantly smaller oxygen concentrations, as small as 10 µg/L, can reduce the FAC rate even when a large excess of hydrazine is present in the process water. This phenomenon has been demonstrated both in PWR and fossil-fuel power plants. Oxidizing conditions will exist in the systems with reducing agents when the oxygen level is only slightly above10µg/L, whereas at an oxygen concentration of 30–150 µg/L the electrochemical potential of the steel increases with hundreds of millivolts resulting in other corrosion problems [5, 27]. According to the data collected in the test loops and power plants, the lowest threshold limit for the reduction of FAC with oxygen is 1µg/L [15]. In summary, in PWRs, the FAC rates are inversely affected by the amount of dissolved oxygen in the feedwater, and low oxygen levels are harmful to carbon-steel piping. The FAC rate decreases rapidly when the water contains more than 20 parts per billion (ppb) oxygen [20]; however, the precise oxygen level required to prevent FAC depends on other factors, such as pH and the presence of contaminants.

In BWRs, hydrogen water chemistry (HWC) can be applied with the main intention to suppress intergranular stress corrosion cracking susceptibility and crack growth rate. The FAC rate has been measured in a laboratory test to be higher for a period of 8 months after starting HWC. After this time, the FAC rate appears to be similar to that in a reference normal water chemistry environment. General Electric guidelines consider an oxygen level of 20 to 50 ppb advisable for hydrogen for HWC. Some plants are required to add oxygen to their feedwater when using HWC, while others are not. The effects of higher hydrogen levels under normal water chemistry depends on plant conditions and must be taken into account. The use of noble metals to reduce the quantities of hydrogen required to establish HWC conditions in a BWR has not had a more pronounced effect on FAC than the application of HWC itself.

Main steam lines made of carbon steel are susceptible to FAC in the wet steam phase, because most of the oxygen, being a gas, remains in the steam phase and does not partition to the liquid. For the same reason, injection of oxygen into the wet steam will not prevent FAC. Injection of hydrogen peroxide has been explored as a possible mitigation for FAC, because most of the hydrogen peroxide partitions to the liquid phase, spontaneously decomposes into oxygen and water, and thus enriches the liquid phase with oxygen. However, although the FAC rate is decreased, hydrogen peroxide injection is not as effective as a remedy against FAC as replacement of materials to low alloy steel (alloyed with chromium) or the presence of a stainless-steel coating.

4.2 Water pH

The pH is the second most important water chemistry influence on FAC. The at-temperature pH has a first-order effect on the FAC rate due to its effect on magnetite solubility, as shown in Figure 11. Small changes in at-temperature pH can have major effect on solubility of magnetite and consequently on the FAC rate. According to the literature, solubility of magnetite at 198°C decreases by a factor of 2 for every 1 unit of at-temperature pH above pH 5.3 [16].

It has been experimentally established that the FAC rate has a nonlinear dependency on pH [17]. The magnetite removal rate was found to decrease steeply around pH 9.0 to 9.5. The FAC rate generally followed the form of the magnetite solubility curve. However, while solubility decreases by two orders when pH changes from neutral to 10.4, the FAC wear rates decrease less dramatically. In general, increasing the pH value reduces the wear. The FAC wear rate of carbon steels increases rapidly in the pH range of 7–9 and drops sharply above pH 9.2 [4]. As the fluid becomes more acidic (low pH), more pipe wall losses are expected. The pH value can be affected by the choice of water chemistry control agents (e.g., morpholine or ammonia) and by other impurities in the water. In two-phase flows, the critical parameter is the pH of the liquid phase, not the steam. This can be significantly affected by the partitioning of the control agent between the steam and liquid phase. No adjustment of pH is performed in BWR plants [15].

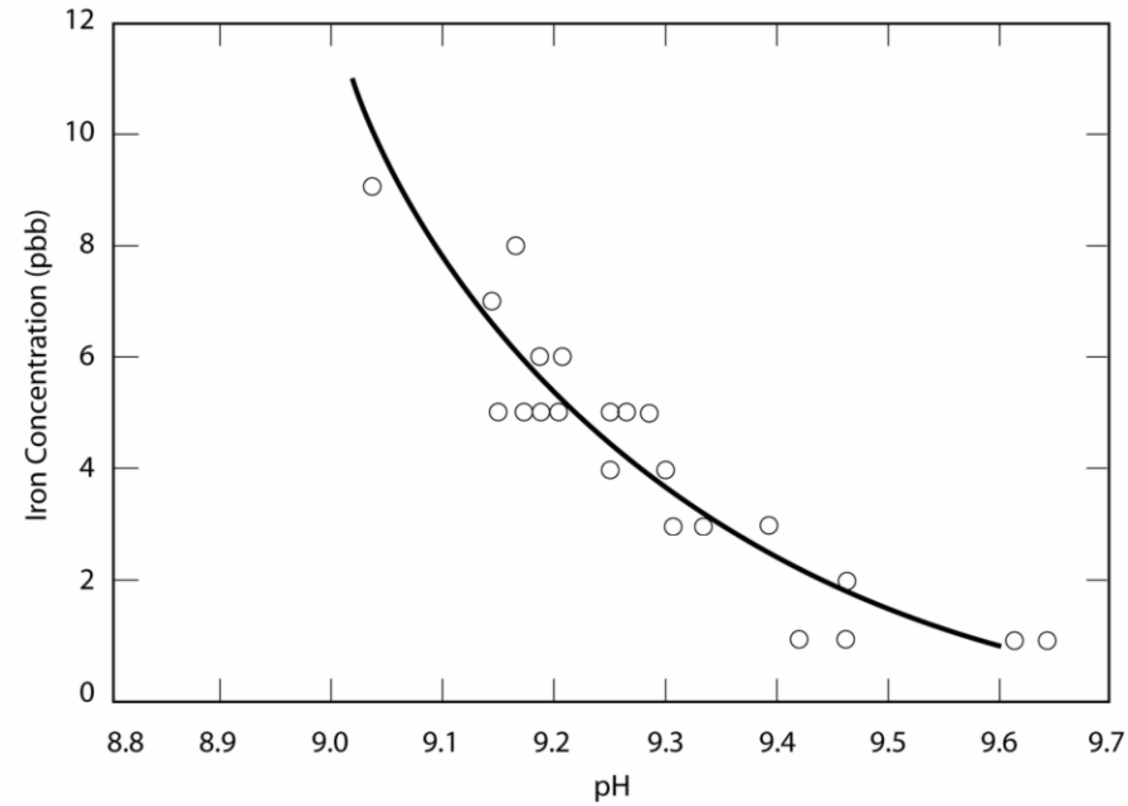


Figure 11. Iron concentration dependence on water pH. Source [16].

4.3 Water Temperature

The third most important variable affecting the FAC rates of carbon and low-alloy steels is system water temperature. The rate of FAC is temperature dependent, and the maximum rate of single-phase FAC occurs at temperatures of 150 ± 20°C [16]. While the FAC rates are the highest around the aforementioned temperature, FAC occurs in the wide temperature range of 75–300°C, and serious incidents of FAC have occurred across the temperature range of 142–232°C [23].

Most of the reported cases of FAC incidents under single-phase conditions have occurred within the temperature range of 80 to 230°C, whereas the range is displaced to higher temperatures (140 to 260°C) under conditions of two-phase flow. This is an important distinction, because for two-phase FAC modeling, higher temperatures will be required to attain in a test rig. The locations of the maximum wear rate change with pH, oxygen content, and other environmental variables. Experience has shown that the wear rate is highest at around 150°C and increases with fluid velocity. However, FAC can occur in low-temperature, single-phase systems under unusual and severe operating conditions. The FAC temperature dependence is shown in Figure 12. Notice how the FAC maximum rates are affected by pH of the solution. Additionally, the solubility of magnetite is shown in Figure 13. Notice the wear rate and solubility curves peak at the same temperature—around 150°C [23].

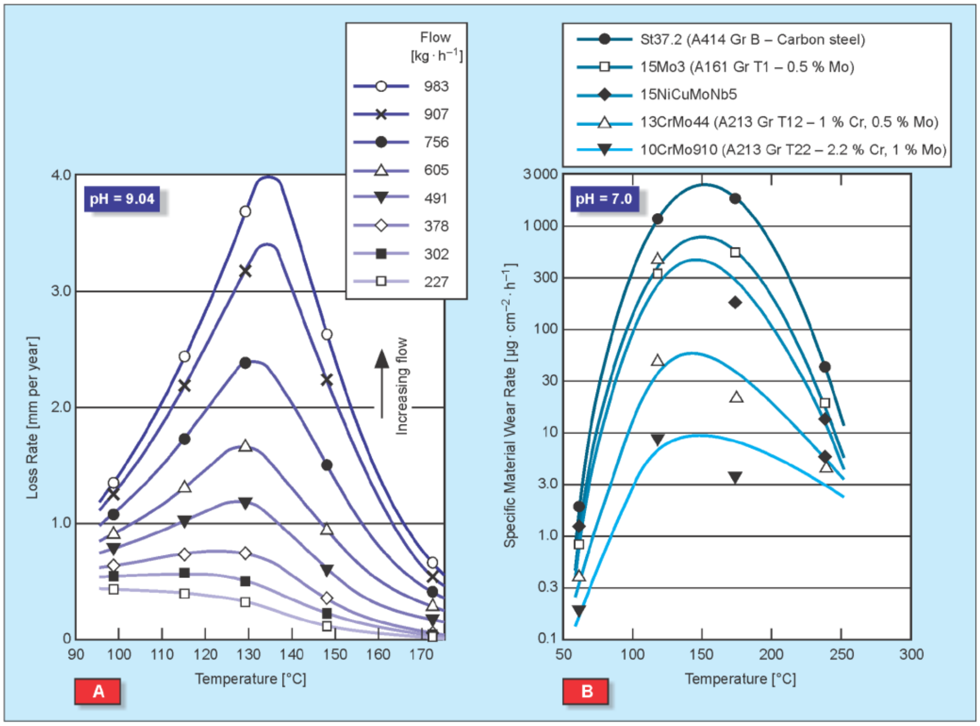


Figure 12. Examples of the temperature dependence of single-phase FAC under different flow (A) and chemistry conditions (B). Sourse [11].

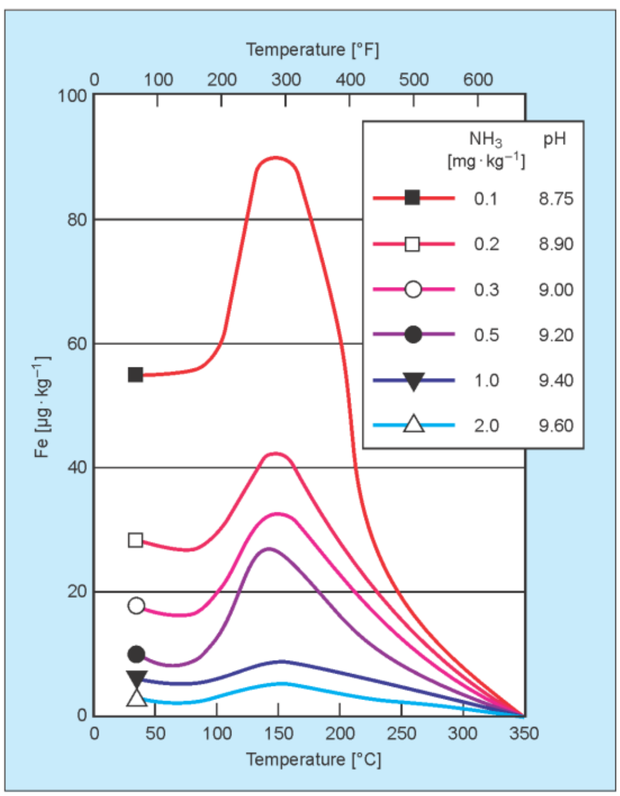


Figure 13 Solubility of magnetite as a function of temperature at various ammonia concentrations, Source [11].

Experimental data show that the temperature of the maximum FAC rate appears to increase with increasing flow rate or mass transfer. The observation of high FAC rates above 140–150°C at experimental test rigs is consistent with the numerous examples of FAC in fossil-fuel power plant feedwater systems (economizer inlet header piping and tubing). It is assumed that the lower FAC rates at temperatures above 200°C reflect the temperature dependence of other physical and chemical parameters that influence mass transfer (fluid density, viscosity, etc.).

4.4 Chromium Content

Extensive worldwide research over the past 25 to 30 years has shown that small additions of chromium to carbon steel has a dramatic diminishing effect on both single-phase and two-phase flow FAC rates. Up to about 25 times improvement in FAC rates can be achieved by using 1.0 or 1.25% chromium alloys. Similar results have been reported for some other additives, such as Cu or Mo. The dependence of FAC rate on Cr content of the steel alloy is most studied and presented in Figure 14. The FAC rate is highest in carbon-steel piping with very low levels of alloying elements. The presence of chromium, copper, and molybdenum, even at low percentage levels, decreases the FAC rate considerably. The relative corrosion rate of steels is reduced by 80% at a chromium content as low as 0.2 % [21]. The FAC rate is decreased by a factor of 4 with the steel type 2-1/4% Cr and 1% Mo (2-1/4 Cr-1 Mo steel) [21]. Austenitic stainless steels are virtually immune to FAC [21].

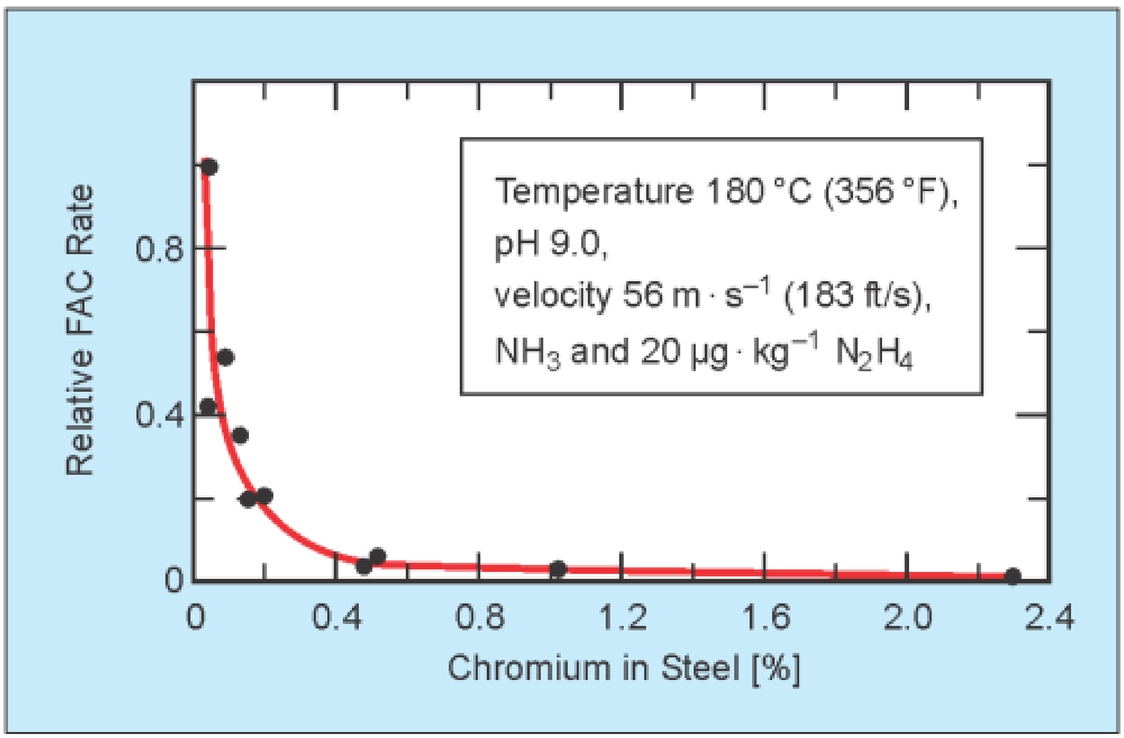


Figure 14. The effect of chromium on the rate of single-phase FAC. Source [21].

With the current understanding, improved performance has usually been related to the presence of chromium building up gradually in the oxide film, reducing the solubility of the oxide. However, actual solubility data on oxides of this type are scarce, and it needs to be recognized that the morphology of the oxide and its solubility, which forms on a ferritic steel containing chromium, is different than the oxide, which grows on carbon steel. On the former, there is usually an inner layer of an iron/chromium spinel oxide. Investigations of fossil-fuel power plant FAC have also shown [11] that FAC often does not occur in identical plant components when the chromium levels are slightly higher (sometimes as small as 0.1%).

4.5 Pipe Geometry

Geometries different from straight pipes or tubing affect mass transfer due to changes in local flow turbulence. While FAC does occur in straight pipes or tubes, it is most often encountered at points of hydrodynamic instabilities. These include elbows, tight bends, reducer tees, locations down-stream of flow-control orifices and valves, and even fabrication discontinuities in straight piping. The geometric augmentation and richness of these features increases turbulence and mass transfer [18]. Extensive data on the geometric factors exist, because they are needed to prioritize inspection locations and for the various analytical models. Similar to many of the factors influencing FAC, the geometric factors and mass transfer coefficients do not provide unique suggestions for the locations of FAC. For example, as FAC proceeds, the surface becomes roughened, and this surface will by itself increase the rate of mass transfer and Re number, thereby increasing the FAC rate. Hence, while geometric factors provide initial information on presumable FAC location, they may not be definitive as FAC progresses.

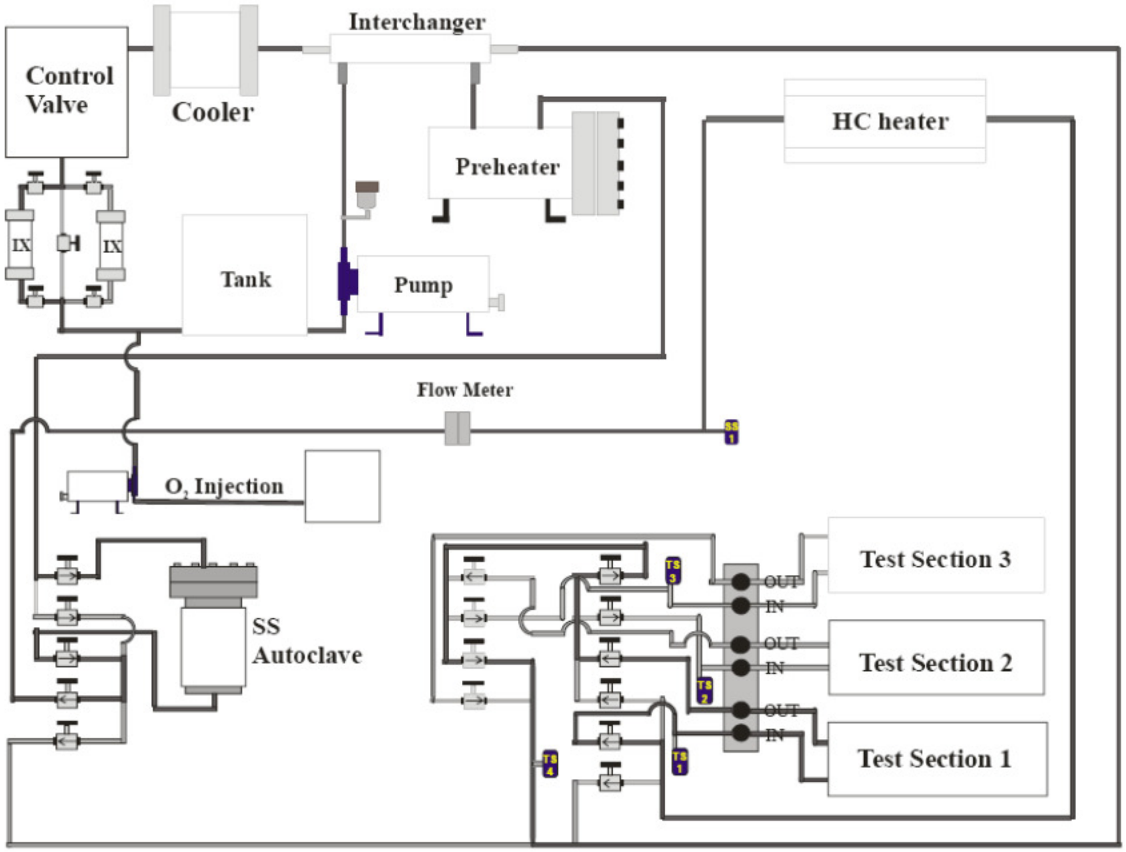
In contrast to geometric factors, FAC is not directly dependent on flow velocity, and recent computational analyses confirmed that the mean flow rate is not a good indicator of the FAC process even if it does affect the flow turbulence [19].

In the 1990s, a new FAC wear effect was discovered and documented. This effect has been called the leading edge effect or the entrance effect. This effect occurs when flow passes from a FAC-resistant material to a non-resistant (susceptible) material, causing a local increase in the corrosion rate. The CODAP event database includes several examples of pipe damage caused by the entrance effect [13]. The effect is especially prominent in aging plants where some piping has been replaced with FAC-resistant components but some of the original piping remains.

5. EXPERIMENTAL STUDY OF FAC

Experimentally, FAC is usually investigated with test flow loops that are built to mimic conditions in a susceptible system. Currently, there are three experimental test rigs specifically dedicated to studying FAC [22]. A typical FAC flow loop is shown in Figure 15 and its description follows [22].

The FAC-dedicated rig is made mostly of Hastelloy-C and stainless steel and can operate at temperatures up to 310°C and pressures up to 11 MPa. Although designed as a once-through system, its coolant fluid is recirculated from the pressure-reducing valve to the positive-displacement pump via a cooler, ion-exchange columns, and a controlled-atmosphere tank where the chemistry is adjusted with ammonia, hydrazine, etc. The pump can deliver up to 3.5 L per minute of coolant to the test section, which is fitted with bypass piping to enable corrosion-potential probes to be inserted or removed without shutting down the whole loop. Rates of FAC are monitored online with tubular corrosion probes made of the carbon steel of interest. The tubes are typically 90 mm long with bores of 1.6, 2.4, or 3.2 mm, and they have a middle length of about 12 mm turned down to a wall thickness that gives an electrical resistance that can be measured accurately; changes in resistance of 10 μΩ (±4%) can be detected reliably



[22].

Figure 15. Schematic diagram of FAC loop. Source [22].

The increase in pipe resistance is measured with multimeters, that are then converted to a measure of the FAC rate as the wall thins. Electrochemical corrosion potential (ECP) of a resistance probe relative to a high-temperature Ag/AgCl reference electrode is also measured to obtain the corrosion rate baseline. Two or three probes are typically installed simultaneously in the test section, and tubes of similar sizes are installed downstream to be removed as required for surface analysis. Water is supplied from a 100-L tank through a centrifugal pump driven by a variable-speed electric motor. The air is supplied from the main laboratory compressor, and the flow rate is adjusted by a control valve and is measured using an air rotameter with an accuracy of 2% full scale. The water mass flow rate is controlled by a variable-speed pump in addition to a gate valve located on the water flow line. The water flow rate is measured using a turbine flow meter with an accuracy of 2% full scale, and the temperature is measured using thermocouples at various locations along the flow loop. Experiments were performed using 1-in.-diameter straight tubing at a Re of 20,000. A straight section of approximately 75 mm in diameter is installed upstream of the test section to ensure fully developed inlet flow conditions. An additional straight section of 100 mm in diameter pipe is installed downstream of the test section [22].

6. COMPUTATIONAL FAC MODELS

There are several thousand piping components (valves, elbows, orifices) and miles of piping in a typical NPP that are potentially susceptible to FAC degradation. Without an accurate FAC-predictive analysis of the plant, inspection schedules, inspection details, and a complete piping database that includes inspection and replacement histories, the only way to prevent leaks and ruptures is to inspect every susceptible component during each outage [1]. Such an inspection program would be extremely time-consuming, as well as costly. The main goal of a FAC-predictive analysis is to identify the most vulnerable components, thereby reducing the number of unnecessary inspections that are performed.. In the past, some plants have used a simplified prognostics approach, often involving empirical rating factors for this susceptibility analysis. However, due to the precautionary conservatism involved, a conservative analysis still results in a large number of inspections. Consequently, U.S. nuclear units no longer use this approach. Plants that have used conservative FAC management plan may inspect as many as 300 to 500 piping locations.

FAC predictive models rely on the results of plant-specific inspection data to develop plant-specific correction factors, that are used to forecast degradation. This correction accounts for random uncertainties in plant data, systematic discrepancies caused by plant operation, and also for specific design features of a plant, as well as the piping replacement history. The median numbers of inspections for utilities that have relied on ultrasonic and radiography inspection data to refine wear rate predictions and have reduced susceptibility are approximately 70 large-bore and 18 additional small-bore locations per refueling cycle. While the number of inspection locations examined per refueling cycle is very plant-specific—depending on plant age, history, initial wall thickness, wall thickness thresholds, piping materials, length of refueling cycle, and susceptibility—the above figures reflect a sample of industry experience as of 2012 [23]. Operating experience has demonstrated that until a comprehensive analysis of all susceptible piping systems has been performed, plant personnel cannot be confident that all FAC- susceptible components have been identified and are under surveillance to prevent leakage or rupture [23].

Currently available computer programs for tracking and predicting FAC wear rate include:

- CHECWORKS (Chexal-Horowitz Engineering Corrosion WORKStation)
- BRT-CICERO
- COMSY
- WATHEC.

Where computer codes are used to monitor the rate of pipe wall thinning, the feedback of operating experience and inspection data is necessary to improve the accuracy in the FAC wear predictions. The conjoint requirements for FAC provide the basis for the formulation of mitigation strategies, e.g., changing the water chemistry or material composition. This section summarizes the different national approaches to FAC mitigation. Unfortunately, all FAC management software is proprietary, and their review can only be performed based on the data published in open literature. The authors of this report has no experience with any of the software and base their review on existing literature.

6.1 CHECWORKS™

U.S. utilities utilize the CHECWORKS computer code for tracking and predicting wear. While the general formulas for the model had been published the software remains proprietary and its analysis can only rely on publicly available descriptions [23]: The following description of the CHECWORKS software follows the description presented in [23]. Application of the CHECWORKS includes three major steps, according to [23]:

1. Pass 1 Analysis – A Pass 1 Analysis is based solely on the plant predictive model, which includes water chemistry, geometry, piping composition, etc., and does not take into account the results of the plant wall thickness measurements. This is normally performed after initial installations of the software.

2. Pass 2 Analysis – In a Pass 2 Analysis, results of the plant wall thickness measurements obtained during periodic inspections through UT or RT measurements are used to enhance the Pass 1 Analysis results.

3. Predictive Methodology – A predictive methodology uses empirical correlations to predict the rate of pipe degradation due to FAC and the total amount of FAC-related wall thinning to date in a specific piping component, such as an individual elbow, orifice, or straight run. The predictions are based on correlating factors between such parameters as the piping geometry, piping material, and flow conditions, and resulting wall thinning. An example of a predictive methodology is the Chexal-Horowitz correlation incorporated in the CHECWORKS code. It should be stressed that the CHECWORKS is the not a first-principles model as it does not take into account physical chemistry of FAC The CHECWORKS relies on empirical correlations.

   According to [23], The CHECWORKS predictive methodology incorporates the following attributes by having a factor accounting for them:

- Geometry, temperature, fluid velocity, water chemistry, and material content of each piping component. Wide spectrum of hydrodynamic conditions (i.e., diameter, fitting geometry and fasteners, temperature, steam-water quality, and velocity) expected in a NPP. It is desirable to have the ability to calculate the flow and thermodynamic conditions in lines where only the line geometry and the end conditions are known.
- Water treatments commonly used in NPPs. The water chemistry parameters that should be addressed are the pH range, the concentration of dissolved oxygen, the pH control amine used (PWRs only), the hydrazine concentration (PWRs only), and the main steam line oxygen content (BWRs only). It is particularly desirable to have a method of calculating the local chemistry conditions around the steam circuit since for the two-phase flows the FAC parameters cannot be averaged.
- Range of material alloy compositions found in NPPs.
- The effects of power changes, fluid chemistry changes, replacements of plant equipment, and configuration changes to rates of FAC.
- History of multiple operating conditions over the life of the plant.
- Use of the hydrodynamic, water chemistry, and materials information mentioned above to predict the FAC wear rate accurately. To perform such forecast, the model is initially tuned on laboratory data scaled to plant conditions. The model should be validated by comparing its predictions with wear measured in power plants.
- Wear rates of components and the remaining useful life before a specified minimum wall thickness is reached. Various rankings of piping components are provided as part of these calculations.
- Capability to use measured wear data to improve the accuracy of the plant predictions (i.e., perform Pass 2 Analyses).
- Periodic reviews of the accuracy of the predictive correlations and, as necessary, their refinement by the developers of the predictive methodology.

Components can be inspected for FAC using wearable/portable ultrasonic techniques (UTs), radiography techniques (RTs), or visual observation. Both UT and RT methods can be used to determine whether or not wear is present. However, the UT method provides more accurate data for measuring the wall thinning rates of large-bore piping. RT is commonly used for complex geometries and components with irregular surfaces, such as valves and flow nozzles. RT has the advantage of providing broad coverage with a visual indication of current metal loss. An additional advantage is the ability to perform

RT without removing the pipe insulation, when the plant is online, and, in some cases, with reduced scaffolding needs. Although there may be advantages applying radiography it may have impacts on other outage and non-outage tasks due to radiological exposures. Nearly all utilities are using the manual UT method with electronic data loggers to perform most of the large-bore inspections. Visual observation is often used for initial examination of very large-diameter piping (e.g., cross-under and cross-over piping), followed by UT/RT examinations of areas where significant damage is observed or suspected [23]. The results of all the inspection are back fed into CHECWORKS predictive algorithm to produce an updated forecast. The current accuracy of CHECWORKS is believed to be ±50% [23].

6.2 BRT-CICERO™

The EDF's BRT-CICERO™ software is based on Sanchez-Caldera model [24].The Sanchez-Caldera model is the first-principles model which takes into account the physical chemistry of the FAC degradation. In this model, the removal of material by corrosive-erosive wear is a result of several degradation phenomena, starting with the initial reaction of pure iron with water and the final step of mass transport of hydroxides into the bulk flow of water. The oxide layer formed on iron plays an important protective role by restricting the water access to the bare metal and the flow of hydroxides by diffusion from the iron surface to the water flow; those factors, in turn, affect the hydroxide's concentration gradient at the iron-oxide and oxide-water interfaces [24]. The gradient plays a crucial part in the corrosion process as its creation is aided by the flow. The process of corrosion-erosion includes complicated chemical kinetics and fluid mechanics. Due to the complexities involved in the process, it is difficult to incorporate all of the process laws in the derivation of the model; instead, Sanchez-Caldera et al. looked for the minimum number of variables necessary to explain the experimental data [24]. Thus their model is by definition is a reductionist model. The experimental data indicated that (a) the wear is a linear function of time, (b) the wear rate is maximum at a temperature near 150°C, and (c) the wear increases with fluid velocity. With these ideas in mind, the following equation was derived [6]:

$$\frac{dm}{dt} = \frac{\theta(c_e - c_\infty)}{\left(\frac{1}{k}\right) + (1-f)\left[\left(\frac{1}{K_d}\right) + (d/D)\right]} \qquad (4)$$

where

$\frac{dm}{dt}$ = wall thinning rate in mol cm^{-2} s^{-1} (to be determined)

c_e = equilibrium concentration of iron species (in mol cm^{-3}), which depends on temperature, hydrogen concentration, and pH

θ = porosity in cm^2 of open area/cm^2 of metal or cm^{-3} H_2 O/cm^3

K_d = mass transfer coefficient in cm s^{-1}

k = Aexp(−E/RT) = the reaction rate constant in cm s^{-1}

f = fraction of oxidized metal converted into magnetite at the metal-oxide interface, d-magnetite thickness in cm

D = diffusion coefficient of iron cations in water

$c\infty$ = iron species concentration in the bulk fluid, mol cm^{-3}.

The authors' assumptions in deriving Equation (4) have been the following [24]:

1. A steady state is considered. The oxide layer has been developed, and its thickness (d) and porosity (θ) have attained a constant value as a function of time.
2. Of the amount of iron oxidized at the metal-oxide interface, a fraction f is converted into magnetite; this is the same amount being removed at the oxide-water interface. It has been assumed that f has a

fixed value of 0.5. This value is based on steel corrosion experiments performed in stale water where, in general, a bilayer oxide is formed and the outer oxide layer has the same amount of iron as the inner layer [6].

3. There is no net circulation or flow of water inside the oxide; therefore, the simulation of the transport of species inside the layer can be considered as a concentration diffusion problem.

4. The water contains low concentrations of oxygen (<200 ppb), and the only oxide present is magnetite.

The model has been subjected to initial validation with experimental data [24]. The study has shown that the most important assumptions made, i.e., a constant wear rate and a reaction rate constant following an Arrhenius function with temperature, have been proven appropriate. The values of the parameters used for K_d, D, d, and θ were verified and calculated by different relations. An additional hypothesis of the authors is that at higher temperatures, the faster chemical reactions lead to a decrease in porosity [24].

The BRT-CICERO uses input-databases [20, 21] that are specific to a plant and are built up for a complete analysis of the degradation by FAC of the secondary circuit main pipes. This input-database contains the pipe isometrics, pipe material, mechanical pipe characteristics, hydraulic conditions for each line, operating times and chemical data for each cycle, design codes, and material standards. In addition, BRT-CICERO enables the user to introduce thickness and chromium content measurement results obtained during outage inspections. The thickness measurements are performed on pipe elements according to a predefined mesh, and the results are edited into a specific file format. The in-service measure thickness is used by BRT-CICERO as a new reference thickness, whereas the chromium content is used in the FAC rate calculation. All of the pipe thickness measurements realized on the French NPP secondary circuits since the 1986 Surry accident are now available in the input databases.

The degree of confidence in BRT-CICERO is shown in Figure 16 [21]. Some points appear to be predicted with a high degree of conservatism; this is generally due to a lack of information on the chromium content or an initial thickness much higher than specified, which is often the case for thick components (headers, tees, large bore reducers). Some cases can also be due to a geometry factor that is too conservative.

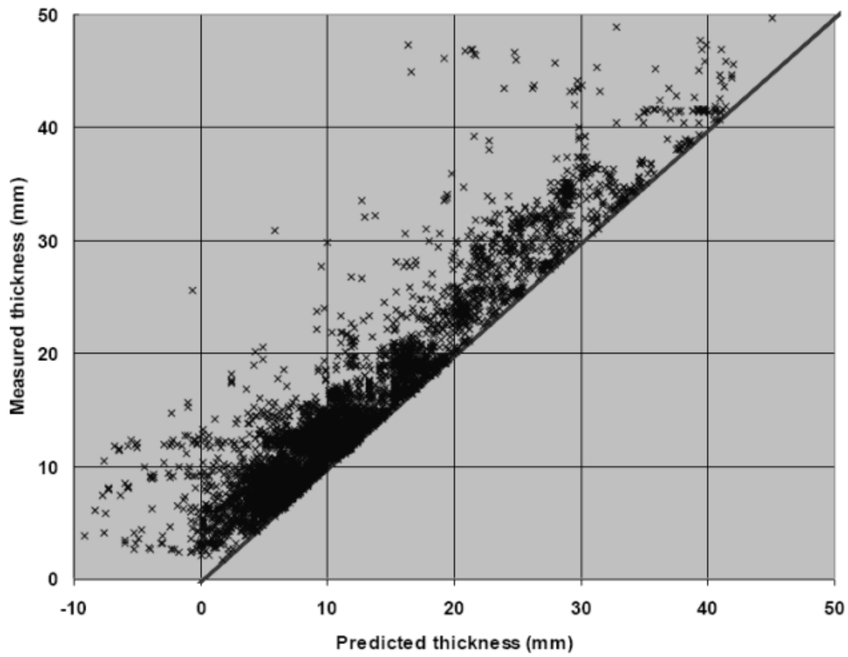


Figure 16. Comparison between minimum measured thickness and calculated thickness for pipe components with BRT-CICERO. Source [22].

The selection of inspection locations is based entirely on predictions by the BRT-CICERO [22]:

- Each pipe section modeled in BRT-CICERO and predicted to be below design wall thickness at outage N+1 must either be inspected (by chromium and thickness measurements) during outage N, or a written justification for continued operation must be submitted to the recognized inspection service for review and approval. A special inspection program is required for welds that are assessed to be susceptible to FAC (e.g., locations immediately downstream of flow control valves, elbows, reducers).
- For lines susceptible to FAC that are not yet modeled in BRT-CICERO (e.g., small-bore piping), an inspection program must be developed that includes the most sensitive areas according to engineering evaluations that address local flow conditions, service experience, and base metal chromium content.

In summary, the Sanchez-Caldera model and BRT-CICERO software have the advantages of being rather simple yet encompassing several of the most important factors influencing FAC. This is why it has been widely used as a basis for software prediction tools of the wall thinning rates due to FAC. However, the model does not take into account the bilayer structure of the oxide film or the possibility of an alteration of the mechanical and electrochemical properties of the surface layer at the oxide/electrolyte interface [22].

6.3 KWU WATHEC/AREVA COMSY

KWU WATHEC/AREVA COMSY is a family of FAC prediction codes developed by Siemens based on the Kastner model [24]. The WATHEC/COMSY code can be applied to both single-phase water flow as well as to two-phase water/steam systems [25]. The software only uses data which are currently available to the design engineer or the operator of a plant. No interpolations are used. The parameters which affect material loss in low-alloy piping due to erosion corrosion were established in a series of laboratory experiments performed by Siemens/KWU. Kastner et al. [25] have demonstrated that besides the geometry conditions, the most important factors which needs to be taken into account are the material composition (principally the chromium and molybdenum and also the copper content) and the flow velocity of the water. Those three factors plays the most prominent role in the model. The next most important factors are the temperature, pH, and oxygen content of the water. This is slightly different for the BWR plants as in BWR plants, highly pure deionized water is used as the fluid of the steam-water cycle. The liquid contains oxygen and has a pH close to neutral. The pH is highly conducive to FAC degradation. The presence of an adequate amount of oxygen in the feedwater (optimum is found to be around 50 ppb) results in benign water chemistry and in good protection against erosion corrosion. The water oxygenation was recently considered by utilities as an FAC mitigating measure.

In most cases, the fluid temperature can be measured, and water chemistry can be adjusted only within a limited range as it depends on other parameters. For this reason, the following factors are of great practical importance in the COMSY software as they ultimately affect the predictive performance [25]:

- Piping material selection: austenitic stainless steels while susceptible to erosion, are not susceptible to corrosion; the resistance of carbon and low-alloy steels increases dramatically with chromium, molybdenum, and copper content [25]
- Flow velocity can be limited for a given mass flow by selecting appropriate line cross sections
- Pipe geometry can be optimized to improve flow Re number by selecting sufficiently large elbow radii, replacing T-fittings with laterals, etc.

All the factors factors are listed in the order of importance for the COMSY model.

COMSY is a correlation-based model based on a series of laboratory experiments which were carried out to elucidate an empirical relationship for the calculation of material loss due to erosion corrosion. This correlation relationship was found to apply initially to single-phase flow only. However, with slight modification, the relationship could be applied to two-phase flow, provided that the pipe wall is moistened by a continuously moving, solid film of water [25], which may be a valid assumption. In this case, similar to the single flow mechanism, the flow velocity can be taken to be the mean velocity of the water film along the pipe wall, which is dependent on the water flow rate, density of the water under saturation conditions, steam quality, and void fraction [25]. At the same time, the pH and oxygen content parameters that are used in the calculation have taken into account the temperature- and pressure-dependent distribution coefficients for alkalizing agents and for oxygen.

The WATHEC program was developed to determine the rate of metal removal to be expected in different power plant components, not necessarily NPP, or piping systems and/or to forecast the remaining useful life expectancy of a component under the given loading conditions. This application is best used as part of a weak point analysis, the sequence of which is as follows [26].

- Similar to US practice, on the basis of operational data, the most vulnerable plant systems are identified and analyzed.
- As the second step, within these systems, the points most susceptible to damage are identified on the basis of the existing piping geometry and flow conditions. The material loss to be expected at these potentially weak points is then calculated with the aid of the prediction model. The results of these calculations are subjected to a secondary analysis which includes an appraisal on the basis of the

measurement data available in the database and comparison with previously performed measurements.

- The prediction model has been found to be of broader benefit for two reasons: in plants in which the crucial aspects identified have been fully taken into account, for instance in terms of flow conditions or of pH levels, the model could give indications of the current component condition. Additionally, application of the model has been demonstrated to be particularly important in reducing measurement and monitoring effort and in extending the life expectancy of components of whole piping systems.

The lifetime prediction chart (Figure 17) shows the conservatively predicted wall thinning (red line) and the calibrated wall thinning (blue line) versus the operation time of the component [25]. The colored ranges indicate piping integrity criteria (manufacturing tolerance, minimum wall thickness, yield stress condition, and tensile stress condition). The green color tolerance bar indicates the wall thickness examination result. Similar to US approach, based on the evaluation with respect to the degradation potential and remaining useful life, components are prioritized for examination programs and condition-oriented inspection plans are generated. The COMSY software system acquires and evaluates data from nondestructive component evaluations which are applied to welding, wall thickness , ultrasonic examination, visual inspections, etc. The inspection results are recorded in standardized formats and are assigned to the examined component for documentation of the actual condition for the corresponding point in time in the operating history of the plant and integrated in the virtual power plant data model.

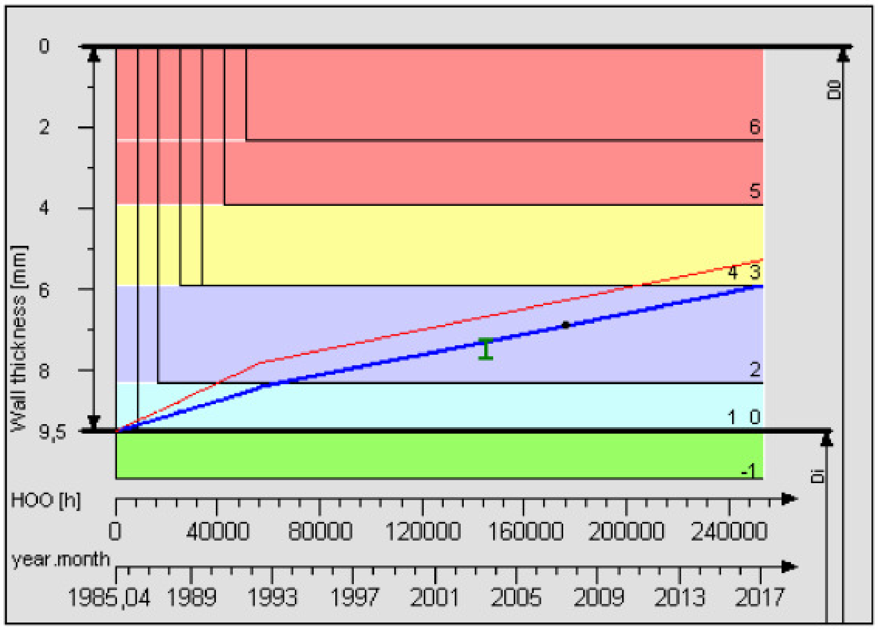


Figure 17. Lifetime prediction chart of the COMSY code [25].

Components can be inspected for FAC damage using a variety of techniques. Key techniques in current use are UT, RT, visual testing (VT), and pulsed-eddy current testing (PEC). UT provides the most accurate measurement of wall thickness but requires that the inspection be performed during a unit outage with insulation removed from the area to be inspected. RT and PEC can be performed on insulated lines and components but do not provide as accurate data as UT provides. UT, RT, and PEC methods can be used to investigate whether or not wear is present [23]. However, the UT method provides more comprehensive data for measuring the remaining wall thickness. VTs, such as direct observation or use of video camera probes, are often used for examination of very large-diameter piping and vessels where inside access is possible. It is recommended that VT should be followed by UT examinations of areas where significant damage is observed or suspected. For large-bore piping, the commonly accepted UT inspection process consists of marking a grid pattern on the component and using the appropriate transducer-receiver and data-acquisition equipment to perform wall thickness readings at the grid intersection points [23]. If the readings indicate significant thinning, the region between the grid intersection points should also be scanned or the size of the grid reduced to identify the extent and depth of the thinning. Although scanning the entire component and recording the minimum thickness are not recommended, scanning within grids and recording the minimum found within each grid square constitute an acceptable alternative to the above method. The inspection data are used for three purposes [36]:

1. To determine whether the component has experienced wear and to identify the location of maximum thinning.
2. To ascertain the extent and depth of the thinning.
3. To evaluate the wear rate and wear pattern to identify any trends, if data from multiple inspections are available.

To attain all three of these objectives, it is recommended that the component be inspected using a complete grid coverage with a grid size sufficiently small in order not to miss the damaged areas. The selection of grid size and inspection time represents a trade-off, which should be found for every inspection program individually.

Although scanning will meet the first two objectives, it will not provide sufficient data to determine component wear rates or to develop sufficient data to perform a detailed stress analysis of a damaged component. Further, scanning is of limited use in some piping areas and specific situations such as in trending the wear found.

In summary, the COMSY code is similar in its functionality to other software packages and its accuracy is comparable with other models.

7. PROPOSED RESEARCH FRAMEWORK

The currently implemented FAC management programs in the US consist of two parts: (1) the wear rate estimation obtained with CHECKWORKS using currently available data and (2) pipe inspections using UT, RT, PEC, or VT. The results of the inspections are fed back into the CHECKWORKS code to correct and improve forecasts. The inspection process is complicated by several factors, including the following [23]:

- Unknown initial wall thickness (if baseline data were not obtained)
- The presence of “entrance” effect
- Variation of wall thickness along the axis and around the circumference of the component
- Lack of accuracy or precision in nondestructive examination measurements
- The possible presence of pipe-to-component misalignment, backing rings, or the use of counterbore to match two surfaces
- Data-recording, storage, or -transfer errors
- Inconvenient locations that that prevent complete gridding (e.g., a welded attachment)
- Discrepancies in statistical interpretation of the inspection data. Currently, eight different statistical techniques are applied to interpret the wall thickness data obtained though NDE inspections.

The challenge is to minimize the effect of these factors by applying uniform evaluation methods and utilizing engineering judgment. Currently, the scheduled inspections are performed during refueling outages. During power operations, the plant relies almost entirely on previously made FAC forecasts. The proposed approach aims to alter this situation with online monitoring of FAC and corrosion process monitoring with potential benefits of switching to "as needed" inspections, thus significantly reducing the labor and operating costs. The proposed approach is depicted in Figure 18. As discussed above, one of the existing programmatic deficiencies is the potential for higher than predicted pipe wall-thinning during plant operation. This higher-than-predicted wear rates can be attributed to changed chemistry conditions, power uprates, inaccuracy in measurements and superposition of several piping degradation mechanisms in addition to FAC. Departing from any of the best understood FAC management operating practices presents a clear challenge to the existing FAC management programs as elevated wall-thinning rates may go unnoticed between inspections. The proposed research framework aims to address this through continuous online monitoring. This would provide data on key structural health monitoring parameters on a more frequent basis that could be used to monitor the rate wear and performance of key structures.

The proposed framework consists of three levels of online monitoring: system-wide, component-wide, and local. One difficulty of existing FAC management programs is that their focus on highly localized examination of the vulnerable locations while not monitoring the overall corrosion in a system. The proposed approach aims to address this through additional sensor modalities that can be deployed more broadly, providing monitoring coverage of more parts of a system than currently viable today. This would provide the capability to monitor the health of more parts of the system then just the most likely 'trouble' spots, and provide a more suitable and proactive basis for informed decisions about aging management of piping and related structures. Iron concentration in the secondary circuit could be such global parameter that monitors the overall piping degradation and delivers system-wide monitoring. The iron concentration can be measured using noninvasive ultrasonic concentration sensors described below.

The second component-wide level will be engaged, if the overall situation is found to be deteriorating. The component-wide level will be responsible for monitoring separate vulnerable components. The component-wide level of online monitoring can be implemented through fiber optics strain sensors, vibration sensors, or guided wave sensors. The component-wide level can cover up to 30 feet of piping components. After a vulnerable component is identified, the last local level of monitoring will be engaged to pinpoint the exact location of the flaw. This could be an ultrasonic sesnors. All three levels will be integrated in one system and will share some sensor modalities.

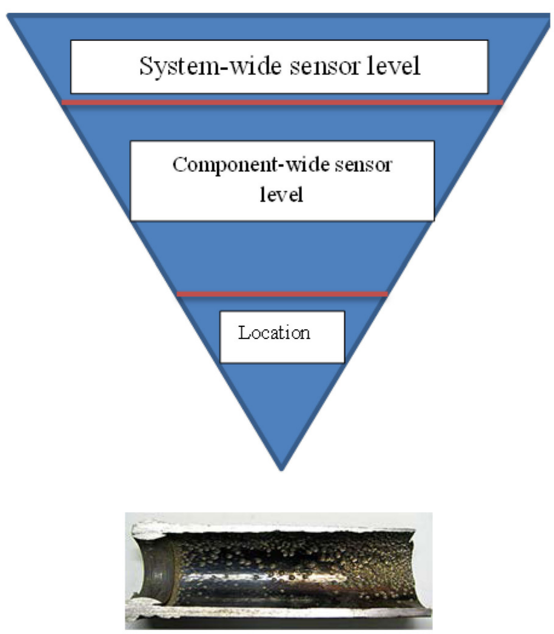


Figure 18. Schematic of online FAC monitoring system.

The first system-wide level of sensors will focus on obtaining a bird's eye view of corrosion processes in the secondary circuits. These sensors will include clamp-on iron concentration sensors attached to the piping system. If elevated iron concentration is detected, the second level of sensors, which includes guided wave, vibration, direct current potential drop, fiber optics strain, and resistance sensors, will be engaged to localize a possible wall thinning. The second level of sensors is capable of covering long stretches of piping with one scan. If the wall thinning is detected, highly localized techniques, such as ultrasonic phase arrays, eddy current sensors, and Bragg grating sensors, will be applied to pinpoint the flow location with high accuracy. The information from all three levels will be integrated into a single diagnostics and prognostics framework. This sensor network will be developed using the experimental test rig, which will be implemented as a flow loop or as a rotating drum. A schematic of the proposed flow loop to investigate FAC is shown in Figure 19.

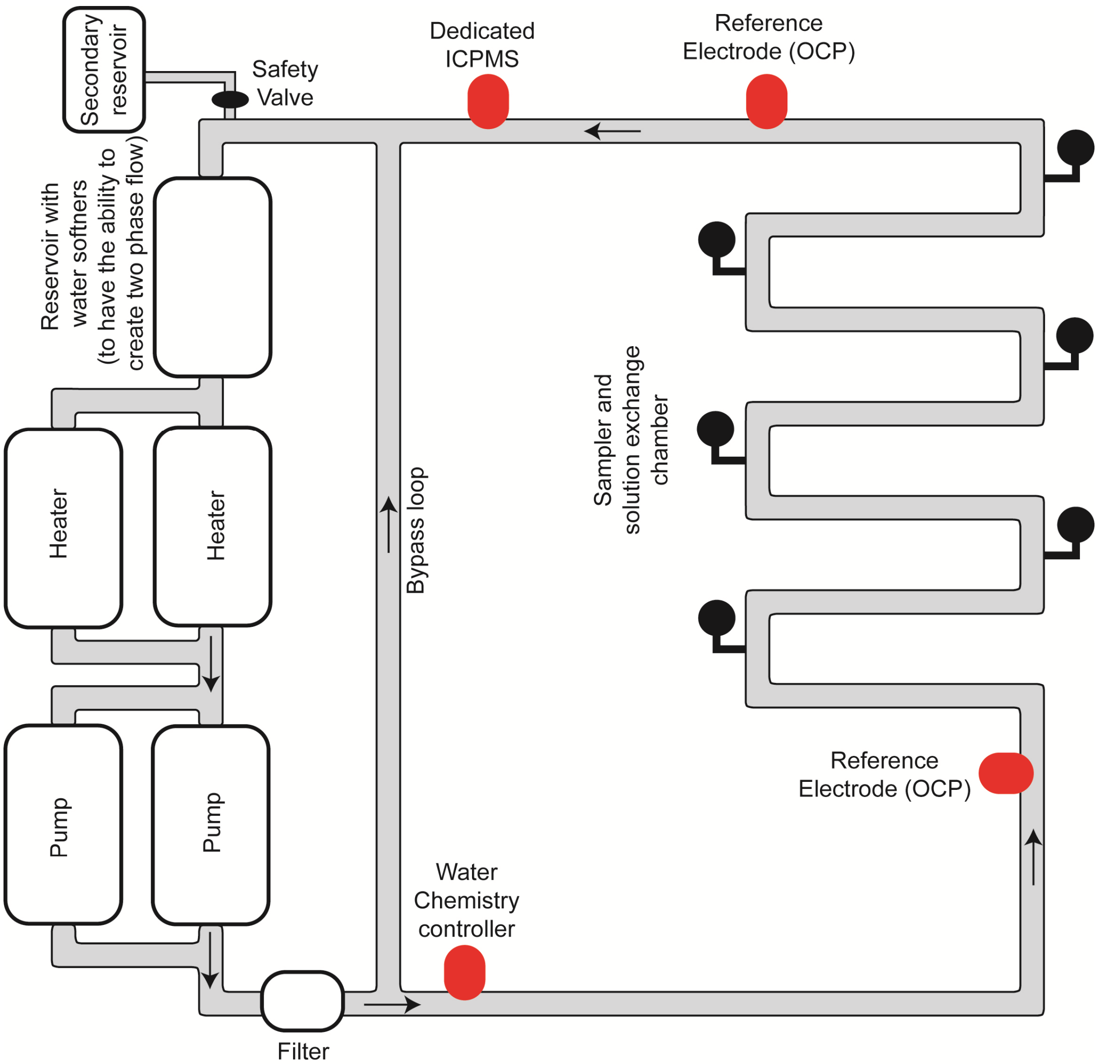


Figure 19. The proposed loop design to study FAC in carbon-steel pipes.

While the flow loop is an ideal setup to study different sensor modalities, its development and construction requires significant financial outlay. An alternative way to study FAC is a rotating drum approach depicted in Figure 20 [32]. The following description is adopted from [32].

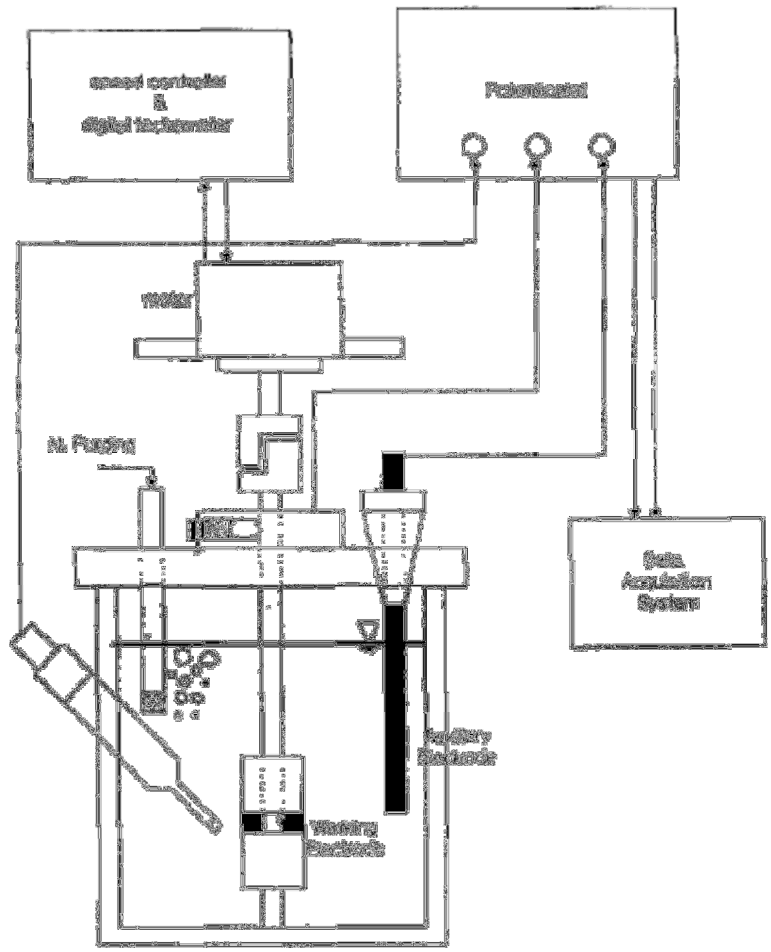


Figure 20. Schematic of the rotating drum to study the FAC. Source [32].

Laboratory flow loop test rigs often require complex and expensive plumbing fixtures, maintenance procedures, and sensors calibration to obtain accurate and reproducible results move for a metal sample. However, the necessity for large-scale laboratory flow loop can often be avoided by moving the metal sample with respect to the fluid instead as described in [32]. One widely-used instrument to imitate moving a metal sample with respect to a fluid is the rotating cylinder electrode (RCE) [32]. This apparatus includes an electrode rotator and a control unit (see Figure 20) capable of accurately adjusting the rotation rate of a vertically oriented sample drum. A special tip to hold a cylindrical metal sample is mounted at the lower end of the shaft. The tip is manufactured mostly from chemically inert and electrically insulating materials, but buried within the tip is a metal shank, which provides mechanical stability and electrical contact with the metal cylinder sample (see Figure 20).Having being immersed and rotated in a test solution, the hydrodynamic flow conditions generated by the RCE, even at relatively low rotation rates, can be quite turbulent. This makes the RCE an ideal probe for studying corrosion processes under low to medium velocity for laminar and turbulent conditions. However, the RCE is not suitable to study the corrosion processes under purely laminar conditions. By adjusting the RCE rotation rate up or down (typically in the range of 200 to 2,000 revolutions per minute), it is possible to tune the hydrodynamic conditions adjacent to the metal sample. The goal is to adjust the rotation rate so that the laboratory fluid flow conditions match (or mimic) those found in the pipes. Once this is accomplished, the corrosion process can be monitored by classic mass loss methods or by electrochemical methods. It should be noticed though, that the fine tuning of the speed and flow conditions for the RCE could be a daunting task.

Determining iron concentrations in the steam/water cycle is crucial in determining the effectiveness and optimization of the feedwater treatment program and unit management practices. Iron concentration is an indication of two-phase FAC in heater shells, drain lines, and low-pressure evaporators in heat recovery steam generators as well as single-phase FAC in secondary piping. Iron concentration is a vital monitoring parameter and is independent of the feedwater chemistry program. Iron analysis may be conducted on a series of samples representing values at a given instant in time, a composite of aliquots collected over a specified period, and/or passing water through filter paper and totaling the flow (for example, using an integrated corrosion product sampler). Measuring the iron concentration in instantaneous samples is usually performed using inductively coupled plasma atomic emission, mass spectrometry or spectrophotometric techniques. These techniques have a number of limitations based on iron particle size, the requirement for sample processing time, and detection and accuracy limits. To address this problem we suggest using noninvasive ultrasonic concentration sensors which can offer a number of advantages.

To monitor the dissolved iron, clamp-on ultrasonic sensors will be used, similar to one shown in Figure 21.

Figure 21. Clamp on ultrasonic concentration sensor. Source [31].

The clamp-on ultrasonic concentration sensors have a number of attractive features that can be used in NPP applications [31]:

- Noninvasive measurement using the clamp-on technology
- Precise bidirectional, highly dynamic flow measurement
- Measurements of concentration, density, degree of conversion, or other qualitative material properties from the measured sound speed and medium temperature
- Optional capabilities: determination of mass flow and mass
- No contact with the liquid, no special materials required, hygienic measurement, and suitable for ultra clean media
- Ideal for aggressive, toxic, or abrasive media
- Frequency-modulation-approved transducers for hazardous areas available
- Maintenance-free measurement and no wear

- Transducers available for a wide range of inner pipe diameters (0.25–256 in.)
- Fluid temperature: −40. + 392°F.

The major problem with using this type of sensor for iron concentration surveillance in NPP is its sensitivity, which is currently in the range of several parts per million. The concentration of iron species in secondary water is several parts per billion, so the sensors need to be significantly increased. In the current project, it is planned to do by calculating the rate of change in concentration rather than concentration itself. The rate of concentration can be expressed through a mass balance equation as:

$$R_{iron} = F_{water}^{inlet} \cdot \left(C_{iron}^{out} - C_{iron}^{in}\right) + V\frac{dC_{iron}^{out}}{dt} \qquad (5)$$

where

R_{iron} = the rate of iron species production in bulk water

C_{iron}^{out} *and* C_{iron}^{in} = inlet and outlet concentrations of iron species in water

F_{water}^{inlet} = water flow rate

V = volume of water in the component.

Because the inlet and outlet concentrations are measured, Equation (5) can be used to calculate the rate of iron production. Notice that the last term in Equation (5) includes derivative of the outlet iron concentration and hence is a high pass filter that amplifies minor changes in the outlet concentration. The difference between measurements of raw concentration and production rate is shown in Fig 22.

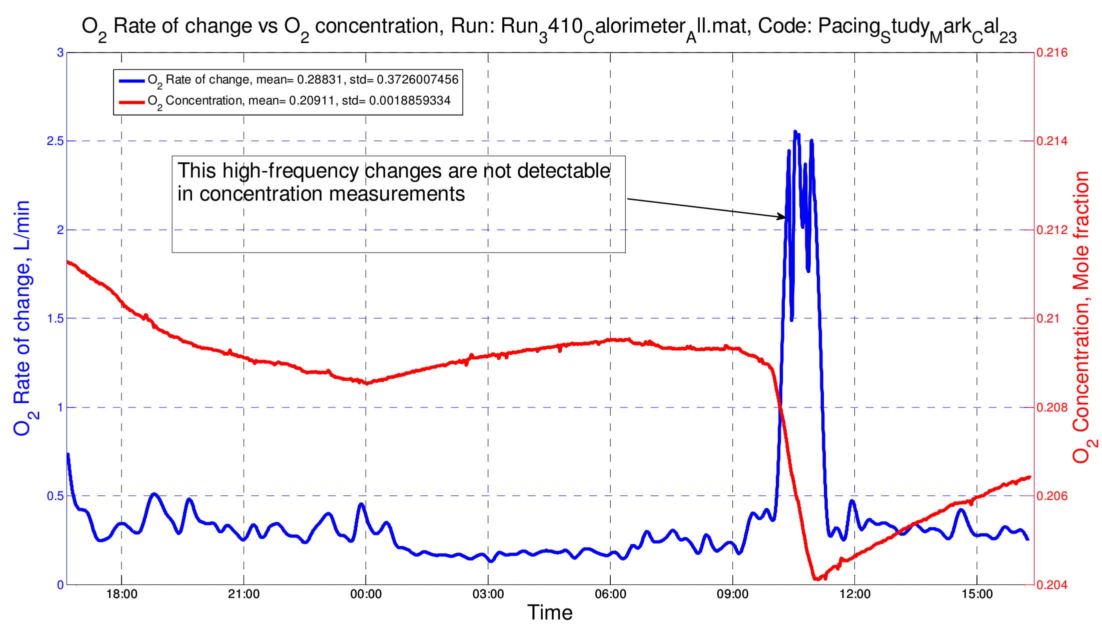


Figure 22. The concentration versus the rate of change.

Notice that the standard deviation of the rate of change is 400 times higher than the concentration, thus significantly improving the sensitivity to minor deviations in concentrations.

For the component-wise level of monitoring, it is planned to investigate a large number of sensor modalities, such as guided wave, vibration, direct-current potential drop, fiber optics strain, and resistance sensors. All of these sensor modalities have the ability to cover up to 100 m of pipe in one scan, and some can handle elbows and valves, as well.

Also, the following sensor approaches will be investigated:

1. Self-powered wireless sensor nodes to monitor the FAC by systematically combining thermal, mechanical, and electrical sensors. One major goal is to determine the pipe wall thickness accurately and effectively using multiple sensing mechanisms. Figure 23 shows an example of a self-powered wireless sensor node directly printed on a pipe elbow using additive manufacturing process. The self-powered wireless sensor mode includes a sensor, a wireless communicator, a thermoelectric power harvester, and other power-management and -storage devices.

Figure 23. A self-powered wireless sensor node directly printed on a pipe elbow

2. Thermal sensors. These can be a novel means to monitor the change of pipe materials structure and wall thickness. When FAC happens, the pipe materials will undergo substantial changes near the interfaces of the solids and fluids, which can further lead to changes in both convection and conduction heat transfer from the hot fluids to the outer surface of the pipe. In the meantime, the decrease of pipe wall thickness due to corrosion results in reduced wall thermal resistances and corresponding changes in wall surface temperatures and heat flux, all of which can be detected by thermal sensors.

We plan to develop new temperature sensors that can actively monitor the pipe surface temperatures and thermal conductance. Both contact measurement (thermocouples, hot wires) and noncontact measurement (optical fibers) will be explored for temperature sensing. To assist data analysis, a computational fluid dynamics model will be used to simulate the fluid flow and heat transfer processes in the pipe system in conjunction with the flow-assisted corrosion.

As the pipe wall thickness changes due to FAC, the pipe vibrational mode, and displacement are also changing [33]. Therefore, an optical fiber to monitor the vibrational mode can be implemented as a nondestructive method to monitor the pipe thicknesses. Using the mechanical signal is a new and promising method to monitor FAC. We will use finite element modeling to analyze the correlations between the pipe wall thickness and the corresponding vibrational mode and displacement. We will also study the sensitivity of different optical sensors to the small changes of vibrational mode in order to identify the most sensitive sensors.

While vibration sensing is a local sensing technique that is beneficial for small regions, such as pipe elbows, we plan to use the direct-current potential drop method to monitor pipe wall thickness in large areas. Again, Finite Element Modeling (FEM) simulation will be used to determine the pipe wall thicknesses using the signals from direct-current potential drop measurement.

One major barrier in implementing a large number of sensors in an NPP is the significant cost of cable installation and maintenance needed to power the sensors. Solid-state power harvesting technologies will play a crucial role in establishing self-powered sensors for the nuclear industry. Self-powered sensor nodes, such as the one shown in Figure 24, offer the potential to significantly expand the remote monitoring of nuclear facilities and offer significant cost savings over current approaches that require cable installation and external power sources [34, 35].

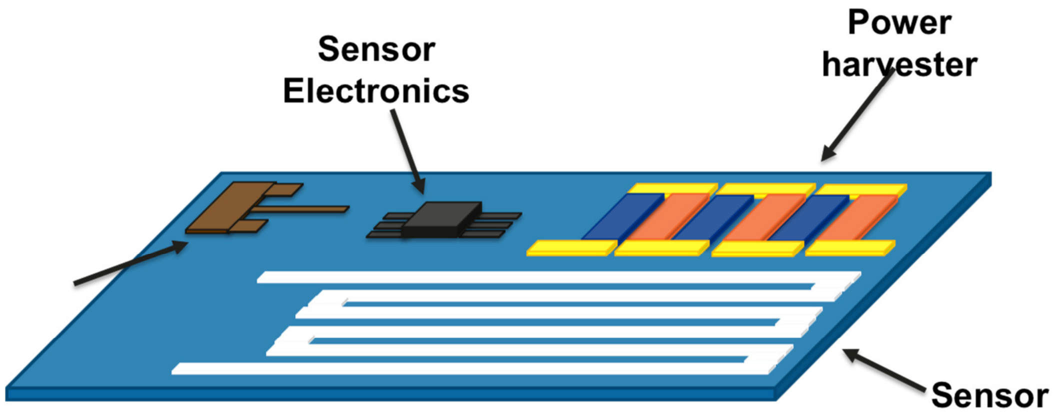


Figure 24. An integrated sensor, communicator, and power harvester.

8. CLOSING REMARKS AND PLANS

Nondestructive evaluation (NDE) is an integral part of the maintenance programs in NPP. Performing NDE is expensive, requires time and careful planning to be carried out during refueling outages, and and must provide clear answers to ensure plant safety while online. Each instance of NDE involves labor intensive procedures such as insulation removal and replacement, scaffolding construction and deconstruction, radiation shielding practices, and others.. The, implementation of in-situ sensors have the potential to significantly reduce labor efforts during busy outages, realize substantial cost returns, and reduce worker dose.. The proposed approach aims to utilize the well-established science of corrosion and erosion of piping systems to develop a structural health monitoring framework for secondary system piping and related structures. Implementing online monitoring of the structural health monitoring framework via in situ sensors and signal processing algorithms will provide a continuous monitoring capability of the performance of key systems. It will also provide the capability to extend monitoring beyond areas of suspected concern to more areas of the system, which can increase our confidence in monitoring results and provide a more complete basis for making informed decisions about aging management of materials in the balance of plant. Overall, this will increase the effectiveness of monitoring programs while reducing their costs, and radiation dosage to personnel. The availability of on line monitoring techniques can increase the frequency and confidence in obtained inspection data and also produce more accurate forecasts using a pedigreed monitoring framework, such as CHECWORKS. Also, the proposed approach should lead to greater accuracy over time, thus avoiding reductant and costly piping replacements. Modern FAC monitoring programs tend to be rather conservative. This results in high piping replacement ratios and excessive costs. The proposed online, monitoring approach will attempt to address all these issues.

Although all nuclear utilities in the United States have FAC management programs the efforts against erosion are less coordinated and visible. Meanwhile, the erosion processes contribute to the wall thinning and sometimes may be more damaging than FAC. For example, the rate of FAC can be significantly reduced with alloy additives, while the measure is completely ineffective against erosion degradation. The most common forms of erosion encountered in NPP—cavitation, flashing, liquid droplet impingement, and solid particle erosion—have caused wall thinning, leaks, cracks, and ruptures that have resulted in significant financial losses. Piping degradation due to corrosion has led to costly repairs, decreased piping integrity, and radiation exposure. Tackling the problem of erosion in NPP alongside with the FAC will constitute the future challenge for the on-line monitoring programs.

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