Canadian Nuclear Safety Commission
Commission canadienne de sûreté nucléaire

CMD 24-H3.20

File / dossier : 6.01.07
Date: 2024-10-31
Edocs: 7396867

Written submission from RESD Inc.

Mémoire de RESD Inc.

In the Matter of the

À l'égard d'

Ontario Power Generation Inc.

Ontario Power Generation Inc.

Application for a licence to construct one BWRX-300 reactor at the Darlington New Nuclear Project Site (DNNP)

Demande visant à construire 1 réacteur BWRX-300 sur le site du projet de nouvelle centrale nucléaire de Darlington (PNCND)

Commission Public Hearing
Part-2

Audience publique de la Commission
Partie-2

January 2025

Janvier 2025

RESD Inc.	Document Identification				
	Project	Type	Division	Serial	Revision
	CNSC 007	REPT	ENG	0001	00
	Date Effective: Nov 4, 2024		Retain Until: Nov 4, 2031		

Independent Review of Flow-Induced Vibrations for the BWRX-300 Condenser Tubes

Prepared by: Paul Sedran, P.Eng
Principal, RESD Inc

Date: November 4th, 2024

1. Introduction

For the Darlington New Nuclear Project, OPG opened a competition among three candidate Small Modular Reactor (SMR) designs to be selected for construction at the site of the Darlington Nuclear Generating Station:

1. the BWRX-300, by General Electric – Hitachi (GEH)
2. the IMSR400, by Terrestrial Energy
3. the Xe-100, by X-Energy.

In 2021, OPG announced the selection of the BWRX-300, a new Generation 3 SMR design by GEH for the Darlington New Nuclear Project.

The BWRX-300 is Generation III, 300-megawatt electric (MWe) water-cooled, natural circulation boiling water reactor. The Reactor Pressure Vessel (RPV) and its contents are being designed by BWXT.

In October 2022, OPG applied for a licence to construct one BWRX-300 reactor at the Darlington site. In April 2024, the CNSC announced the Commission decision that the existing environmental assessment (EA) for the DNNP, which covers the full project lifecycle, is applicable to the BWRX-300 reactor, allowing for the license application to proceed.

As part of the licensing process, the Canadian Nuclear Safety Commission (CNSC) will hold a 2-part public hearing on October 2, 2024 and in January 2025, to consider the application from OPG for a licence to construct a single BWRX-300 reactor at Darlington.

As part of the January public hearing, the CNSC has funded the author to review some of the design aspects of the reactor from the perspective of his specialised experience, under Contribution Agreement reference number: PFP 2023 DNNP-01. For the review, the author has assessed the susceptibility of the BWRX-300 Condenser Tubes to flow-induced vibration (FIV) during normal operation.

The author's rationale for the review was based on the personal observation of four specific instances, over the last 10 years, in which the fundamentals of FIV in condensers were misunderstood or were misapplied, as discussed with OPG on October 16th, 2024.

These observations may indicate a general trend, which suggests that similar deficiencies could possibly find their way into the BWRX-300 condenser design. The author considers that this possibility provides a justification for an independent review of FIV in the BWRX-300 Main Condenser, as a precaution.

A summary of the FIV assessment for the BWRX-300 Condenser Tubes is presented in this report.

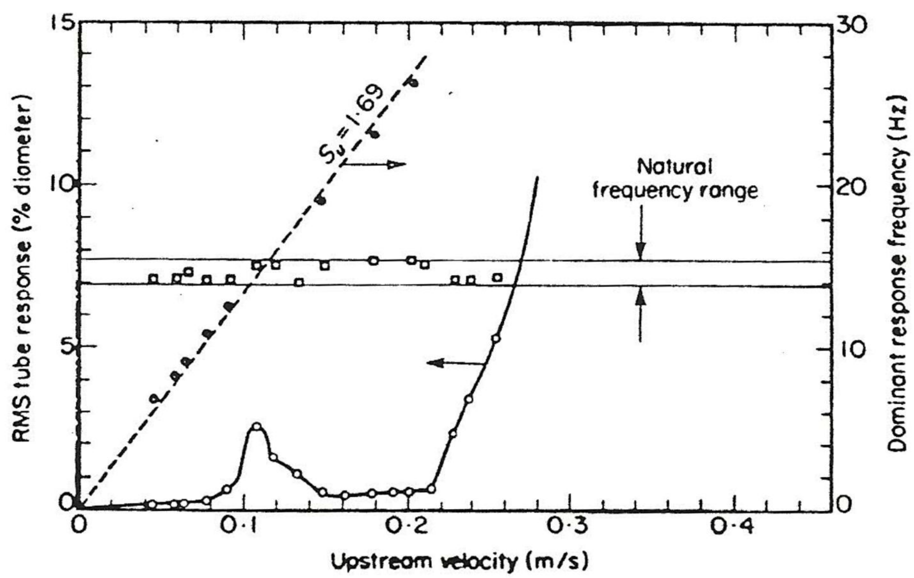
2. Technical Background

The BWRX-300 Main Condenser is an example of a tube and shell heat exchanger. There is a long and extensive history, from the 1960s and 1970s, of gradual in-service damage and sudden catastrophic failures of the tubes in tube and shell heat exchangers [1], due to FIV. Although FIV analysis and condenser design capabilities have improved since the 1970s, FIV may be a concern for the BWRX-300 Main Condenser, which needs to be assessed. Of several FIV mechanisms, fluid-elastic instability is the only mechanism known to cause destructive levels of vibration in the tube bundles [2].

Figure 1, from Reference [3], depicts the effects of fluid elastic instability on the vibration of a tube in a triangular tube array in water. In the figure, the tube vibration amplitude is plotted on the primary Y axis versus the flow velocity on the X axis. The frequency of tube vibration is plotted on the secondary Y axis. At lower flow velocities, the tube vibration is stable. For a flow velocity of 0.22 m/s, the tube undergoes the onset of fluid-elastic instability, indicated by the sudden increase in the tube vibration amplitude. With further increases in flow velocity the tubes will move closer to instability but before undergoing unstable vibration, neighbouring tubes may collide repeatedly, leading to potentially severe damage of the tubes. The average pitch velocity (in the gap between the tubes) along the tube span for the onset of fluid-elastic instability is the critical velocity, V_c. As indicated in the figure, the frequency of vibration in fluid-elastic instability corresponds to the tube natural frequency, similar to resonant forced vibration. The subtle difference between resonance and fluid-elastic instability is that there is no external periodic exciting force in the latter, just a fluid flow into the tube bank.

Section 2.1 describes the basic fluid-elastic instability model used to predict the condenser tube critical velocity for this assessment. The damping factor in the model has a significant effect on critical velocity and has a greater degree of uncertainty than other parameters. .

Figure 1 – Fluid-Elastic Instability in a Tube Array



2.1 Theoretical Model for Fluid Elastic Instability

Reference [2] provides the following semi-empirical model for the critical velocity of flow into a tube bank that would result in elastic instability:

$$V_c = f_1 DC \left[\frac{m(2\pi\xi)}{\rho D^2}\right]^a \qquad (1)$$

where

V_c is the average pitch velocity of the shell-side fluid at the onset of fluid-elastic instability
f_1 is first natural frequency of lateral vibration of the condenser tube
D is the condenser tube outer diameter
C is an empirical constant
m is the effective mass per length of the tube, including water
ξ is the damping factor (fluid + structural)
ρ is the fluid density
a is an empirical exponent.

Equation 1 was used to calculate the critical velocity for the BWRX-300 Condenser Tubes, as summarised in Section 4.2.

The values of a and C for the particular arrangement can only be found experimentally, but Blevins in *Flow-Induced Vibrations* [2] recommended C = 3.3, and a = 0.5 as a general conservative approach.

Note that the pitch velocity is the cross-flow velocity perpendicular to the tubes inside the minimum gap between the tubes.

For a pitch, p, and tube outer diameter D, the pitch velocity, Vp is given by Vp = [p/(p-D)] Vu where Vu is the approach velocity; the flow velocity of the fluid just at the entrance into the tube array.

Equation 1 is based on a dimensional analysis which identified the parameters and dimensionless groups that govern the vibration of the tubes in cross flow. The form of the equation was finalised by fitting it to a large database of experimental measurements, as outlined in Reference [2].

For an underdamped system such as the condenser tubes, the logarithmic decrement, *δ* is a standard measure of damping in the system. It is defined as the natural log of the ratio of the peak displacement amplitudes in two successive cycles of unforced vibration.

The damping factor, ξ is the following function of the logarithmic decrement

$$\xi = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}}. \qquad (2)$$

3. Input Parameters for the Assessment of the BWRX-300 Condenser Tubes

Condenser Tube dimensions and properties and the mass flow rate of steam into the Condenser, provided by OPG, are presented in Table 1.

Table 1 - Inputs Provided by OPG

Parameter	Value
Steam Mass Flow Rate into the Condenser	Approximately 250 kg/s
Steam Density at Turbine Exhaust	Approximately 0.03 kg/m^3
Condenser Tube Outer Diameter	27 mm
Condenser Tube Wall Thickness	0.7 mm
Condenser Tube Material	Stainless Steel 316L
Condenser Tube Pattern / Lattice Pitch	Still in development

Missing from Table 1 are the Condenser Tube span length and the width of the baffles.

Based on previous experience with CANDU condenser designs, a span length of 36 in and a baffle with of 13/16 of an inch were selected as trial values for the calculations.

The conversion of the Condenser Tube dimensions from metric to British units (for use in the analyses of Sections 4.1 and 4.2) is given in Table 2.

Table 2
BWRX-300 Condenser Tube Dimensions

Do	Do	w	w	Di	Di
(mm)	(in)	(mm)	(in)	(mm)	(in)
27	1.063	0.700	0.028	25.600	1.008

Do is the Tube outer diameter
w is the Tube wall thickness
Di is the Tube inner diameter

As indicated in Table 1, the lattice pitch, (p) for the Condenser was not provided. To proceed with the assessment, it was assumed that [p / (p-D)] = 5, which is the case in the CANDU condensers and could well be case in the BWRX-300.

Based on experience with the Bruce B Condensers, and assuming that the flow area into the BWRX-300 Condenser will be 3 7ths (0.429) of the flow area in Bruce B, the approach velocity of the steam into the BWRX-300 Condenser was estimated to be 61.0 ms^{-1}, which corresponds to a pitch velocity of 305.2 ms^{-1} . The 3/7 fraction corresponds to the reactor power fraction: 300 MW/700 MW for the BWRX-300 compared with a 700 MW CANDU reactor.

4. Condenser Tube Analysis

The analysis was performed in two basic steps: (1) the Condenser Tube first natural frequency was calculated, as presented in Section 4.1, and (2) an assessment of fluid-elastic instability was performed, as summarised in Section 4.2.

4.1 Condenser Tube Natural Frequency Calculation

Equation 3, from Reference [4] was used to predict the first natural frequency for lateral vibration of the condenser tube, with pinned-pinned support conditions.

$$f_1 = \frac{10.838 * 9.9}{l^2} \left[\frac{EI}{w_o}\right]^{0.5} \quad \text{.......... (3)}$$

where l is the tube span length, E is the tube elastic modulus, I is the tube cross-section area moment of inertia, and w_o is the effective weight of the tube per unit length, including the weight of the water inside the tube. Do and w are the tube outer diameter and wall thickness, respectively. For the effective weight calculation, the added mass of the steam was found to be negligible. The constants in the equation are for the support condition and a weight to mass conversion.

For the purposes of this analysis, the Condenser Tube first natural frequency was calculated using simply-supported (pinned) support conditions for each tube span, having a length of 36 in. This assumption will result in some underestimation of the first natural frequency for the tube but is consistent with conventional modelling practises in TEMA [4]. At this stage, the use of pinned supports is considered to be acceptable since there is no justification for stiffer support conditions at the present time.

Table 3 presents a summary of natural frequency calculation, in which the first natural frequency of lateral vibration was found to be f_1 = 59.5 Hz.

Table 3 – Summary of the Condenser Tube Natural Frequency Calculation

E	Do	w	Di	I	w_o	L	f_1
(psi)	(in)	(in)	(in)	(in^4)	(lb/ft)	(in)	(hz)
28000000	1.063	0.028	1.008	0.012	0.647	36	59.5

59.5 hz is considered to be a slightly conservative estimate of the Condenser Tube natural frequency of vibration, owing to the pinned-pinned support conditions used.

4.2 Fluid-Elastic Instability Assessment

Following the completion of the natural frequency calculation, an assessment of fluid-elastic instability for the Condenser Tubes in the first few rows at the entrance to the Condenser, was performed in three steps:

First, the steam approach velocity for normal operation of the reactor at 300 MW was estimated in Section 4.2.1.

Second, the critical velocity analysis for the Condenser Tubes was performed as detailed in Section 4.2.2.

Third, in Section 4.2.3, fluid-elastic instability for the first few rows of Condenser Tubes was assessed by comparing the estimated steam pitch velocity under normal conditions with the critical velocity.

4.2.1 Estimation of Steam Approach Velocity

The approach velocity of the steam into the Condenser was not provided in Table 1. However, for this assessment, the BWRX-300 Condenser approach velocity under normal operating conditions at 300 MW was estimated to be 61.0 ms^{-1}. The estimate was based on comparisons of steam density and steam mass flow rate from Table 1, with corresponding typical values for a 700 MW CANDU reactor, for a CANDU-specific approach velocity of 85 ms^{-1}. For an approach velocity of 61 ms^{-1}, the pitch velocity for normal operation would be 305.2 ms^{-1}.

4.2.2 Critical Velocity Analysis

It should be noted that the critical velocity analysis applies only to the first few rows of tubes where the steam enters the condensers. In general, the first few rows of tubes are the most susceptible to fluid-elastic instability. For the most part, an analysis of the first few tubes in the flow is sufficient for a fluid-elastic instability assessment. However, in practise, all the tubes in a condenser should be assessed for fluid-elastic instability.

A summary of the analysis is presented in Table 4.

Table 4 – Summary of the Condenser Tube Critical Velocity Analysis

f_1 (Hz)	D (in)	C	m (lb/in)	ξ	ρ (lb/in^3)	a	V_c (in/s)	V_c (m/s)	$V_{u\ crit}$ (m/s)
59.5	1.063	3.3	0.054	0.0266	1.084E-06	0.5	17914.9	455.0	91.0

where

V_c is the critical velocity of the steam at the onset of fluid-elastic instability
f_1 is first natural frequency of lateral vibration of the Condenser Tube
D is the Condenser Tube outer diameter
C is an empirical constant
m is the effective mass per length of the Tube, including water
ξ is the damping factor (fluid + structural)
ρ is the steam density
a is an empirical exponent.
$V_{u\ crit}$ is the the critical approach velocity, the approach velocity for pitch velocity = V_c

For Table 4, V_c was calculated in inches and was converted to m/s and was reported in both units.

Of all the parameters in Table 4, the damping factor is the most difficult to determine and has a significant influence on the critical velocity. The value of 0.0266 for the damping factor, used in this assessment, is lower than conventional values used in CANDU but was chosen as an empirical lower-bound damping factor, based on CANDU experience.

The empirical damping factor of 0.0266 is associated with squeeze-film damping for a baffle with a width of 13/16 of an inch. Therefore, using a damping factor of 0.0266, it is assumed that the baffle width in the BWRX-300 Condenser is also 13/16 of an inch.

As seen in Table 4, the BWRX-300 Condenser Tube critical velocity was calculated to be 455 ms^{-1}. Table 4 also shows that at an approach velocity of 91 ms^{-1}, the Tubes would have a pitch velocity of 455 ms^{-1}, equal to the critical velocity.

Overall, a critical velocity of 455 ms^{-1} is consistent with CANDU critical velocities, but, is expected to be somewhat conservative because of the 0.0266 damping factor used in the critical velocity analysis.

4.2.3 Fluid-Elastic Instability Assessment

The assessment was performed by comparing the steam pitch velocity for normal operation of the BWRX-300 Condenser, from Section 3, to the critical velocity, from Table 4. Table 5 presents the critical velocity for comparison with the pitch velocity. For reference, the approach velocity and the critical approach velocity were also provided.

Table 5
Comparison of BWRX-300 Steam Velocities and Critical Steam Velocities

V_c	$V_{u\ crit}$	V_u	V_p
(m/s)	(m/s)	(m/s)	(m/s)
455.0	91.0	61.0	305.2

In Table 5, it is seen that the normal operating pitch velocity of 305.2 ms^{-1} is substantially lower than the critical velocity of 455.0 ms^{-1}.

The predicted approach and critical velocities given in Table 5 are comparable to those of other similar condensers and so, are expected to be accurate. However, it should be noted that independent QA verification of the natural frequency and critical velocity calculations was not performed for this assessment.

5. Conclusions

1. The assessment has shown that the first few rows of Condenser Tubes in the BWRX-300 would not be susceptible to fluid-elastic instability for a steam approach velocity of 61.0 ms^{-1}, assuming a 36 inch Condenser Tube span length and a baffle width of 13/16 of an inch, with [p / (p-D)] = 5.

2. A significant margin between the critical velocity and the normal operating pitch velocity has been predicted for the Condenser Tubes, which means that variations from the assumed span length, baffle width, and lattice pitch values are possible without incurring fluid-elastic instability.

3. At the final design stage, a more detailed analysis should be performed to assess the Condenser Tubes inside the tube bank for fluid-elastic instability.

6. References

1. P.D. Stevens-Guille, Steam Generator Tube Failures: A World Survey of Water-Cooled Nuclear Reactors in Operation During 1972, AECL-4753, 1974.

2. Flow-Induced Vibration, 2nd Edition, R.D. Blevins, Krieger Publishing Company, Malabar, Florida, 2001.

3. D.S. Weaver, An Introduction to Flow Induced Vibrations, Course Notes, Department of Mechanical Engineering, McMaster University, Hamilton ON, 1988.

4. Standards of the Tubular Exchanger Manufacturers Association, TEMA, 2007.

7. Acknowledgements

OPG staff members are acknowledged for conducting two information sessions and meetings to discuss the intervention with the author. The author also appreciates the timely provision of information in Table 1 and written comments from OPG on a draft of this report.