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Materials performance in CANDU reactors: The first 30 years and the prognosis for life extension and new designs

R.L. Tapping

Chalk River Laboratories, Chalk River, Ontario, Canada K0J 1J0

ABSTRACT

A number of CANDU reactors have now been in-service for more than 30 years, and several are planning life extensions. This paper summarizes the major corrosion degradation operating experience of various out-of-core (i.e., excluding fuel channels and fuel) materials in-service in currently operating CANDU reactors. Also discussed are the decisions that need to be made for life extension of replaceable and non-replaceable components such as feeders and steam generators, and materials choices for new designs, such as the advanced CANDU reactor (ACR) and enhanced CANDU-6. The basis for these choices, including a brief summary of the R&D necessary to support such decisions is provided. Finally we briefly discuss the materials and R&D needs beyond the immediate future, including new concepts to improve plant operability and component reliability.

1. Introduction

Materials selection for the first and second generations of nuclear power reactors was supported by extensive research and development (R&D). These material selections were also influenced by early and unanticipated component failures. For new reactors, including those regarded as third generation designs (for instance, such as the advanced CANDU reactor, ACR), and for refurbishments and life extension of existing reactors, introduction of new materials requires extensive R&D and qualification to meet safety and regulatory requirements, and to meet the requirements for extended life (60 years for new designs) compared to the 30–40-year design life of reactors in-service today. For CANDU[1] stations, refurbishments planned to date are not introducing new out-of-core materials during component replacements, but are introducing components with improved materials specifications (for instance carbon steels for feeders) whilst staying within the original design basis. In some cases, degradation-susceptible materials are being replaced with more resistant materials (for instance, Alloy 600 steam generator (SG) tubing is replaced with Alloy 800 tubing), but these materials are already well-known and qualified for application in the nuclear industry. Defense of a 60-year materials or component life requires on-going R&D to confirm that the introduction of these improved materials is the correct choice to minimize corrosion-related aging, and to better predict and understand the excellent performance to date of materials such as Alloy 800 steam generator tubing.

Additionally, effective life management and future materials/component performance prediction for reactor components requires an integration of in-service degradation experience with R&D knowledge on aging mechanisms. For critical out-of-core components, such as SGs, feeder pipes, heat transport piping, balance of plant piping (feedwater, service water) and heat exchangers, various aging-related degradation and failures have occurred, some of which were not anticipated at the time of plant design and materials selection. These experiences must be considered in the context of our advancing technical understanding of aging mechanisms affecting CANDU reactors, and discussed in the context of providing tools for designers, operators and researchers to optimize materials selection and management.

For CANDU reactors, the fuel channels can be considered as replaceable components (although replaced fuel channels are significantly improved over earlier components, whilst staying within the materials specification), and these, along with related fuel channel structures and fuel assemblies, which are replaced on a regular basis, are not discussed further in this paper. Also not included are active components such as pumps, valves, cables and seals, which can be replaced during normal operation. Thus this paper focuses on other key (out-of-core) components, which may be regarded as susceptible to aging-related degradation. Damage mechanisms that are a consequence of design deficiencies, such as excessive vibration or fretting wear, are not discussed in any detail in this paper, although they can impact plant life management strategies.

The major areas of interest to CANDU reactors include feeder pipes, steam generators, heat transport system (HTS) piping, feedwater/steam cycle piping and components (including condensers), and service water systems. Degradation of these systems and components requires considerable attention from plant operators.

E-mail address: tappingr@aecl.ca

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Perhaps of most importance is fabrication and chemistry; fabrication can introduce cold work and stresses that may shorten projected design life, and chemistry is the major contributor to corrosion, and thus requires significant operating attention, as well as accurate specification. There are also many other components that may be susceptible to degradation over time, based on either CANDU plant experience and R&D or on experience elsewhere. An example of the latter is the potential for stress corrosion cracking (SCC) of Alloy 600 components in the HTS (such as flow orifices in the outlet feeders of CANDUs), given the susceptibility of this and related materials in pressurized water reactor (PWR) heat transport circuits and steam generators.

2. An overview of CANDU materials degradation experience

Table 1 summarizes the materials selection and provides a brief operating experience (OPEX) for the major out-of-core components in a CANDU. For the advanced CANDU reactor (ACR), this experience has been taken into account and appropriate materials selection made. In most cases no new R&D is required to improve the materials selection; instead the approach has been to use materials that have proven successful in the evolution of the CANDU design or elsewhere, and to ensure that their application to CANDU conditions will be acceptable. For instance, ACR feeders will be fabricated from type 316LN SS because of the inherent flow accelerated corrosion (FAC) resistance of this material. Because this material has proven possibly susceptible to SCC under highly oxidizing conditions (oiling-water reactor (BWR) conditions, which do not exist in CANDU reactors) and when highly cold-worked, ACR feeders will be fabricated and installed using methods designed to reduce any possibility of cold work or other highly stressed conditions.

CANDU reactors, in common with other reactor types and other industrial systems, have mixed metal systems that require careful control of water chemistry in order to optimize both system and component life. The HTS operation is dominated by the SG, which is the repository of much of the material that circulates with the water (either dissolved or as particulate). This material deposits on the primary side of CANDU SG tubes, reducing heat transfer and increasing radiation fields for maintenance activities, and on the secondary side, where it can interfere with SG thermalhydraulics and can initiate corrosion. This material originates from feeder corrosion (FAC) on the primary side and from feedwater system corrosion and entrained impurities (from the water treatment plant, condenser leaks, etc.) on the secondary side. Balancing water chemistry to reduce feeder pipe corrosion, deposition on fuel, fuel channel corrosion and SG tube corrosion on the primary side requires chemistry to be reducing and controlled to a pH which minimizes dissolution of iron (minimum in magnetite solubility). This has led to the CANDU HTS pH specification being 10.2–10.8, although recently it has been suggested that the range of 10.0–10.4 is preferable to minimize feeder FAC [1].

On the secondary side, minimizing SG tube degradation requires a reducing chemistry with no oxidants, and minimizing carbon steel corrosion, both in the SG and in the secondary side piping, requires a high pH (>9.8) controlled with a volatile amine that partitions between the steam phase and the water so that all wetted surfaces are protected against FAC. This high pH is feasible only

Table 1

Summary of CANDU materials selection and known degradation mechanisms for major out-of-core components

System or components	Materials	Degradation
Feeder pipes	A106B/C for existing CANDU-6	FAC of outlet feeder carbon steel piping; FAC rate reduced 50% with Cr > 0.024 wt%. Cracking of some outlet feeders at Point Lepreau Generating Station (PLGS), and in one repaired weld at Gentilly-2 (G-2)
	A106C for new or refurbished CANDU-6	FAC predicted at rates 50% of those for low Cr A106B in early CANDUs
	Type 316LN stainless steel for ACR	SCC in BWRs if heavily cold-worked
Steam generator tubing	Alloy 600 tubing (Bruce Nuclear Generating Station (BNGS)	SCC and pitting; almost all at Bruce A
	Alloy 400 tubing (Pickering Nuclear Generating Station (PNGS), KANUPP, Indian reactors)	Intergranular attack (wastage or pitting) and FAC/erosion; some limited cracking (environmentally-assisted cracking (EAC) initiating at defects) recently detected
	Alloy 800 tubing (CANDU-6, Darlington Nuclear Generating Station (DNGS) and new designs)	Phosphate wastage (PLGS) and some pitting (PLGS), Embalse, DNGS
Steam generator internals/shell	Carbon steel (CS) SG support plates, lattice bars, etc. (BNGS, PNGS, Embalse)	FAC and crevice corrosion
	Stainless steel (type 410 SS) support plates, lattice bars, etc. (CANDU-6, DNGS; new designs)	No degradation
	Alloy 600 lattice/U-bend supports (Wolsong-1)	
	Carbon/low alloy steel shell, shroud, etc.	Minor pitting at shell-to-drum weld (PNGS); cracking of weld in pressured water reactors (PWRs) where not post-weld-heat-treated; primary side divider plate FAC
	Other CS secondary side components, including preheater and feedwater box components	FAC, for instance separators (BNGS) and feedwater inlet sleeves (PNGS); crevice corrosion; wastage/erosion of tie rod ends
HTS piping	A106B CS	Minor FAC detected
Feedwater/steam cycle piping	CS in older CANDU-6; CS plus SS in FAC-susceptible locations in newer CANDU-6/ACR	FAC of CS in both turbulent single phase and two-phase regions; mitigated by replacement with SS. Copper alloy components now removed from most CANDU feedtrains (G-2, Embalse and KANUPP retain copper-alloy-tubed condensers)
Condenser	Copper alloy tubes	FAC of brass tubes (BNGS, Embalse, G-2, KANUPP); also copper transport to SG contributes to SG tube degradation
	Titanium or stainless steel tubes	Titanium susceptible to hydriding when used with copper alloy tubesheet (PLGS) and to inlet steam erosion (PWRs)
Service water systems	CS piping; heat exchangers with miscellaneous materials	Susceptible to under-deposit pitting and/or microbiological corrosion and fouling, especially in buried lines. Recirculating cooling water systems do not experience this degradation. Alloy 800-tubed heat exchangers exposed to raw water experience pitting under-deposits (PNGS)
Instrument lines and other small diameter stainless steel piping	Instrument lines and other small diameter stainless steel piping	Cracking and/or pitting of stainless steel associated with chloride contamination (pitting) and severe cold work (cracking)

for all-ferrous systems; if Cu-bearing alloys are present, the pH must be lower to reduce the risk of Cu transport into the SGs. Development of improved amines for secondary side fouling control also required validation that the use of these amines would not cause any degradation of SG and feedtrain components. Hydrazine, used to remove oxygen from the SG, must be minimized to reduce environmental impacts and, possibly (R&D evidence is not unambiguous), to improve the resistance of carbon steel piping to FAC. Slightly oxidizing conditions are also important for controlling FAC, but are not compatible with the SG tubing, especially under shutdown or layup conditions. Laboratory studies have shown that high hydrazine concentrations, greater than about 50 ppm, can reduce the passivity and protectiveness of the SG tubing alloys used today, including Alloy 800 [2]. These levels of hydrazine are used only at shutdowns and during layups, but it would appear that such operating states may contribute significantly more to aging of plant components than normal high temperature operation [3].

The experience with CANDU feeder piping has contributed some recent and unanticipated aging degradation experience, as noted earlier. FAC under HTS conditions, and cracking of feeder pipes were both unanticipated. As noted earlier, all older CANDU-6 reactors have feeders with low Cr contents, partly because the low Co specification (typically <0.02–0.03 wt%) led to A106B steel with very low Cr concentrations. Thus, outlet feeder pipes in the older CANDUs have areas in the first and second bends that are experiencing FAC at about the same rate (50 to a few with a maximum of 175 μm/year), a rate sufficient that achieving 30 year life for some feeders will not be possible [1,4]. A few feeders have already been replaced because of excessive wall thinning.

At PLGS, several feeders have cracked, either from the primary side or from the secondary side, and the mechanisms have yet to be unambiguously determined. The intergranular IDSCC is likely SCC of cold-worked material in a slightly oxidizing environment. The ODSCC appears to be hydrogen-assisted creep cracking. Although this SCC has been found only in 11 feeders at one CANDU station [4], there are several other CANDUs with feeders that have the same fabrication history as that for PLGS. These have yet to experience cracking, despite equivalent operating times, and there are approximately 360 feeders at PLGS that have yet to show any cracking. However, as noted for SGs, it would be unwise to assume that the uncracked feeders have any special resistance to cracking until the cracking mechanism is well-defined.

Cracking of feeders is restricted to outlet feeders, and has initiated both on the inside (ID) surface, and on the outside (OD) surface of 11 feeders at PLGS to date. Initially it was thought that A106B feeder material would have high resistance to SCC, and since only 11 of approximately 20000 feeders in-service have cracked (to 2006 December), this initial belief has so far proven correct. However it is not known why only 11 have cracked to date, and not more with the same history and service experience, and there is a need to better understand this. It is hypothesized that this cracking, which is intergranular (IGSCC) in nature, is stress corrosion cracking (SCC) on the ID surface and creep cracking, probably assisted by FAC-generated hydrogen, on the OD surface. In both cases there is no evidence of intergranular segregation of impurities known to cause IGSCC of steels, nor unambiguous evidence of pure creep cracking or fatigue, but the cracks are known to occur at regions of high residual stress, and possibly initiation and propagation is also driven by dynamic loads ('ripple' loads) associated with startups or normal operation. The IDSCC occurs in the presence of FAC, and whilst these two forms of degradation are usually regarded as mutually exclusive, it is possible that creep may contribute to the IDSCC, and that slightly (or even highly oxidizing) conditions that could occur during shutdowns, layups and startups initiate the IDSCC. It is important to consider that only a few outlet feeders have cracked at one CANDU reactor, even though other reactors have feeders with similar composition and fabrication history. The sole feeder-to-feeder weld that has cracked at G-2 was a weld that was repaired after its initial manufacture; the cracking initiated internally in the weld and propagated to the OD surface. This weld was in a highly stressed condition; stress relief of any repaired welds is now recommended.

Other components and systems have experienced various forms of aging-related degradation, with the most common being FAC of piping and secondary side SG components in any areas where turbulent flow of water or two-phase water-steam mixtures occurs, and under-deposit pitting and microbiologically-influenced corrosion (MIC) of low temperature water piping. FAC is a well-known phenomenon for materials such as carbon steels, mild steel and copper alloys. However, 30–40 years ago the phenomenon was not completely understood in terms of corrosion rates and predictability of susceptible areas of piping, and thus over the first 30 years of reactor life the failure susceptibility of various locations and components has become better understood. For existing plants the remedy for FAC-induced piping failure has been replacement with a more corrosion-resistant material, such as Cr–Mo steels and stainless steels. Similarly, condenser tubing, originally often fabricated from copper alloys, experienced FAC failures that not only required maintenance and repair, but also led to contamination of the steam generators with corrosive impurities. Most of these copper alloy condenser tube bundles have been replaced with stainless steel tubes (fresh water) or titanium and high-molybdenum super-alloy tubes (sea water). Removal of copper alloys from the feedtrain has allowed for more flexible chemistry control in the sense that high pH can be maintained without concern for copper alloy corrosion and transport. New plants specify FAC-resistant materials for FAC-susceptible areas, and there is an increasing move towards specification of steel with >0.2 wt% Cr for all the feedwater piping.

MIC has caused significant corrosion and fouling of both CANDU and PWR/BWR plant systems and components. This degradation mechanism has become better understood in recent years, especially in the context of the design and operation requirements needed to eliminate this degradation. In CANDU reactors, as elsewhere, MIC has been observed on carbon steel, copper alloy and stainless steel (welds) components, and MIC-induced fouling has led to under-deposit pitting and significant blockage of many plant piping systems. In CANDU-6 reactors, there is a closed circuit recirculating cooling water system that allows for high pH chemistry control, which minimizes the possibility of bacterial infiltration and growth in all components fed by this system, and thus eliminates MIC. In other systems that are not as carefully controlled, features such as dead legs and stagnant zones, and operating practices that require piping to be periodically flushed (which introduce fresh nutrients that sustain MIC), can be changed in both existing and new designs.

Similarly, the well-known phenomenon of under-deposit pitting, and crevice corrosion, can be designed out or managed by eliminating practices that allow deposits to build up, especially when oxidizing conditions and corrosive impurities are present (chlorides, sulphides, copper, etc.). This affects both steel and stainless steel components. Highly stressed stainless steel (cold-worked by bending, grinding, etc.) cracks readily when contaminated with chlorides in a wet or wet/dry environment. This type of cracking is common in instrument lines that are contaminated with chlorides from wet insulation or exposed to moisture that has been in contact with insulation.

3. A summary of key R&D activities

Early activities in CANDU materials R&D were focussed on verification of design-related specifications and materials selection.

Thus there was significant effort on SG and heat exchanger tubing chemistry and corrosion, on carbon steel corrosion, and on various aspects of stainless steel corrosion that could impact components such as the end fittings (type 403 SS), SG supports (type 410 SS) and the calandria vessel and internals (type 304L SS). As plants were commissioned and began service the R&D became oriented around degradation mechanisms that were discovered in CANDUs, or that were experienced in PWRs and BWRs and which were regarded as of potential concern to CANDU. The focus has remained on understanding degradation mechanisms that are of significance to operating plants, but has begun to shift towards including R&D to better understand behaviour of materials for extended plant life. Part of the intent here is to ensure capability is retained to be able to understand and manage any new or unforeseen aging-related degradation, including degradation experienced in other reactor types but which could impact CANDU integrity or operation. Table 2 summarizes these R&D activities.

There have been several unforeseen degradation mechanisms that have required, or will require, significant R&D focus, both for existing CANDU reactors and for new designs. These are

- Feeder cracking (carbon steels and role of cold work and low temperature creep; PLGS only to date).
- Pb-accelerated SCC of SG tubes (Alloy 600 to date, but laboratory studies indicate Alloys 800 and 690 are also susceptible).
- Cracking of cold-worked unsensitized L-grade SS (primarily BWRs, but potentially possible in all reactors).
- Weld cracking of Alloys 600/182/82 (PWRs primarily).
- FAC and cracking of Alloy 400 SG tubing (CANDU only).

Table 2
Summary of key materials R&D areas

Time period of CANDU R&D emphasis	Primary CANDU R&D areas investigated
1960s and 1970s	Alloy 400 corrosion SG tube denting and crevice chemistry (Alloys 600 and 800) SG tubing primary side cracking (Alloy 600) SG and feedwater chemistry Carbon steel corrosion in HTS chemistry
1980s	SG tubing primary and secondary side cracking (Alloys 600 and 800) SG and HX tube crevice chemistry HX tube corrosion (condenser tubes, moderator HX; brasses, super-stainless steels, Ti, Ni alloys) Carbon steel corrosion
1990s	SG tubing secondary side cracking (Alloys 400, 600, 690 and 800) SG tubing secondary side corrosion (pitting, IGA; Alloys 400, 600, 690 and 800) Crevice chemistry SG tubing fatigue (Alloys 600 and 800) Corrosion related to SG cleaning (primary and secondary side technologies) Lead (Pb) chemistry and Pb-induced SG tube cracking (Alloys 600, 690 and 800) FAC of carbon steel in feedwater and in HTS conditions MIC of carbon/mild steel piping
2000s	SG tube crevice chemistry (including effects of crevice geometry) Lead (Pb) cracking and Pb chemistry of SG tubing (Alloys 600, 690 and 800) Secondary side cracking, IGA and pitting (susceptibility mapping for Alloys 400, 600, 690 and 800) Fatigue/EAC of HTS carbon steel piping Role of hydrazine in SG tubing corrosion and on carbon steel FAC FAC of carbon steel under feedwater and HTS chemistries IGSCC and creep cracking of carbon steel in HTS chemistries Dissimilar weld corrosion/cracking (SS to CS welds) MIC of service water piping Stainless steel corrosion in low temperature water (type 304L SS)

Some of these are captured in Table 3, and all except the Alloy 400 FAC are part of the current R&D program activities for CANDU and elsewhere. Several advances have been made in the understanding of some of these degradation mechanisms, and FAC of carbon steels in HTS chemistry is now well enough understood that further R&D may not be necessary (although there is still no understanding of how very low levels of Cr can have large impacts on carbon steel FAC resistance). For instance, Fig. 1 shows data for experimentally-measured FAC rates of carbon steels as a function of Cr content [5]. The apparent 'threshold' around 0.04 or 0.05 wt% Cr is well-established from plant data (and is a function of geometry and hydrodynamic conditions and system chemistry), but as-yet no quantitative mechanistic explanation for the protective ability of relatively low levels of Cr on FAC of carbon steels is available.

The role of Pb in accelerating cracking of SG tubing may be its effect on surface films on these materials, but it would appear that there is no safe lower limit for the impact of Pb on Alloy 600 (Fig. 1), or whether much of the observed secondary side SCC of Alloy 600 SG tubing could be ascribed to Pb contamination. Recent studies have shown that crack tips in Alloy 600 SG tubing that has undergone cracking in lead-contaminated environments are <10 nm wide and contain Pb incorporated into a spinel oxide lattice [7]. It is not clear how these observations can be explained in terms of a cracking mechanism involving Pb, but the chemistry at these crack tips clearly is thermodynamically different from the bulk Pb-contaminated solution in which Pb-induced SCC (PbSCC) initiates. Currently it is not known if SGs tubed with Alloys 690 and 800 could be considered 'resistant' in-service to this form of degradation, since there has been no confirmed reports of cracking of either alloy to date (to 2006). It is known, however, that both alloys can crack under laboratory accelerated testing conditions, which suggests that over long service lives such degradation could occur. Further R&D is needed to close the gap between laboratory data and predictable in-service behaviour (see, for instance, Ref. [8]).

The FAC mechanism is now reasonably well-understood and predictable, both for feeders and other plant systems. Because the CANDU core is non-ferrous, and the temperature of the water as it transits the core increases by approximately 50–60 °C, which increases the under-saturation, the outlet feeders are thermodynamically predisposed to dissolve. In addition to the degree of iron under-saturation, the rate of dissolution increases with turbulence such that the tight radius bends immediately downstream of the core outlet are at risk since the HTS core outlet flow changes direction and is subject to highly turbulent conditions. FAC is also dependent on Cr concentration and the early CANDUs had low Cr content in their feeders as a consequence of the low Co specification. R&D at AECL and elsewhere has shown that small increases in the Cr content of carbon steel can have significant impacts on FAC, and, under feedwater conditions, has a 'threshold' behaviour which can make prediction of FAC rate in operating systems difficult (for instance, see Fig. 2) [5]. For feeders operating at 310 °C, the increased Cr content implies a decrease in FAC rate of 50% (Fig. 2) [1,9]. For A106 carbon steel, there is an allowable range in specified Cr content of up to 0.4 wt%, and thus increased FAC resistance can be obtained within the A106B specification.

The FAC behaviour of A106B carbon steel feeder piping has been investigated in the laboratory, generating data which have been corroborated by plant experience, and shows that small increments of Cr reduce FAC rates by up to 50% under CANDU HTS conditions (Fig. 3). This result is important in specifying replacement

Table 3
Summary of the knowledge base for out-of-core degradation affecting CANDU components and systems

Degradation mechanism	Material affected (in CANDUs)	CANDU components affected	Anticipated during design?	Predicted from R&D?	Now understood?	How managed?
FAC	Carbon and low alloy steels (including welds), copper alloys, Alloy 400	Outlet feeder pipes, SG secondary side components, SG primary side divider plates, feedwater/steam cycle piping, HTS piping, Alloy 400 SG tubing, brass condenser tubes	No for HTS; FAC assumed to be uniform degradation and rates assumed to be low. For secondary side degradation assumed to be uniform. Not anticipated as an Alloy 400 degradation.	Partially; not for CANDU HTS conditions. Predicted for mild steels and for copper alloys	Yes	Inspection and replacement as required (or tube plugging for SGs)
SCC	Carbon steels, Alloy 600 (and I82/182 weld metals)	Outlet feeder pipes (PLGS) and welds (Gentilly-2), Alloy 600 SG tubes (BNGS) (note that flow restriction orifices, Wolsong-1 SG tube support structures have no history of SCC in CANDU service)	Partially; A106B feeder material was selected to minimize risk of SCC based on available knowledge; Alloy 600 cracking not considered an issue at time of decision to move away from Alloy 400.	No for carbon steel in CANDU HTS conditions; yes for Alloy 600. Also thought that Alloy 800 would be crack resistant (especially under HTS conditions). SG chemistry designed to minimize risk	Partially; major factors involved are reasonably well-understood, although role of cold work requires further development. Crack growth rates not available	Inspection and repair (replace for feeder pipes; plugging for SG tubes)
Pitting/wastage	Carbon and low alloy steels, Alloys 40, 600 and 800	HTS and plant piping, SG structures, SG tubing	Yes (chemistry specifications designed to prevent this form of degradation)	Yes	Yes	Inspection and repair as required (plugging of SG tubing)
Fatigue and environmentally-assisted fatigue	All	Piping, SG tubes, condenser and heat exchanger tubes, etc.	Yes for mechanical fatigue (design to ASME); no for environmentally-assisted fatigue	Yes for mechanical fatigue, although thermal fatigue perhaps not fully appreciated. No for environmentally-assisted fatigue at time of design	Partially; mechanical factors reasonably understood, but effects of cold work and environment still need further development	Inspection and repair, replace, plugging as required
Fretting wear	All where component-to-component contact can occur	Piping (at supports and pipe-to-pipe contacts), SG and HX tubing	Yes (designs have evolved to minimize risk), although for SGs and HXs there are many cases where manufacture did not meet design requirements	Yes	Yes	Inspection and repair, replace, plugging as required
Microbiologically-influenced corrosion (MIC) and fouling	Low temperature piping and other components with low velocity water open to atmosphere	Service water systems (piping and HX); fire protection systems, etc.	Probably not; MIC has been known for some time, but only recently has been sufficiently understood to influence design appropriately	Partially	Yes, although predictive models still required	Inspection and repair as required

and new feeder materials. The figure also reveals some interesting behaviour of the two types of steel, one low Cr and the other high Cr, but both within the A106B specification. Initially the FAC rates are similar; in fact there is an increase in FAC rate of the higher Cr steel. However, after some exposure time the FAC rate of the higher Cr steel decreases and stabilizes at ~50% of the low Cr steel. This same behaviour is reflected in early plant monitoring data, and suggests that low levels of Cr reduce FAC rate through some dynamic process, possibly by concentration of the Cr to the metal–oxide interface.

Unpublished work at Chalk River Laboratories has also shown that intergranular cracking of A106B can be achieved in the laboratory, in conditions simulating CANDU HTS chemistries, only in an oxidizing environment and when the steel is heavily cold-worked. Non-cold-worked steel exhibits transgranular cracking, which has not been experienced in operating reactor outlet feeders. Other recent studies have shown that creep cracking of cold-worked A106B carbon steel can occur, in air, at temperatures as low as 310 °C. Thus, these early results suggest that both SCC and creep cracking are possible for cold-worked carbon steel, and these mechanisms, or a combination of them, may be responsible for the IGSCC seen at PLGS.

4. Materials performance for plant life beyond 30 years

As CANDU reactors enter into refurbishments, there is a need to confirm the integrity of any non-replaced materials for up to 30 years beyond the original design life of 30 years. New designs, such as the advanced CANDU reactor (ACR) and enhanced CANDU-6 (CANDU-6E) will require a service life of non-replaceable components of up to 60 years. The key components that are regarded as non-replaceable are piping, steam generators and building structures. Note that this may not imply that the component is non-replaceable from an engineering or feasibility perspective, but that

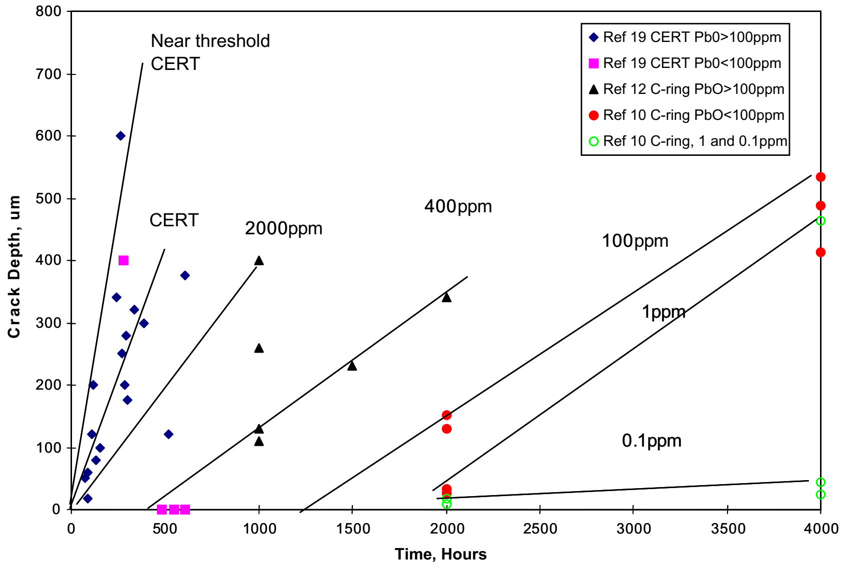

Fig. 1. Effect of varying Pb concentrations on stress corrosion cracking of Alloy 600 SG tubing [6].

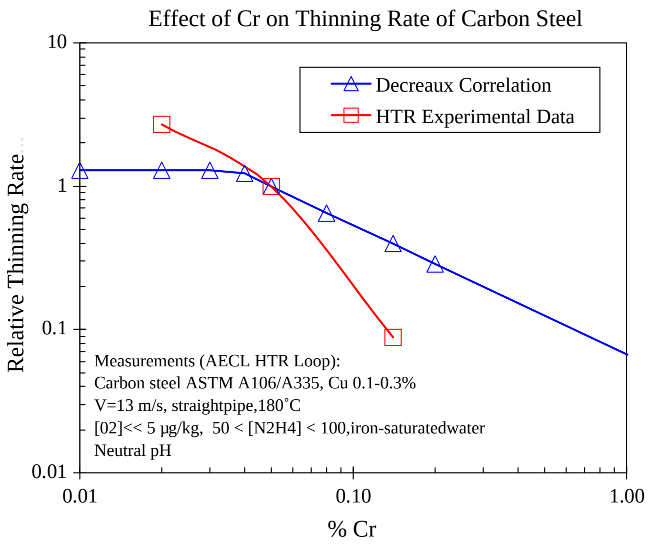

Fig. 2. Effect of Cr on FAC of carbon steel in feedwater [5].

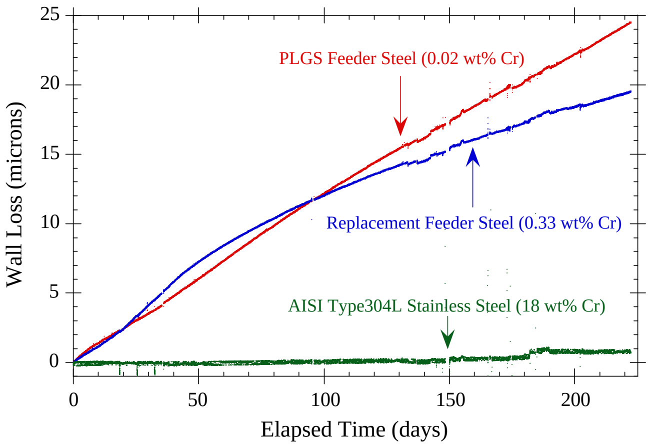

Fig. 3. Effect of time and Cr content on FAC rate of carbon steel [9].

economic plant operation requires that such replacements not be required. Further, another factor is the need to reduce inspection and maintenance requirements by reducing degradation of the materials of fabrication and construction, and improving the predictability of any degradation that could occur later in life (degradation rates). Concrete structures clearly represent a materials challenge, including reinforcing materials, but this material is not considered in this paper.

Steam generators are critical, and expensive, components that have required extensive inspection and maintenance in PWRs and some CANDUs. Reactors should be designed such that steam generators can be a replaceable component, but should still have a 60-year life with appropriate materials selection. Replaceability is important here because, over a 60 year life, and as already experienced for SGs with Alloy 600 where there is a long history of SG degradation in PWRs (see Fig. 4), unanticipated degradation cannot be completely ruled out, although it is unlikely based on current knowledge of the behaviour of Alloys 800 and 690. For Alloy 600 it could be argued that most of the degradation experienced was unanticipated (although some of it could be regarded as known to be a potential degradation based on R&D knowledge) and some of which has been duplicated in CANDUs. The PWR experience is for Alloy 600 SG tubing, which, in CANDUs, is used only at one CANDU reactor site. This unit, BNGS, has experienced significant SCC, at the U-bend and at the top-of-tubesheet, and layup-induced pitting (inappropriate layup conditions) [6,10], and this has led to decisions to replace these SGs as part of refurbishment activities. There has been little evidence in other CANDU SGs of any SCC, and none for Alloy 800, and thus the equivalent figure for CANDUs would show only approximately 2000 Alloy 600 tubes plugged for SCC, mostly for ODSCC related to Pb. Alloy 400 used for SG tubing at PNGS has also experienced significant pitting/intergranular attack under oxidizing conditions [11]. There are also examples of pitting for Alloy 800 in-service [12].

The point here is that although the operating experience for CANDU SG tubing is much better than that for Alloy 600 in PWRs, it would be unwise to ignore the history in Fig. 3 and assume that over long times (up to 60 years) there will be no further degradation or even no surprises (degradation as-yet unknown in SG tubing), even though materials such as Alloy 800 have achieved up to 33 years of SCC-free service so far in CANDUs and German PWR

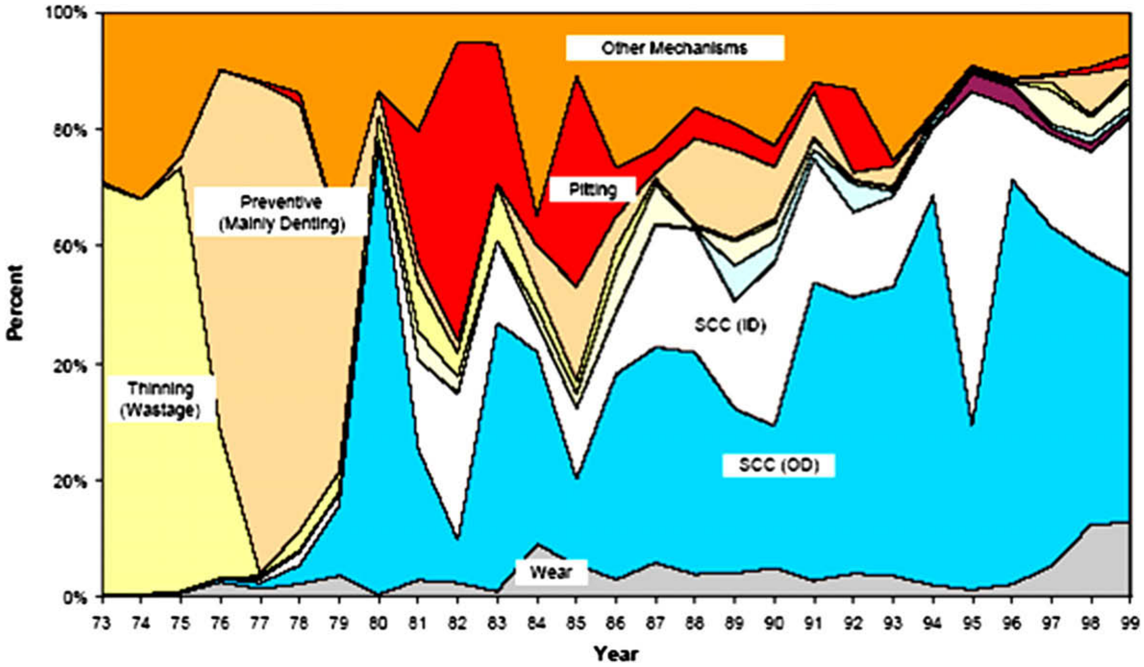

Fig. 4. World-wide causes of SG tubing degradation [14].

SGs. The as-yet unknown role of Pb, and the risk it poses, needs to be defined [13].

It is very difficult to have effective aging management strategies if the degradation mechanisms are not well-defined. The examples given previously, which are for situations where degradation mechanisms are not yet well enough defined to unequivocally provide quantitative degradation rates and mitigating actions, have led to aging management strategies that involve extensive, and expensive, inspections. Establishing 60-year (or extended life) life management strategies with reduced inspection and maintenance requirements is the challenge for materials selection and R&D.

The ACR, for instance, has been designed such that the only major components that need replacement are the fuel channels. It is anticipated that the current CANDU-6 SG design, with Alloy 800 tubing,

Table 4
Summary of potential impacts of known degradation mechanisms for future CANDU service

CANDU degradation mechanism	Mitigation	Future concern?	Unknowns that could impact long-term integrity
Feeder thinning (carbon steel)	Cr > 0.24 wt% for A106B/C (>0.3 wt% typically achieved)	No; thinning rates are predictable and will provide for design life achievement. Inspection required	
Feeder thinning (stainless steel/ACR)	Use type 316LN SS	No	
Feeder cracking (carbon steel)	Stress relieve tight radius bends. No warm bending; repaired welds should be stress relieved	No, assuming appropriate non-oxidizing HTS chemistry in maintained	Impacts of unanticipated cold work after installation
Feeder cracking (stainless steel/ACR)	Minimize cold work, no cold bending without appropriate stress relief	No under CANDU conditions that maintain non-oxidizing HTS chemistry	Impacts of unanticipated cold work after installation
SG tube cracking	Use Alloy 800 or 690 tubing	No, assuming appropriate chemistry management and Pb control	Long-term impacts of Pb contamination
SG tube pitting	Maintain appropriate chemistry	Yes; all SG tubing will pit under-deposits and if oxidants and corrosive impurities are present	None?
Piping FAC	Cr > 0.2 wt% for all piping; maintain chemistry and avoid turbulence/high flows with design	No, but inspections required using appropriate management program (for instance, using codes like CHECWORKS to guide locations at risk)	None?
Fatigue	Design to avoid vibration, thermal stress, etc. Avoid components such as weldolets, etc. where small piping can vibrate	No, but inspection and fatigue management program required	Unanticipated sources of cyclic stress; synergistic interactions with environment
MIC and pitting	Design to avoid deposits, crevices, deadlegs, cyclic air exposures, low flow/stagnant conditions, etc.	No, but inspection required, plus a management plan to identify at risk locations	None?

stainless steel supports and internals subject to FAC, and a feedwater system optimized to minimize corrosion product transport and FAC, is a 60-year design. The type 316LN stainless steel feeders should also provide low maintenance 60-year life. Piping, both for the primary side and the feedwater systems should be specified to >0.2 wt% (ideally >0.3 wt%) Cr and thus provide 60 year life.

Table 4 provides an attempt to summarize the discussions above in terms of predicting the potential long-term impact of degradation on CANDU components that require >30 year life. The table is limited to known mechanisms that have been observed in CANDU or other reactor types to date, or has been demonstrated in laboratory studies.

5. Conclusions

In summary, the key to enabling >30 year life for reactor components is the need to strictly manage chemistry to specifications, and to ensure that, during fabrication and operation, materials are not subjected to mechanical damage (cold work, scratches, etc.) that can compromise life by providing conditions for SCC. Given the conservative nature of the nuclear industry, it is unlikely that new materials can be introduced without extensive qualification and code casework. Thus, future materials advances may be limited to components and technologies that improve small replaceable components such as valves, pumps, etc. However, there is still a need to better quantify degradation mechanisms and rates for the major materials used in nuclear power plants, including carbon and low alloy steels, stainless steels, and nickel alloys, to ensure that extended life is predictable and manageable without excessive inspection and maintenance. Studies of degradation mechanisms must also continue to look ahead to determine if there are any as-yet-undetected degradation mechanisms that could impact materials and component integrity. Over the first 30 years, and in some cases after significant operating experience, unanticipated degradation mechanisms have impacted CANDU reactor operation. These include intergranular SCC of carbon steel in HTS water, FAC of carbon steel in HTS conditions, and PbSCC of SG tubing alloys. Managing or eliminating this experience for new reactors, and for the next 30 years of refurbished reactors, will require continued investigation and new approaches to predicting future component life.

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