Impact of Flow Accelerated Corrosion (FAC) on Feeder Refurbishment Planning

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Abstract

Feeder wall thinning due to flow accelerated corrosion (FAC) may result in a large number of feeder replacements in the future. In this study, the process of FAC is modelled using a probabilistic approach and used to predict the expected number of degraded feeders and their replacements in the future. Because of the high cost associated with feeder replacements, it may be optimal to replace the entire feeder population during a single refurbishment outage when the unit cost of replacement is likely to be less. The results of this study demonstrate, however, that the unit cost of feeder replacement must be sufficiently lower than the standard replacement cost and the refurbishment performed at an optimal time to realize the economic benefits associated with the refurbishment.

1. Introduction

Flow accelerated corrosion (FAC) is a serious form of degradation affecting the outlet feeders of CANDU stations [1]. Wall thinning due to FAC has been observed along the entire length of the feeder piping, however, the rate of wall loss is highest in the tight-radius bends near the outlet feeder Grayloc weld, due to the highly disturbed flow in this region.

The main impact of FAC on feeder life cycle management (LCM) is attributed to the regulatory process, which requires developing and executing a comprehensive aging management program to manage the degradation process. This involves extensive monitoring and inspection efforts to characterize the extent of the degradation, and furthermore, to track and predict the evolution of the process in the future [2].

It is evident that excessive thinning by FAC can jeopardize the station's fitness for continued service and result in an increased chance of leakage of the reactor pressure boundary. Due to safety concerns associated with feeder wall thinning, a specified lower limit of wall thickness must be established for each feeder to ensure adequate safety and fitness-for-service prior to the next scheduled inspection [3]. The critical minimum thicknesses are estimated based on a design pressure consistent with Section III of the ASME Boiler and Pressure Vessel Code [4]. Degraded feeders must be removed from service when they are predicted not to meet the minimum thickness requirement before the next scheduled outage.

By definition, exceeding (i.e., being below) the regulatory limit does not result in immediate feeder failure (e.g., leak or rupture) and subsequent forced outage. However, repair/replacement or other intervention must take place for continued service, resulting in increased economic consequences. The main purpose of this paper is to investigate the economic impact associated with these regulatory replacements, that is, the replacement of degraded feeders that are predicted not to meet the minimum thickness criteria prior to the next outage.

Typical feeder thinning rates observed in the industry range from 60 µm/EFPY (effective full power years) to 140 µm/EFPY. These rates may result in substantial number of feeder replacements for some stations within their operating lives. For stations considering life extension and refurbishment, it is therefore essential to determine not only the number of feeder replacements prior to the refurbishment outage, but also the resulting economic impact. If the predicted number of feeder replacements is very high, then does it make sense, at least economically, to replace all feeders again during the refurbishment outage? This paper will explore these and other issues associated with the feeder system management in the long term.

2. Model development

Feeder FAC is a time-dependent process of uncertain nature. Predicting the remaining life of the feeders is therefore challenging, due to the numerous uncertainties involved, including lack of data, e.g., unknown initial wall thicknesses, probe measurement errors, non-stationary nature of the FAC process, and other factors, such as changes in chemistry and other operational parameters affecting the wall thinning process [2].

Assume the wall thinning process follows the probabilistic random rate model as presented in [2]. According to the model, the feeder wall thickness as a function of time is expressed as [2]

$$WT(t) = WT(0) - R \cdot t \tag{1}$$

where $WT(t)$ is the wall thickness at time t, $WT(0)$ is the initial wall thickness, and R is the thinning rate. Because of lack of baseline information, the initial wall thickness, $WT(0)$, is treated as a random variable with a probability distribution. The thinning rate, R, is also a random variable and varies across the population of feeders.

Assuming the initial wall thickness and thinning rate follow the Normal distribution, the wall thickness at any time t will then also follow the Normal distribution with

Mean $$m_t = m_o - t \cdot m_R \tag{2}$$

Standard deviation $$s_t = \sqrt{(s_o)^2 + t^2 (s_R)^2} \tag{3}$$

where m_o and s_o are the mean and standard deviation of the initial wall thickness, respectively, while m_R and s_R are the mean and standard deviation of the thinning rate, respectively. The probability of feeder wall thickness being below the minimum thickness requirement at time t can then be estimated from the Normal distribution with mean and standard deviation given by Equations (2) and (3), respectively.

Assuming the wall thinning process due to FAC is independent for each of the feeders, the expected number of substandard feeders at any time t can be estimated by summing up the individual probabilities of all the feeders in the reactor. Note that a *substandard feeder* in this study refers to a feeder having a wall thickness below the minimum requirement. The expected number of substandard feeders can then be used to estimate and plan feeder replacements in future outages (to ensure fitness-for-service between the planned outages).

3. Model application and results

Consider a reactor with a total of 480 outlet feeders, consisting of 90 2 inch and 390 2.5 inch diameter feeders. For the sake of illustration, assume that all the feeders are uninspected. Because of lack of information, the initial thickness of these feeders is assumed to be a random variable. Similarly, the thinning rate is also assumed to be a random variable with a probability distribution. Table 1 summarizes the assumed distribution parameters of the initial wall thicknesses and thinning rates for the population of 2 inch and 2.5 inch feeders in this problem. As shown by Table 1, the standard deviation reflects the degree of uncertainty and variability in the initial wall thicknesses and thinning rates.

Table 1 Distribution parameters for the initial wall thicknesses and thinning rates.

Parameter	Distribution	Feeder	Mean	Standard Deviation
Initial wall thickness *WT*(*0*)	Normal	2”	5.34 mm	0.16 mm
	Normal	2.5”	7.0 mm	0.21 mm
Thinning rate *R*	Normal	2”	90 µm/EFPY	20 µm/EFPY
	Normal	2.5”	135 µm/EFPY	20 µm/EFPY

The minimum required thicknesses are assumed to be equal to 2.75 mm and 3.33 mm for the 2 inch and 2.5 inch feeders, respectively. These critical values can then be used to compute the probability of having a substandard feeder (i.e., a feeder with wall thickness below the minimum requirement), and subsequently the expected number of substandard feeders over time.

3.1 Feeder replacement planning

The expected cumulative number of substandard feeders over time for the reactor unit is presented in Figure 1. It is assumed that the year 2010 corresponds to approximately 15 EFPY for this unit. As shown in Figure 1, the number of substandard feeders begins to increase rapidly after year 2015 as a result of the FAC process. Between year 2018 and year 2025 approximately 40 new feeders are expected to become substandard each year. It is estimated that there will be approximately 100 substandard feeders by year 2019, which will further increase to approximately 300 substandard feeders in the following five years (i.e., by year 2024). The results of Figure 1 are directly related to the high wall thinning rates used in this problem (as presented in Table 1).

Assume the reactor unit follows a 3-year planned outage cycle. Because the substandard feeders are not allowed to remain in service, the number of planned or regulatory replacements in a given outage is estimated as the expected number of additional or new substandard feeders predicted to occur before the next outage. It is assumed that the replacement feeders are not subject to the FAC process due to improved physical properties, etc.

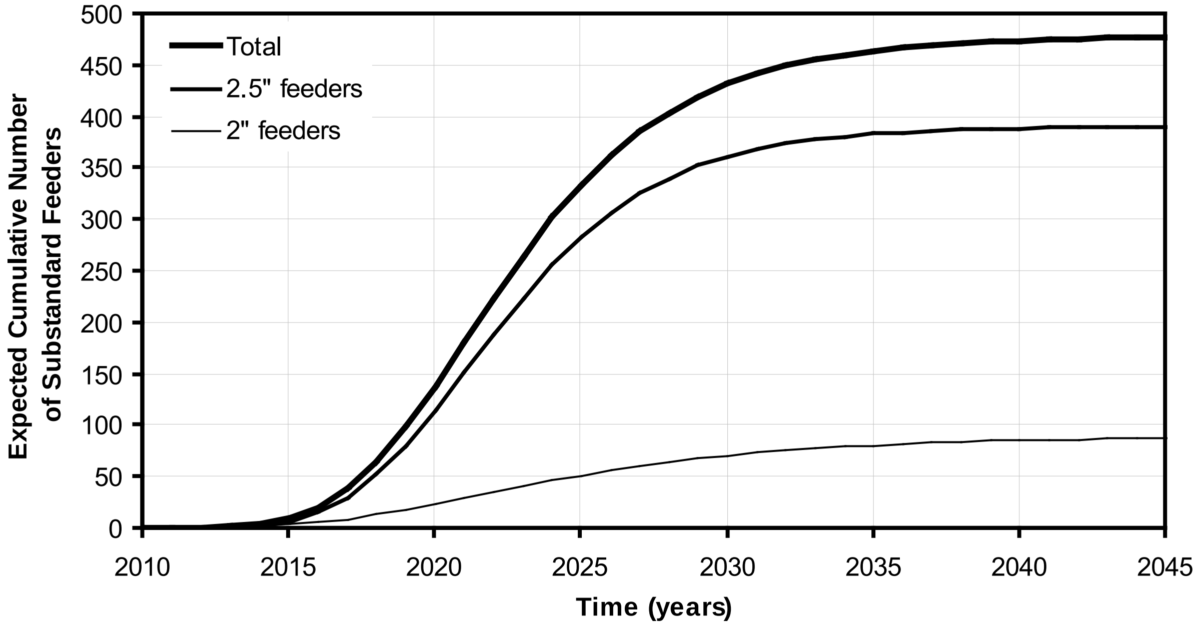

Figure 1 Expected cumulative number of substandard feeders over time.

Table 2 shows the number of feeders expected (i.e., required) to be placed in each planned outage in the future following the 3-year outage interval. It is evident from the results that feeder degradation due to FAC may result in a significant number of feeder replacements in the future with substantial economic consequences.

Table 2 Number of outlet feeders expected to be replaced in each planned outage.

Planned Outage Year	**Number of Feeders Expected to be Replaced**			
	2”	**2.5”**	**Total**	**Cumulative**
2012	3	8	11	11
2015	11	47	58	69
2018	15	99	114	183
2021	17	101	118	301
2024	14	68	82	383
2027	10	36	46	429
2030	7	18	25	454
2033	4	7	11	465
2036	3	3	6	471
2039	2	2	4	475
2042	1	0	1	476
2045	1	1	2	478

3.2 Economic analysis

The main challenge with managing the feeder system is the high cost associated with replacements. Because of their close proximity to the reactor core, low clearances and stacked arrangement, and their function in forming the primary pressure boundary for the reactor, the replacement cost of a single feeder is typically in the order of $ 1 million. As the feeders become thinner due to the FAC process, the expected number of planned or regulatory replacements of degraded feeders will begin to increase rapidly over time as shown in Figure 1. Choosing to replace all outlet feeders in a single outage may therefore become more attractive, since the overall replacement cost per feeder will be potentially much lower during the refurbishment outage.

Consider the following two planning alternatives. Alternative 1 consists of operating the feeder system *without refurbishment* and continuing to replace the feeders as predicted in Table 2. Alternative 2 involves the one time replacement of all feeders in a future refurbishment outage, including the feeders that may have already been replaced in earlier outages. Assume the study period is from year 2010 to year 2045 with a discount rate equal to 10 % in both cases and the cost of feeder replacement equal to $ 1 million per feeder during the regular planned outages (i.e., not the refurbishment outage when the unit cost of replacement is assumed to be less).

3.2.1 Alternative 1: No replacement of feeders during the refurbishment outage

Assume the feeders are replaced according to the planned replacement schedule shown in Table 2. Because the study period is from year 2010 to year 2045, the replacement of two feeders during the planned outage in year 2045 is ignored in the analysis. Assuming the cost of feeder replacement is equal to $ 1 million per feeder and the planned replacements can be performed during the scheduled outages without additional penalties, the total risk or expected cost associated with this scenario is equal to $ 176 million as net present value (i.e., the annual discount rate is assumed to be equal to 10 %). Although other critical systems, such as pressure tubes and steam generators may be replaced during the refurbishment outage, this is the total expected cost associated with the feeder system assuming the feeders are *not replaced* during the refurbishment outage.

3.2.2 Alternative 2: Replace all feeders during the refurbishment outage

If it is possible to replace the entire feeder population in a single refurbishment outage at a lower unit cost than the planned (regulatory) replacements, then it may be possible to find an optimal time for the refurbishment. Assuming the study period length remains unchanged (i.e., from 2010 to 2045) regardless of the actual date of refurbishment (i.e., the reactor is assumed to operate from year 2010 to year 2045 regardless of whether the refurbishment outage takes place, for example, in year 2016 or year 2020), Figure 2 shows the impact of refurbishment date on the total expected cost for given unit cost of feeder replacement during the refurbishment outage. The cost of planned (regulatory) replacements is assumed to remain constant and equal to $ 1 million per feeder.

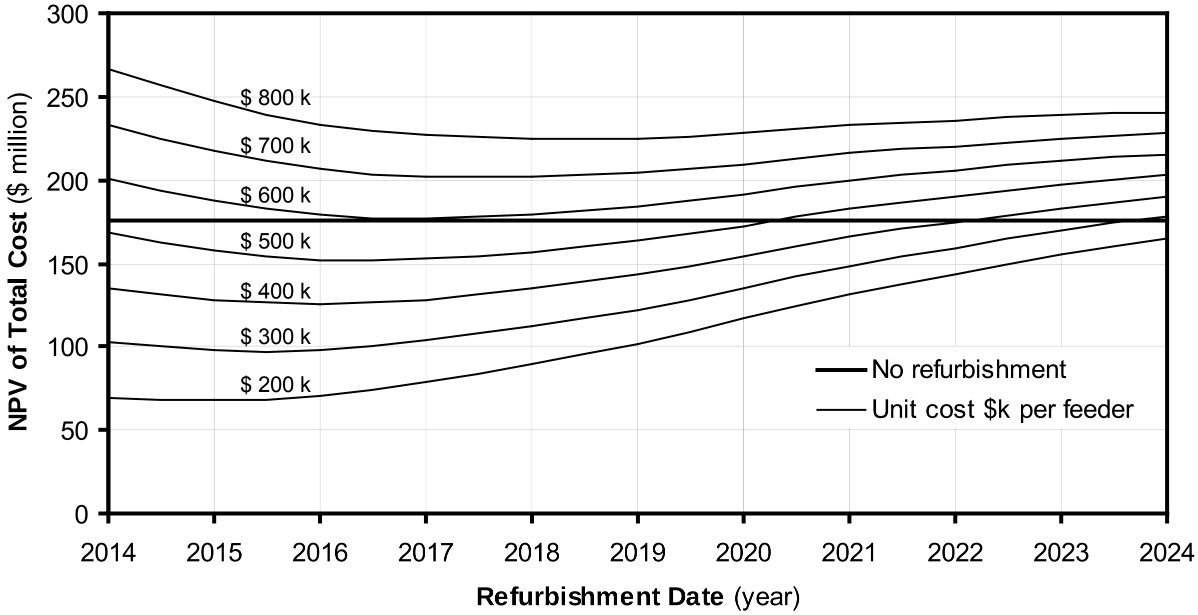

Figure 2 Impact of refurbishment date on total expected cost for various unit costs of feeder replacement during the refurbishment outage.

Assuming each feeder can be replaced for $ 200 k during the refurbishment outage (for a total cost of $ 96 million for the 480 outlet feeders), the minimum of the respective curves (the lowest curve in this case) in Figure 2 indicates that the optimal date of feeder refurbishment would be in the year 2015. This means that a total of 11 feeders would be replaced in the 2012 outage (refer to Table 2) for $ 1 million each followed by the replacement of all 480 feeders (including the 11 already replaced) in year 2015 for $ 200 k each. No feeder replacements are assumed to take place in the outages following the refurbishment outage as the replacement feeders are assumed not to be subject to significant FAC. Based on Figure 2, the overall economic risk associated with this optimal scenario would be approximately $ 70 million, which is about $ 100 million less than the previous scenario (Alternative 1) of having no refurbishment outage for the feeders.

The existence of the optimal time of feeder refurbishment for the various options in Figure 2 is due to the discount rate. An earlier refurbishment date would result in a higher total cost, while a later date would have a higher cost due to the increased number of regulatory replacements that would have to be performed prior to the refurbishment outage (for a cost of $ 1 million each).

Figure 2 also illustrates that the unit cost of feeder replacement during the refurbishment outage should be less than $ 600 k (i.e., less than $ 288 million for the 480 feeders) in order to break even with Alternative 1. This means that if the total cost of feeder replacements was greater than $ 288 million during the refurbishment outage, then it would be more cost-effective, at least economically, not to replace the feeders during the refurbishment outage. Clearly, there are other technical and financial factors impacting the decision making with respect to feeder refurbishment, such as the potential for other degradation mechanisms (e.g., cracking) which would have to be considered in the analysis. The reduction in inspection costs would also need to be factored in following refurbishment as the number of feeder inspections would likely be less since the feeder FAC would no longer presumably be an issue. Nevertheless, the preceding results demonstrate the impact of FAC on the economic aspects of refurbishment planning at the station.

3.3 Impact of severity of degradation

The probabilistic model of feeder wall thinning can also be used to investigate the impact of the severity of the degradation on the results. Consider, for example, the case when the feeder FAC is assumed to be less severe than in the previous problem. Assume the mean thinning rates are now 70 µm/EFPY and 105 µm/EFPY for the 2 inch and 2.5 inch feeders, respectively. Table 3 shows the expected number of planned replacements under this scenario. It is evident that the lower thinning rates will result in smaller number of replacements early on, however, the total number of replacements by year 2045 would still be substantial, requiring the replacement of nearly all the feeders in the population by that time.

Table 3 Number of outlet feeders expected to be replaced assuming the mean thinning rates are 70 µm/EFPY and 105 µm/EFPY for the 2 inch and 2.5 inch feeders, respectively.

Planned Outage Year	**Number of Feeders Expected to be Replaced**			
	2”	**2.5”**	**Total**	**Cumulative**
2012	0	0	0	0
2015	2	3	5	5
2018	5	16	21	26
2021	9	41	50	76
2024	10	63	73	149
2027	11	69	80	229
2030	10	60	70	299
2033	9	45	54	353
2036	7	32	39	392
2039	5	21	26	418
2042	5	14	19	437
2045	3	9	12	449

Figure 3 shows the corresponding impact on the refurbishment planning for this scenario. Because of the discount rate (i.e., 10 %), the total cost of operation *without refurbishment* would be less than before and equal to $ 88 million in this case, since most of the planned replacements are now predicted to occur later in the operating life. As a result, the optimal time of refurbishment is also shifted to later years for the various options as shown in Figure 3.

Under this less severe feeder FAC scenario, the unit cost of feeder replacement during a refurbishment outage around year 2019 would now have to be less than $ 400 k per feeder (or less than $ 192 million for the 480 outlet feeders) in order to break even with the basic scenario of only performing the planned replacements according to Table 3 for the unit cost of $ 1 million per feeder.

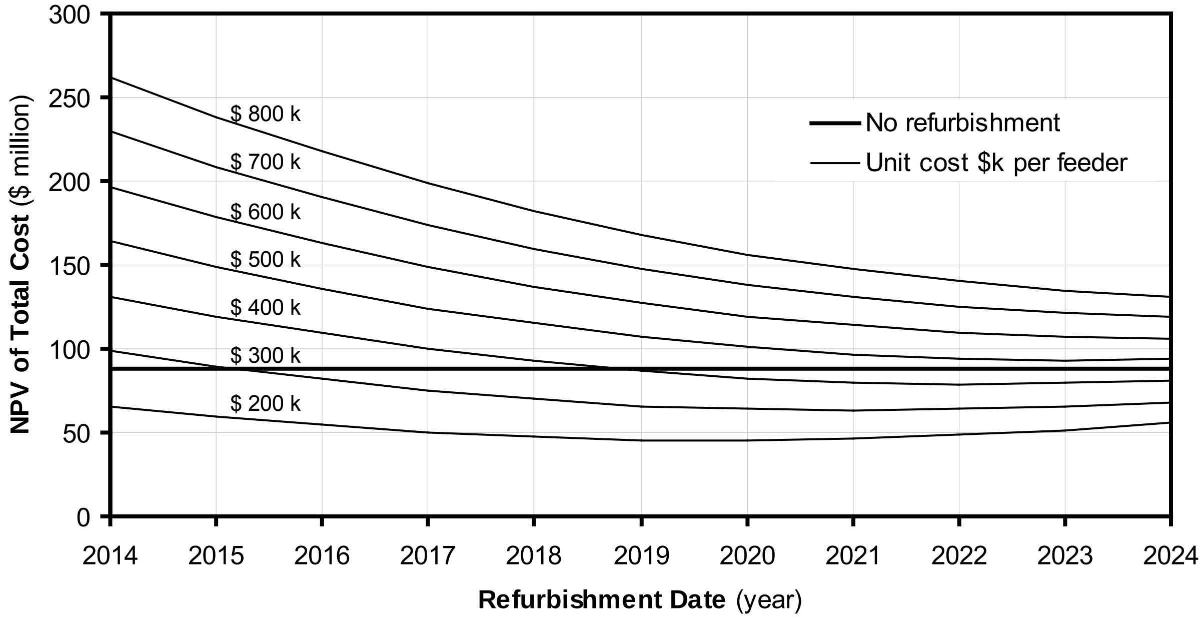

Figure 3 Impact of refurbishment date on total expected cost assuming the mean thinning rates are 70 µm/EFPY and 105 µm/EFPY for the 2 inch and 2.5 inch feeders, respectively.

4. Summary and Conclusions

Wall thinning by flow accelerated corrosion (FAC) is a major degradation mechanisms impacting the outlet feeders in some CANDU stations. Because the structural failure of a single feeder pipe poses a significant hazard to the station, any degraded feeders must be replaced before the minimum wall thickness reaches an acceptable lower limit. Depending on the extent and severity of the FAC process, this necessity for early intervention and loss of useful component life may result in substantial economic consequences at the station.

As shown by the results of this study, wall thinning by FAC has a clear economic impact on the long term planning at the station, including life extension and refurbishment. Because of the high cost associated with feeder replacements, it may be optimal, at least economically, to replace the entire feeder population during a single refurbishment outage when the unit cost of replacement is likely to be smaller. As shown by the results of this study, however, the unit cost must be sufficiently lower than the standard replacement cost and the refurbishment performed at an optimal time to realize the economic benefits. Naturally, other technical and financial factors must also be taken into account in the decision making process.

The developed model can be used to construct various planning alternatives and scenarios, for example by considering the impact both the inspected and uninspected feeder populations, different discount rates, etc., to support the long term business planning and life cycle management (LCM) of the feeder system at the station.

5. Acknowledgements

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6. References

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