A hundred years of corrosion in the pulp and paper industry

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ABSTRACT: Through the decades, the pulp and paper industry greatly expanded production capacity to meet increasing demands. Correspondingly, the cost of corrosion damage soared. The most serious corrosion control challenges were researched and met by university and governmental researchers, and by task groups within the TAPPI Engineering Division's Corrosion and Materials Engineering Committee. Today, thanks to material and process advances, mills encounter less corrosion than in the past. This overview takes a historical look back, covering many decades, at how corrosion problems have been managed in the pulp and paper industry. Yet, corrosion keeps on going, and today mills appear less able to manage corrosion problems for which known solutions are available. This paper also addresses the significant yet underrated task of optimizing corrosion control management in the present and into the future. Discussion is provided on best practices needed to mitigate new and ongoing corrosion problems.

Application: This review should help mills better realize the importance and benefits of systematic corrosion management.

Along with documenting notable corrosion events, this historical look at corrosion problems reveals how changes in paper and paperboard processing methods have influenced corrosion and its related costs. Additionally, advances over the years in materials technology, fabrication methods, and testing and analysis techniques have shaped what is perceived today as corrosion control in the industry. Past lessons can provide insights toward ways to anticipate and control corrosion events of the future. Aside from documenting the most notable events over the decades, this paper also addresses current advances in corrosion management technology that are being adopted by other corrosion-intensive industries, and why similar approaches have been so difficult to implement in the pulp and paper industry.

THE COST OF CORROSION

According to the 2016 NACE International IMPACT study, the global direct cost of corrosion across all industries is estimated to be 3.4% of gross domestic product [1]. Other studies have shown that within the pulp and paper industry, which is among the highest of capital intensive industries, the cost of corrosion is estimated to be near that in petroleum refining and chemical industries combined; between 1.2% and 6% of pulp and paper sales, depending on product and process [2]. Today, there are about 500 paper mills in the United States, with production capacity of about 79,000,000 metric tons/year of paper and paperboard [3]. Thus, the annual cost of corrosion to the paper industry is estimated to be 2.7 to 4.7 million metric tons of paper and paperboard.

Pulp and paper manufacturers can benefit from better corrosion control practices because in most cases the paths to good control are already known. By using best practices in corrosion control, and avoiding actions that involve doing things wrong, 50% or more of all corrosion costs might be avoided [2].

THE EARLY YEARS — 1900 TO THE 1950s

From 1900 to the 1950s, the U.S. paper industry expanded production from 2 million tons/year to near 34 million tons/year [4]. Interestingly, growth in production was not made by building more paper machines, but rather by speeding up existing machines, and replacing machines with wider ones that produced more tonnage. From 1914 to 1940, the total papermaking capacity doubled, but the number of paper machines in the United States remained nearly constant at about 1500 machines. Thus, the average machine capacity also doubled during that time. Along the way, the most significant factors influencing corrosion were process changes, such as the type of paper produced. Because of the increased demand for stronger paper, kraft production surpassed sulfite after 1939. From a corrosion viewpoint, this change was more favorable because the kraft process has proved to be less costly from a corrosion standpoint than sulfite.

Corrosion control was not a priority from 1900 up to 1930 or 1940. Rather, the industry considered corrosion to be more of a maintenance issue, and mill management focused on increasing paper production rather than on corrosion control.

Equipment and materials

Until the 1920s, the materials generally available for equipment manufacture were cast iron, wrought iron, steel, brass, bronze, some Monel nickel alloys, and aluminum. Acid-resistant brick and mortar were used to line towers, tanks, and chests. Paper machine frames were made from gray cast iron, and suction rolls were made from either cast iron or bronze. Nickel and chromium plating were also used to protect steel from corrosion and wear. Because copper, bronze, and brass were used for sulfite pulping, frequent replacement was required, at considerable cost. Lead lining was effective for acid production in the sulfite process. Wood was widely used for corrosion resistant tanks and pipes. Batch digesters were made from riveted carbon steel with brick lining; a few of these early digesters were still in use 100 years later.

In just 15 years, from 1915 to 1930, design engineers found a wider choice of materials for corrosion control. Stainless steels became available, and so did 14%–30% nickel cast iron (Ni-Resist). Some applications for Ni-Resist castings during this period included paper machine fourdrinier frames, dryer rolls, pumps, and pipe fittings. By 1930, carbon steel welding was much better developed and welding was included in the pressure vessel code. However, weldability of the new stainless steels was poor because better gas shielding was still needed to control porosity and embrittlement problems. Carbon control in the production of early stainless steels also was difficult. Nevertheless, by the mid-1930s, 18-8 chromium-nickel with 3% molybdenum (similar to Type 316), and 27Cr-4.5Ni-1.5Mo duplex stainless steels (similar to Type 329 duplex stainless steel) were becoming widely used [5].

In the 1930s, the Tomlinson recovery boiler for kraft paper production was invented, and so was the Kamyr continuous digester. However, the continuous digester did not become fully developed and used until about 1950. Paper machine speeds were increasing – up to 1500 ft/min – double that from just a few years earlier. Multi-stage bleaching with direct treatment with chlorine was well developed by the 1940s.

During World War II, gas-tungsten arc-welding was developed, and welding of stainless steel could be reliably performed. After the war, a wide variety of materials for resisting corrosion became more readily available. These included high alloy stainless steels, and wider ranges of nickel-based and copper-based alloys. Flame spraying of corrosion resistant coatings, although available for decades, became more prominent, but plasma and high velocity oxyfuel coatings would not be available until the 1960s. Better materials testing methods also became widely available, such as ultrasonic testing for thickness and flaw detection.

The first high pressure recovery boilers, 1200 psi and above, introduced to increase energy efficiency, were built during the 1950s.

Associations and research

The Technical Association of the Pulp and Paper Industry (TAPPI) was founded in 1915, and the Institute of Paper Chemistry (now the Renewable Bioproducts Institute at Georgia Institute of Technology) was established in 1920. The Pulp and Paper Research Institute of Canada (PAPRICAN, now FPInovations) was established in 1925, and the National Society of Corrosion Engineers (now NACE International) was founded in 1943. During the 1930s, a TAPPI Materials of Construction Committee set up specifications for stainless steel casting alloys [5]. The first field and laboratory studies on the metallurgical and electrochemical aspects of kraft liquor corrosion were made in the 1950s by Walter Mueller at PAPRICAN [6]. The TAPPI Digester Corrosion Subcommittee (later becoming the Corrosion Committee) was started in about 1950, and its first major task was to survey the extent of corrosion in kraft digesters. The committee published reports on digester corrosion every year for 10 years. From the 1950s on, corrosion became a far more important and costly burden to the paper industry.

Notable corrosion events in the early years

During 1930, a kraft digester catastrophically failed at Berlin, NH, USA. Until that time, carbon steel kraft digesters were not expected to corrode because they operated in an alkaline environment. Digester corrosion surveys during the 1930s into the 1950s showed wide variations in the corrosivity of liquors. Ultimately, study of the effects of varying liquor sulfidity on corrosion rates in carbon steel was published by Wensley et al. [7].

Significant corrosion pitting of stainless steel bleach washers, winding wire, and cloth was reported during the 1930s, and nickel-based materials such as Hastelloy-C, Hastelloy-A, and Monel were tested to resist corrosion from free chlorine in the pulp [5].

Probably the most important process change contributing to corrosion for decades to come was during the 1950s when water reuse began. Recycled water contributed to a buildup of chemicals in water systems, especially chlorides and potassium. Water temperatures also were boosted. All of this increased the corrosivity of water and process systems.

A process change contributing to corrosivity of paper machine whitewater was the use of hydrosulfite as a brightening agent. Unknown at the time (1940s), hydrosulfite would break down and produce thiosulfate ions in whitewater, which would be found to pit Type 304 stainless steel. The cause for the thiosulfate corrosion would not be discovered until 1978 [8].

High-pressure recovery boilers were introduced during the 1950s, with design pressures increasing from about 700–800 psig up to 1250–1650 psig. The higher temperatures resulted in unacceptable corrosion rates in carbon steel tubes, and a decades-long search for optimum tube materials began [9,10].

CORROSION EVENTS OF THE 1960s–1970s

The paper industry was in full swing in the 1960s, and the period into the 1970s was considered the "wave of the good times." In just five years, from 1965 to 1970, more than a 100 continuous Kamyr digesters were built and put into production in dozens of mills across North America [11]. During the 1970s, 70 new recovery boilers were built in the United States, and most were of the high pressure type, averaging above 950 psi in steam pressure [12]. Larger and faster paper machines were built, including the so-called 10 m (390+ in.) width machines.

On the debit side, cast CA-15 and austenitic stainless steel suction rolls had poor corrosion fatigue strength and a terrible lifespan, some failing in less than a year. The first cast duplex stainless steel (DSS) suction roll material (1963), Alloy 63, had good strength and excellent corrosion resistance, but still cracked prematurely and unpredictably. In the following years, more than 30 different stainless steel alloys were developed and put in service in suction rolls, some at the cost of more than a million dollars per roll. Respectable suction roll life was eventually achieved when machine builders recognized the need to design the rolls more conservatively, and shell producers developed stainless alloys with a compromise of good corrosion fatigue strength and low residual stresses. Low residual stress in suction roll shells could only be obtained by slower and more uniform cooling during heat treatment, but at the same time, the stainless metal chemistry had to be formulated to avoid precipitation of undesirable intermetallic phases during the slow cooling process.

Another problem of the times was recovery boiler explosions; first a few explosions, then many. The Black Liquor Recover Boiler Advisory Committee (BLRBAC) was established in 1961 for the purpose of sharing knowledge and generating and maintaining guidelines to facilitate the safe, reliable operation of recovery boilers. In the 20-year period ending in 1980, BLRBAC documented 99 recovery boiler explosions, an average of five per year. Lower furnace waterwall tube corrosion and cracking was a contributor to boiler smelt water explosions, particularly in boilers with operational pressure over about 900 psi. To address the problem, the first composite stainless steel boiler tubes were installed in a new recovery boiler in Scandinavia in 1971, but the first composite tube recovery boiler built in North America was at Continental Can Company, Hopewell, VA, USA, in 1980.

During this period, and into the 1990s, recovery boilers were fired with changes in air distribution and increasing black liquor solids to increase boiler efficiency and reduce total reduced sulfur (TRS), nitrogen oxides (NOx), and carbon monoxide emissions, resulting in greater corrosion of mid-furnace and upper furnace tubes [13].

Bleach plant corrosion also became a serious problem during the 1960s and 1970s, largely because of the combination of bleach filtrate recycling, higher temperatures, and difficulties in controlling carryover of unused chlorine and chlorine dioxide. Where Types 316L and 317L stainless steels were previously resistant to pitting corrosion, the stronger bleach environments of C and C/D stages required the use of higher molybdenum stainless steel alloys or titanium. In the late 1970s, into the 1980s, a TAPPI task group, headed by Arthur Tuthill, conducted numerous plant tests on the performance of stainless steels (including welded coupons) used for piping in bleach plants [14,15]. Ultimately, 6% molybdenum stainless steel alloys became standard in the most severe bleach stage environments. Fiber-reinforced plastics (FRP), although used for bleach plants since the 1950s, got a boost in bleach plant equipment during this period. The year 1978 also marked the first successful operation of electrochemical protection in a bleach washer in Canada, and there were about 100 installations by 1989 [16].

Associations and research

The greatly increased cost of corrosion during the period from 1961 to 1980 prompted several companies, consultants, institutions, and researchers to increase efforts to combat corrosion problems. TAPPI's Corrosion Committee (changed to the Corrosion and Materials Engineering Committee during the 1970s) greatly increased its activity and projects, beginning in around 1972. A series of 11 pulp and paper corrosion forums, sponsored by TAPPI, the Canadian Pulp and Paper Association (CPPA), the Swedish Corrosion Institute, the Finnish Paper Engineer's Association, and NACE were held at 3-year intervals between 1974 and 2004. The Institute of Paper Chemistry established a corrosion department about 1975. Likewise, PAPRICAN increased research on corrosion problems.

CORROSION EVENTS OF THE 1980s TO 2000

SA 210/304L composite tubes were first installed in a recovery boiler in 1980, and in many more high pressure boilers in the United States and Canada afterward. In just a few years, problems with corrosion and cracking of these tubes emerged [17]. During the period from 1983 to 1984, localized corrosion of the outer layer of 304L at air ports was reported. The problem persisted for years until better-designed, well-sealed casting inserts helped to minimize the air port problem [18]. During the early 1990s, cracking of the 304L stainless steel layer of composite tubes was found at air ports and on the boiler floor [19]. During this period, mills experimented with the use of nickel alloy composite tubes and weld overlaid tubes (Alloys 825 and 625). Causes of the composite tube cracking mechanisms were not well defined until 1999 and later [20,21].

Another dilemma in recovery boilers during the 1980s was near-drum corrosion of generating tubes resulting from increased throughput [22]. A mechanism of waterside cracking was identified in 1987 as stress-assisted corrosion (SAC), also known as waterside corrosion fatigue cracking [23]. The SAC damage mechanism was later found to be widespread, up to about 50%, in boilers older than 15 years [24].

In 1980, a Kamyr continuous digester ruptured at Pine Hill, AL, USA. Analysis showed the damage mechanism to be hydroxide stress-corrosion cracking (SCC). After the event, many continuous digesters were found to have similar cracking. Research on the causes of SCC and methods to mitigate cracking were initiated by a TAPPI task group chaired by David Bennett [25].

In 1983 a catastrophic explosion of a feedwater deaerator storage tank occurred, also at the Pine Hill, AL, paper mill. A NACE task group (T-7H-7) was established to study causes and provide recommendations for mitigation of deaerator cracking [26]. Ultimately, 38% to 46% of operating deaerators and deaerator storage tanks were found to have corrosion fatigue cracking severe enough to require weld repairs.

During the early 1990s, elemental chlorine bleaching was completely phased out to reduce toxic dioxins. Substitution with near-neutral chlorine dioxide became the norm. With the combination of recycled filtrate and higher temperatures, the bleach environment continued to be highly corrosive. "Superaustenitic" stainless steel alloys (6% molybdenum) and titanium were largely specified for areas subject to the most aggressive corrosion, including chlorine dioxide washer vats, drums, and piping. Alternate bleaching processes of the 1990s, such as substituting oxygen and peroxide for chlorine and chlorine dioxide, allowed use of lesser alloys, such as 316L and 317L, for washer equipment.

Another notable event during the 1990s was the introduction to North America of second-generation DSS for digesters and liquor tanks. DSS alloys had already been used for years in pulp and paper mills in New Zealand, Australia, and Scandinavia, but the alloys were slow to be adopted by U.S. mills. The first DSS batch digester built in North America was installed at Abitibi Consolidated, Fort Frances, ON, Canada, in 1997 [27]. The motivation for movement into DSS for batch digesters was prompted in part by a catastrophic carbon steel digester explosion in Panama City, FL, USA, in April 1994.

CORROSION — 2001 TO PRESENT

Process stream effects

There seems to have been little change in mill processes that have caused or accelerated corrosion in nearly two decades. Bleaching processes have gradually become less corrosive and lower cost materials have been used for washers, vats, and piping. Pulping and papermaking processes have remained similar to pre-2000 times, although uncontrolled oxidant carryover, such as chlorine dioxide from bleaching, has increased corrosivity affecting paper machine wet-end rolls and exhaust equipment. Recovery processes and the Tomlinson recovery boiler have not changed significantly. The benefits of raising the temperature of superheated steam has been limited by poor resistance of available superheater tube alloys to corrosion in molten salt deposits.

Materials

DSS alloys have gradually been accepted for use in digesters and liquor tanks. However, the economical use of DSS grades throughout the mill has continued to be vexed by spotty availability of lean, more economical DSS grades and volatility of nickel prices and surcharges. Fabricators also have introduced up-charges for DSS weld fabrication.

Fitness-for-service and risk-based inspection

Risk-based inspection methodology was introduced as API 580 and API 581 from 1996 to 2002. The purpose was to use risk-based concepts for optimizing examination of pressure vessels and tanks.

During 2007, the Joint American Society of Mechanical Engineers (ASME)/American Petroleum Institute (API) Committee published the first API 579-1/ASME FFS-1 Fitness-for-Service Code for post-construction of pressure equipment that contained flaws and corrosion damage. The risk-based codes can potentially extend the life of critical equipment. However, as with risk-based examination, the FFS analysis technology seems to be only minimally used by pulp and paper manufacturers.

LESSONS FROM PAST EXPERIENCES

Research and engineering analysis after the events identified almost all of the major corrosion failures, catastrophic events, and their damage mechanisms. In almost every case, the events were triggered by changes in process methods, local chemistry changes, or the rush to apply new construction materials. Notable observations include the following:

- Carbon steel rapidly corroded in kraft (alkaline) cooking – 1930s-1940s
- Hydrosulfite brightening agent contributed to corrosion by thiosulfate ions in whitewater – 1950s
- Water reuse contributed to corrosivity of water process streams – 1950s-2000s
- High pressure recovery boilers suffered excessive sulfidation corrosion of carbon steel tubes – 1950s
- Increased paper machine width caused excessive stresses and corrosion fatigue failure of press rolls – 1970s
- Increased load on chlorine bleach plants and carryover of oxidants caused rapid pitting failures – 1960s-1980s
- Introduction of carbon steel continuous digesters without stress relieving caused stress corrosion cracking – 1960s-1970s
- High solids firing of recovery boilers resulted in tube corrosion higher in the furnace – 1980s-2000s
- Type 304L/SA210 composite tubing in recovery boilers is susceptible to stress corrosion and thermal fatigue cracking – 1980s-1990s
- Older boilers are susceptible to waterside SAC – 1980s
- Near-drum tube corrosion of recovery boilers – 1980s

FUTURE CHALLENGES

Corrosion engineering resources

In 2009, Sandy Sharp gave an informal presentation to the TAPPI Corrosion and Materials Engineering Committee titled "The rise and fall of corrosion engineering in the pulp and paper industry" [28]. Sharp stated that the increase in corrosion engineers employed by pulp and paper companies started in the late 1970s, and that it continued for about two decades. At the same time, the number of corrosion research projects grew in North American institutions (Oak Ridge National Laboratory, PAPRICAN, IPST), with project funding mainly by industry consortiums and the U.S. Department of Energy. The approximate number of full-time corrosion personnel working in pulp and paper in the 1980s and 1990s was a maximum of about 35 in paper companies and 12 in research institutions, totaling some 47 full-time people. Within 10 years, by 2009, this number was reduced to only about five corrosion personnel employed by pulp and paper companies, and five at North American research institutions.

Sharp said that the fall in numbers of corrosion engineers and scientists probably occurred because research solutions had largely eliminated catastrophic failures, and that processes had not changed much, so the value of corrosion engineering was not convincing. He also stated that much of the corrosion expertise had not been transferred to corrosion specialists in pulp and paper mills and that many mill technical positions were eliminated by profitability pressures in the low-profit years. This expertise in the industry also declined through attrition as experts and knowledgeable mill personnel retired.

Overall, current corrosion management in North American pulp and paper is considered by the author to be poor, at best, partly because there are far fewer corrosion engineers working in the industry today than in decades past. Most attempts at corrosion control within organizations have been reactive and "firefighting" by corrosion specialists or reliability engineers, supplemented by a few aging corrosion consultants. In-mill project management by systematic means, such as risk-based inspection and fitness-for-service methodologies, is generally beyond the capability of reliability engineers. Corrosion management methods are unfamiliar to decision makers within pulp and paper mills and their central organizations (higher-level management). Thus, the pulp and paper industry is bypassing the potential for significant savings that is being realized through systematic corrosion management strategies used by other equipment intensive industries, such as the chemical and petroleum industries.

Systematic corrosion management

Notable in the 2016 NACE IMPACT study are the benefits of reducing corrosion: (1) maintenance costs are reduced; (2) inspection costs are reduced and intervals are extended; (3) fewer failures occur, with less production loss and interruption; (4) environmental impact, injuries, property damage are reduced; and (5) the useful life of the asset is extended and capital expenditures are reduced.

As stated in the 2016 NACE IMPACT report, the largest impediment to systematic corrosion control is that cost savings are difficult to measure, because benefits are extended into the future. Corrosion control is generally viewed as a cost, rather than an investment in better practice with future savings. Instead of considering total cost, most design and construction of pulp and paper equipment is directed toward bringing new equipment into operation in the shortest period and at lowest cost, almost always with disregard for maintaining fitness-for-service over its lifetime. Further, capital equipment design and manufacture is invariably performed by equipment suppliers who are less interested in lifecycle cost. Another impediment in the pulp and paper industry is that corrosion control is most often handled by local operations, usually at the maintenance or reliability engineering level, and any systematic means to improve on the life-cycle cost for an equipment asset is bypassed.

On the positive side, there have been relatively few operational changes in the pulp and papermaking for the past two to three decades. Serious and catastrophic events over the decades have already been studied; causes and their solutions to most serious corrosion problems are already known. New or unknown corrosion problems might not surface until significant changes in operation are introduced.

The 2016 NACE IMPACT study also provides models for incorporation of corrosion management systems throughout the asset lifecycles. The study conclusions are that total buy-in from the top down is essential for effective corrosion control strategies to be realized. All levels of the organization—design, construction, operations, and maintenance—must have a level of involvement when planning equipment replacements and upgrades.

To be successful in recovering some of the annual costs of corrosion, higher management in the industry must recognize that significant cost recovery and return on investment can be achieved through establishment of a corrosion management system within the organization. The potential reward for better corrosion management could be up to 6% of total product sales. **TJ**

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ABOUT THE AUTHOR

Corrosion costs have soared over the decades because of changes in pulp and paper industry processes. This paper draws attention to how even small process changes have time and again resulted in catastrophic corrosion failures.

Notable corrosion events have been well documented by TAPPI work groups and researchers. This is a systematic overview of the work of others, with conclusions on how process changes over decades have influenced corrosion.

Literature searches on combating pulp and paper mill corrosion problems in early years, before the 1950s, were difficult because so little documentation exists. Instead, early emphasis was on production, not corrosion.

In preparing this review, I learned that researching historical corrosion events can be very interesting. It was surprising that the petroleum and chemical process industries have found systematic corrosion management to be important and profitable, whereas emphasis on corrosion control is generally minimal in the pulp and paper industry.

Mills might better realize the importance and benefits of systematic corrosion management by reading the NACE 2016 IMPACT study on corrosion, available online at http://impact.nace.org/documents/Nace-International-Report.pdf.

The next step is to continue to promote the use of systematic corrosion management methods in the pulp and paper industry.

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