REGULATION OF AGEING STEAM GENERATORS

by

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ABSTRACT

Recent years have seen leaks and shutdowns of Canadian CANDU plants due to steam generator tube degradation by mechanisms including stress corrosion cracking, fretting and pitting.

Failure of a single steam generator tube, or even a few tubes, would not be a serious safety-related event in a CANDU reactor. The leakage from a ruptured tube is within the makeup capacity of the primary heat transport system, so that as long as the operator takes the correct actions, the off-site consequences will be negligible.

However, assurance that no tubes deteriorate to the point where their integrity could be seriously breached as result of potential accidents, and that any leakage caused by such an accident will be small enough to be inconsequential, can only be obtained through detailed monitoring and management of steam generator condition.

This paper presents the AECB's current approach and future regulatory directions regarding ageing steam generators.

Atomic Energy Control Board
Ottawa, Canada

1.0 INTRODUCTION

1.1 Regulatory Mission

In Canada, the Atomic Energy Control Board (AECB) is the agency of the federal government entrusted with ensuring that the use of nuclear energy poses no undue risk to health, safety, security or the environment. The AECB is responsible, under the current *Atomic Energy Control Act*, for regulating nuclear power plants. Since the provincial governments regulate pressure retaining equipment in general, jurisdiction in such matters was shared with the provinces.

Underlying the AECB's regulation are the following general objectives:[1]

- Nuclear activities should not pose unacceptable risks to workers, the public or the environment;
- Events that lead to the escape of radioactive material or the exposure of people to ionizing radiation should occur with low frequency, decreasing as the consequence increases, so that the likelihood of catastrophes is virtually zero.

Nuclear power plants in Canada were originally licensed based on analyses, documented in the Safety Reports, of postulated accidents initiated by failures in the plant and external events.[2] The analyses were required to show that the public radiation dose resulting from each event is within limits derived from the recommendations of the International Commission on Radiation Protection (ICRP).

1.2 Significance of Steam Generator Ageing

Several Canadian plants have experienced steam generator tube degradation in recent years.[3] This physical ageing changes the licensing assumptions by increasing the potential for tube failures during operation, upsets or accidents. The tubes form part of the reactor pressure boundary, so their failure causes a small Loss of Coolant Accident (LOCA). They form part of the containment boundary also. Thus any radionuclides that escape by leakage to the secondary side are released eventually to the environment. The Safety Reports recognized the possibility of tube ruptures during operation. In the analyses of other events, however, it was assumed that the tubes would not leak more than nominal amounts.

Therefore the need exists to show that the practices followed in ageing steam generators give an acceptable overall level of safety. The AEC Act gave broad discretionary powers to the regulators. In the past, the AECB and its licensees have negotiated resolution of such issues case by case based on their impact on nuclear safety.[4]

The AECB's position has been that regulation of steam generators should ensure the following:

- A low probability of spontaneous tube rupture, in terms of occurrence per plant year, under normal operating conditions.
- A very low probability of tube rupture under accident conditions, in terms of the probability of occurrence of a design basis accident and consequential SG tube rupture.

- Primary to secondary leakage during normal operation and during postulated accidents within siting guide dose limits.

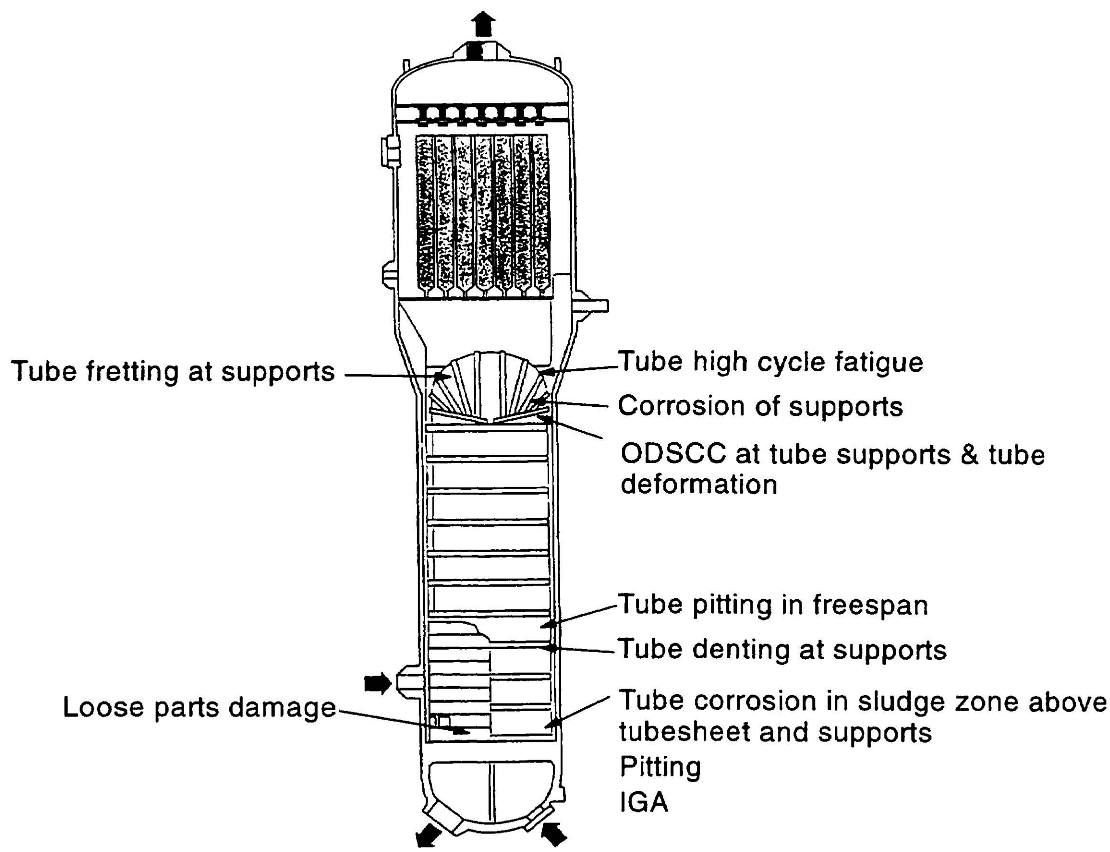

Figure 1: Tube Degradation Mechanisms in CANDU Steam Generators

2.0 EXPERIENCE IN REGULATING STEAM GENERATORS

2.1 Bruce B Fretting

Fretting at U-bend supports in Bruce B steam generators was discovered in 1989 during a periodic inspection. The maximum depth reported was about 50% through wall. A theory was advanced that fretting was "self limiting." Consequently, action was initially limited to periodic monitoring of steam generator condition. Prototype anti-vibration bars were also installed in Unit 5. However, fret depth continued to show an increasing trend until, in 1995, a tube leak occurred in Unit 7. On inspection, several other flaws were found in that Unit to have approached the maximum tolerable flaw size.

At this point, AECB staff asked Ontario Hydro to change its strategy for dealing with steam generator tube fretting to one that manages the risks more rigorously. Ontario Hydro has responded by setting up a schedule of inspection and tube plugging designed to ensure that few tubes will be at risk of failure during the current inspection interval. The latter criterion was supported by a safety assessment of consequential tube failures. The AECB has also asked Ontario Hydro to use inspection results regularly to confirm the models for predicting future steam generator flaw populations.

2.2 Bruce A U-Bend Stress Corrosion Cracking

A series of tube leaks in 1991 caused by circumferential cracks at the U-bends was the first sign of trouble in Bruce Units 1 and 2. Initially, the response was limited to finding and plugging the leaks. The absence of other indications from inspection was assumed to justify continued operation, despite information[5] that the technique did not readily detect circumferential cracking.

After a seventh forced outage, Units 1 and 2 were shut down for investigation. Tube removal revealed that tubes in the U-bend region contained outside diameter stress corrosion cracking (ODSCC). The cracking was especially severe in steam generators 2 and 3 of Unit 2. There, several tubes contained through-wall cracks. The inspection had not detected these defects.

A case for fitness for service of Unit 2 was eventually based on inspection with the specially-developed Cecco-3 eddy current probe.[6] The probe performance was demonstrated on removed tubes. This exercise credited the probe with an 80% probability of detection (POD) for cracks deeper than 60% through-wall. The possibility that some defects may have remained after inspection was addressed by showing that consequential failures in the event of an accident would not cause leakage beyond tolerable limits.

However, reinspection of Unit 2 after a year of operation revealed many new crack indications. Statistical models suggested that faster-than-expected crack growth rates were responsible. These findings implied that tube plugging could soon reach unacceptable levels (Figure 2).

To justify continued operation of Unit 2, AECB staff asked for the following information:

- Acceptance criteria for the maximum numbers of plugged tubes in Unit 2 steam generators;
- An assessment of the remaining life and a planned date for shutdown;
- An inspection strategy;
- Predictions of end-of-interval crack populations and justification of their acceptability.

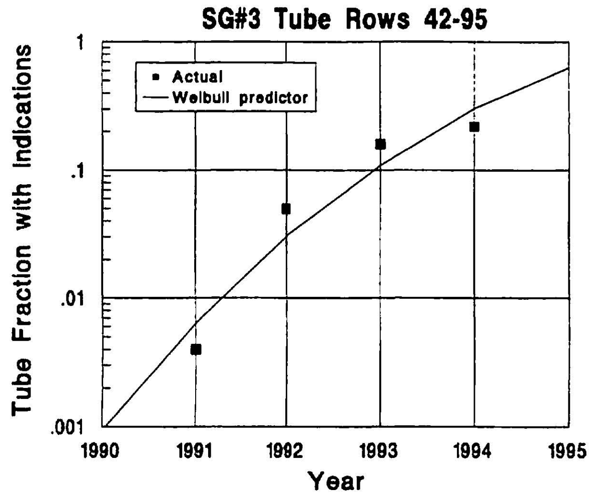

Figure 2: Bruce Unit 2 ODSCC Development

Inspection during a planned outage in 1994 confirmed the trend of crack growth. Unit 2 was laid up in October 1995.

2.3 Pickering B Pitting

Unit 5 at Pickering B experienced tube leaks in the early 1990s due to pitting in the lower regions of the steam generators. Recurring leaks and growth of inspection indications gave evidence of rapid corrosion. More than 1000 tubes were plugged in a short period. Ontario Hydro submitted plans for plugging up to 500 tubes per steam generator. To avoid tube plugging, Ontario Hydro also proposed a novel repair process known as electro-sleeving. The AECB, however, held that laboratory evidence was needed to support field trials, and that long-term field trials were required before large-scale use could be considered. Therefore it is unclear that the problem could have been managed by plugging or electro sleeving. Ontario Hydro acted aggressively to clean the steam generators and to improve the feedwater chemistry and materials. This action appears to have solved the problem.

2.4 Bruce B Preheater Fretting

In June 1997, a tube leak was detected in a Unit 6 preheater. Ontario Hydro subsequently inspected approximately 30% of the tubes in each of the four preheaters in this unit and found tube fretting at the supports. This lead to identification of a generic problem similar to—and, from a safety standpoint, additional to—the steam generators. Until then the preheaters had not been inspected and were assumed to be in good condition. The AECB has requested that Ontario Hydro apply a strategy for managing the preheater tube degradation similar to that for the steam generators.

2.5 Bruce A Top of Tubesheet SCC

In April 1997, Ontario Hydro found that SCC at the tubesheet roll transition was the cause of a tube leak in Unit 1. Tube removals and 100% inspection of the lower 30 inches of the hot leg tubes revealed many other OD and ID flaws in Units 1, 3 and 4.

These findings posed new concerns. The absence of indications from previous inspections implied two equally disturbing alternatives. Either the inspection failed to pick up the problem, or the cracks developed rapidly since the last inspection.

The situation was perceived also to be less tolerant to uncertainties in management than previous cases involving fretting, pitting, or SCC, where the flaws were limited in circumferential extent. "Leak before break" was less assured. Since leak rate increases sharply with increasing circumferential crack extent, the risk of consequential tube failures following a plant upset or accident seemed greater than previously.

Since concerns about inspection accuracy and crack growth rates limited our confidence in continued fitness for service, other assurances were sought. By taking credit for the actual concentration of radioactivity in the reactor coolant, Ontario Hydro demonstrated tolerance for at least one steam generator tube rupture during a plant upset. On this basis, and with a reduction in the limit for primary-to-secondary leakage, AECB staff accepted the return to service of Units 3 and 4 until the planned shutdown in April 1998.

2.6 Darlington U-Bend Fretting

Ontario Hydro recently reported U-bend support fretting in Darlington Unit 2. Indications were detected in 28 tubes with a maximum depth of approximately 35%.

Despite its apparently benign state, experience suggests that fretting will worsen over time. We expect Ontario Hydro to produce plans to define the extent and severity of U-bend fretting and rates of change in all DNGS units. In the longer term we expect measures to manage and mitigate the problem.

3.0 LESSONS LEARNED

3.1 Regulatory Process

A regulatory strategy consists of the processes of setting standards for an activity, evaluating its compliance with the standards, and promoting compliance. In systems engineering terms, the processes overall can be likened to a feedback controller (Figure 3).

For steam generators in operating plants, the main regulatory controls consist of the inspection requirements and acceptance criteria in the CSA standards, called up in conditions attached to the

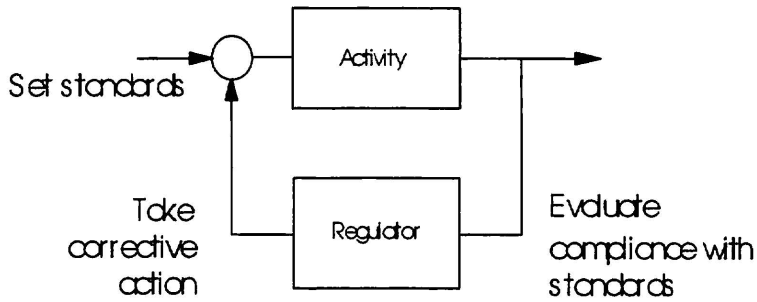

Figure 3: Regulatory Processes

operating licenses, the limits on steam generator tube leakage in licensee Operating Policies and Principles, and requirements for reporting of pressure boundary degradation.

In theory, the regulator evaluates compliance with the criteria stated above, and takes action in response to a detected non-compliance. While this generally has worked in practice, experience has revealed some weak points. These are discussed below.

3.2 Problem Recognition

Awareness of problems in reactors develops gradually. In the early stages, information is often ambiguous. Denial—"it can't happen here"—is a not-uncommon reaction to signs of trouble. Given imperfect information, two decision errors are possible: acting when no problem exists (false call), or failing to act when a problem exists (non-response). While recognizing the possibility of overreaction, AECB staff attempts to act as a catalyst by asking "what if."

A serious weakness is that the CSA standards for periodic inspection specify samples that are too small and too infrequent to detect deterioration of steam generator tubes promptly. In several cases, problems have developed without detection by the periodic inspection program, e.g., Bruce A SCC, Bruce B preheater fretting. Statistics show that at least 20% of the population of tubes must be inspected to give confidence that a given condition affects less than a small fraction. A recent AECB research report on fitness for service guidelines recommended larger inspection samples.[7]

On the other hand, 100% inspection does not eliminate uncertainty. It eliminates sampling error. Several sources of uncertainty remain. Inspection techniques, scope and frequency are inevitably shaped by planning assumptions about the defects of concern, the areas at risk, and rates of development. "100% inspection" is vulnerable to lack of knowledge and inaccuracies in these assumptions.

Even when inspection is accurately targeted, the performance of present day eddy current techniques leaves room for doubt about the flaw population that remains after inspection. Performance demonstration gives valuable evidence of what the technique does and does not detect. However, such exercises may be biased or incomplete. Bias creeps in, for instance, from focussing only on tubes in which defects are called. This procedure controls the "Producer's Risk" in Figure 4 below. However, the regulator is primarily interested in what is left in service, i.e., the "Consumer's Risk." Correcting this bias requires random investigation of tubes with acceptable indications. However, limits exist. Proving the nonexistence of non-detectable defects is logically impossible. Thus, probability of detection exercises should avoid attempting to quantify the unquantifiable.

	DEFECT CHARACTERISTICS	
INSPECTION CALL	**"Good"**	**"Bad"**
Reject	Producer's Risk	OK
Accept	OK	Consumer's Risk

Figure 4: Inspection Outcomes

Leak monitoring supplements inspection to give warning of tube degradation. It also acts as a real check on the consumers risk. Leak monitoring does not by itself guarantee safety, however. In some circumstances, leaks have occurred only after the defects have grown beyond the maximum tolerable flaw sizes, e.g., Bruce A SCC. This experience shows that "leak before risk of break" is not assured in all circumstances.

Other informal sources of information are reports of experience elsewhere, and research. Such information helps to anticipate problems. In systems terms, adding a predictive capability improves the feedback controller's response and reduces time lags and oscillation. This information has not always been effectively used.

3.3 Ageing Management

In the short term, the AECB has responded to reports of steam generator problems by doing or requesting the following:

- Investigation of the noncompliance;
- Assessment of the safety of continued operation, and the tolerance to probable failures;
- Judgement of the time available to gather more information;
- Adjustments to controls: e.g. expansion of inspection to define the scope and severity of the problem, inspection of similar components or other reactor units, and repeated inspections to define its kinetics.

Over the medium term, steam generator tube degradation has been managed by a strategy of periodic inspection and reassessment. The process is depicted in Figure 5. As this figure suggests, statistics usefully describe steam generator ageing, in view of the large tube population, individual variation and inspection uncertainties. The AECB has sponsored research that resulted

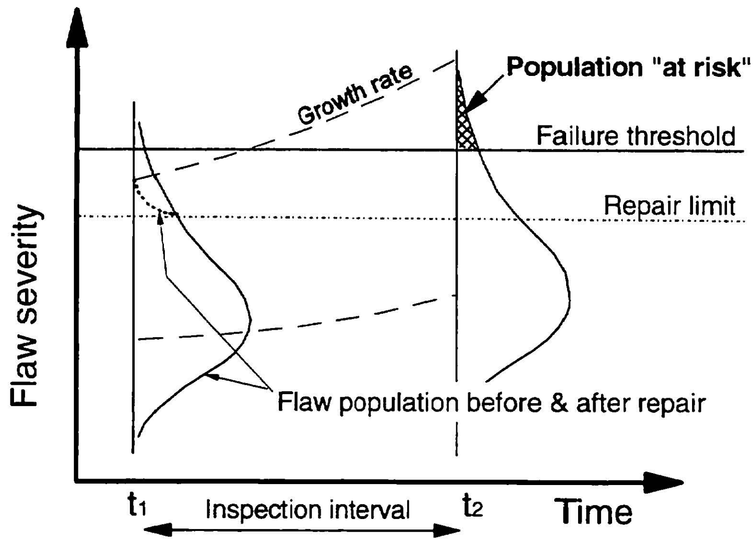

Figure 5: Management of Physical Ageing by Periodic Inspection

in a software package named CANTIA for modelling flaw populations and assessing failure probability.[8]

Elements of the strategy are listed in Figure 6. The objective is to ensure that the population of degraded tubes remains fit for service, while individual flaws meet the CSA standard or alternate repair criteria consistent with the ASME Code. Extreme as opposed to average behaviour is a key issue. Figure 5 shows that the "upper tail" of the population is of concern. Limits on the population "at risk" are based on the need to ensure that radioactive releases caused by tube failures during plant accidents or upsets will not exceed regulatory limits. Because different tube defects and stresses can produce a wide range of primary to secondary leak rates, and because the condition of individual tubes is not well defined, the AECB has generally requested large margins between the consequential leak assessments and the legal limits.

This strategy has worked satisfactorily, but it has the weakness that the regulator and the

i. Confirmation of the ability of the examination method to detect and size flaws
ii. Description of the population of degraded components and rates of change
iii. Failure criteria for normal and accident conditions
iv. Repair criteria with appropriate margins against failure
v. Procedures for repair of unacceptable defects
vi. Acceptance criteria for population at risk
vii. An in-service inspection plan that ensures the population meets the acceptance criteria
viii. Definition of a long-term end point

Figure 6: Elements of Strategy for Managing Ageing Degradation

licensees get comfortable with it. However, if many steam generator tubes are subject to degradation, it is merely playing out the end game. As experience at Bruce A and elsewhere has shown, the situation can deteriorate quickly unless a solution is found.

3.4 Problem Mitigation/Prevention/Solution

The AECB attempts to focus attention on the long term endpoint, on rejection criteria (i.e., conditions beyond which operation will not continue), problem mitigation and solution. Examples of such outcomes include the request in the case of Bruce 2 for a planned shutdown to avoid the risks of indefinite operation, chemical cleaning of Pickering steam generators, which appears to have eliminated leaks due to pitting, and installation of antivibration bars at Bruce B which have been shown to reduce fretting wear.

4.0 REGULATORY DIRECTIONS

Although in the past jurisdiction was shared with the provinces, a 1993 decision by the Supreme Court of Canada made it clear that regulation of nuclear facilities is a federal responsibility. Furthermore, in early 1996, the Minister of Natural Resources tabled Bill C-23, *The Nuclear Safety and Control Act* in the House of Commons. This Act is expected to come into force this year. Besides changing the name of the AECB to the Canadian Nuclear Safety Commission, the new Act provides for more explicit and effective regulation by giving the Commission clear and specific powers.

Consequently, the AECB has started to restructure its regulation of pressure boundaries. As a first step it has changed the license conditions for power reactors to state explicitly the requirements for pressure vessels and piping. These require compliance with the technical content of CSA standards N285.0 and B51. The AECB has arranged with provincial agencies to carry out authorized inspection to administer these conditions.

In future the AECB intends to publish federal pressure vessel regulations and guides to compliance under the Act. The AECB wants to refer to CSA standards for construction and in service requirements. However, the present nuclear standards lack adequate rules for inspection and guidelines for dispositioning flaws. AECB staff would like to correct this deficiency by asking its licensees to develop fitness for service guidelines for steam generator tubes that can be incorporated into the CSA standards. The standards should cover inspection, acceptance criteria, and either prescribe levels of inspection consistent with practices in the nuclear industry or contain the logic that leads to current requirements. To meet targets for publishing new standards and regulations, this needs to be done within about eighteen months.

In absence of such standards, the AECB will continue to mandate actions it considers necessary for public safety.

5.0 CONCLUSIONS

Past practice under a flexible regulatory regime allowed the AECB to make judgements on specific cases of steam generator degradation. This practice was successful up to a point but involved considerable effort in motivating licensees to deal with emerging problems rather than treating the regulators as the problem.

Changes in the regulatory climate in Canada driven in part by the poor performance of the industry, privatisation, ineffective legislation and government reorganization have resulted in stronger emphasis on compliance and enforcement.

The rules on operation with degrading equipment do not exist in a legally enforceable form. In most case the types steam generator degradation encountered to date are manageable and tolerable for limited periods of operation. Degradation can be covered in rules for operation, fitness for service criteria and inspection strategies.

The AECB expects to have in place rules for steam generator degradation within the next 18 months.

6.0 REFERENCES

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DISCUSSION

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Paper: Regulation of Ageing Steam Generators

Questioner: K. Bagli, OH SESD

Question/Comment:

In Nucleonics Week, 1998 May 21, "US Passes Five Years Without a Steam Generator Tube Rupture". A key element is the rigorous inspection program. The main credit goes to the NRC. When is the AECB going to operate in a similar proactive/prescriptive mode rather than in a reactive mode?

Response:

I believe the credit goes to licensee as well as the US NRC to have implemented a rigorous inspection program which has reduced the tube rupture in last few years.

CANDU units have had no steam generator tube ruptures since they went in service. This does not necessarily mean that CANDU units are safer to operate. In other words, actual tube rupture is not the only criteria to measure the safe operation of a nuclear plant.

With the new CNSC Act, expected to be in effect by early next year, AECB (CNSC) intends to have regulations with more prescriptive requirements. AECB has asked the CSA code committee to revise the code to include the technical requirements for CANDU power plants. If the code refers to other codes such as ASME, it should specify the sections that are applicable to CANDU power plants. The AECB have asked the licensees to write FFSA and CLA for SGs. The requirements of these documents will be captured in regulations.

In summary, with the new act and regulations, the AECB will be more prescriptive on compliances, limited flexibility and little or no 'regulation by negotiations'.