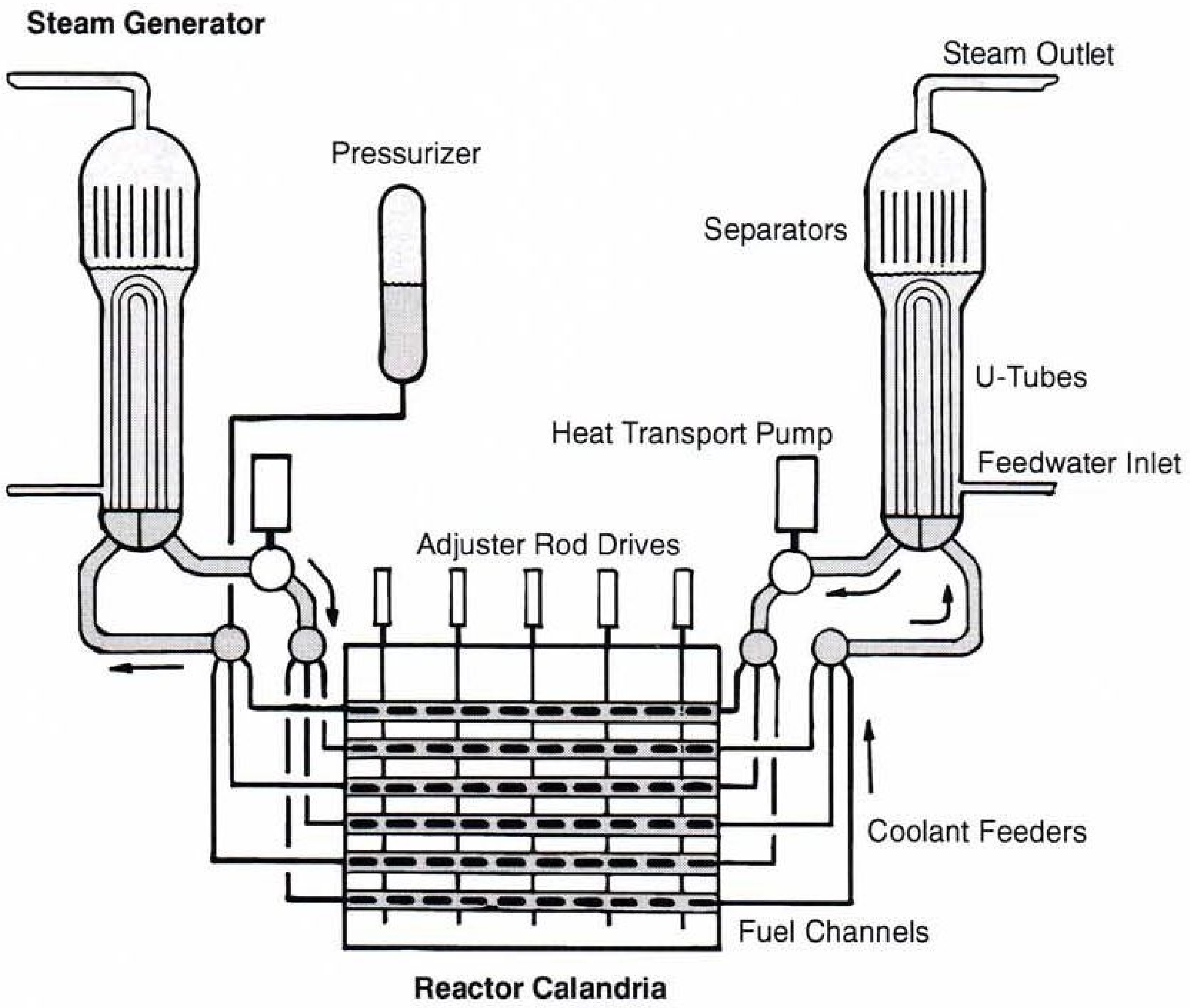
Simulation and Detection of CANDU Fuel Channel Vibrations

Jonathan Bartley, CNL
Salim El Bouzidi, CNL
Oszvald Glöckler, NEP Consulting
Kamal Moravej, CNL
Teguewinde Sawadogo, CNL
Bhaskar Sur, CNL

31st International Meeting on Reactor Noise
Delft, Netherlands 2024 Sep. 9-12

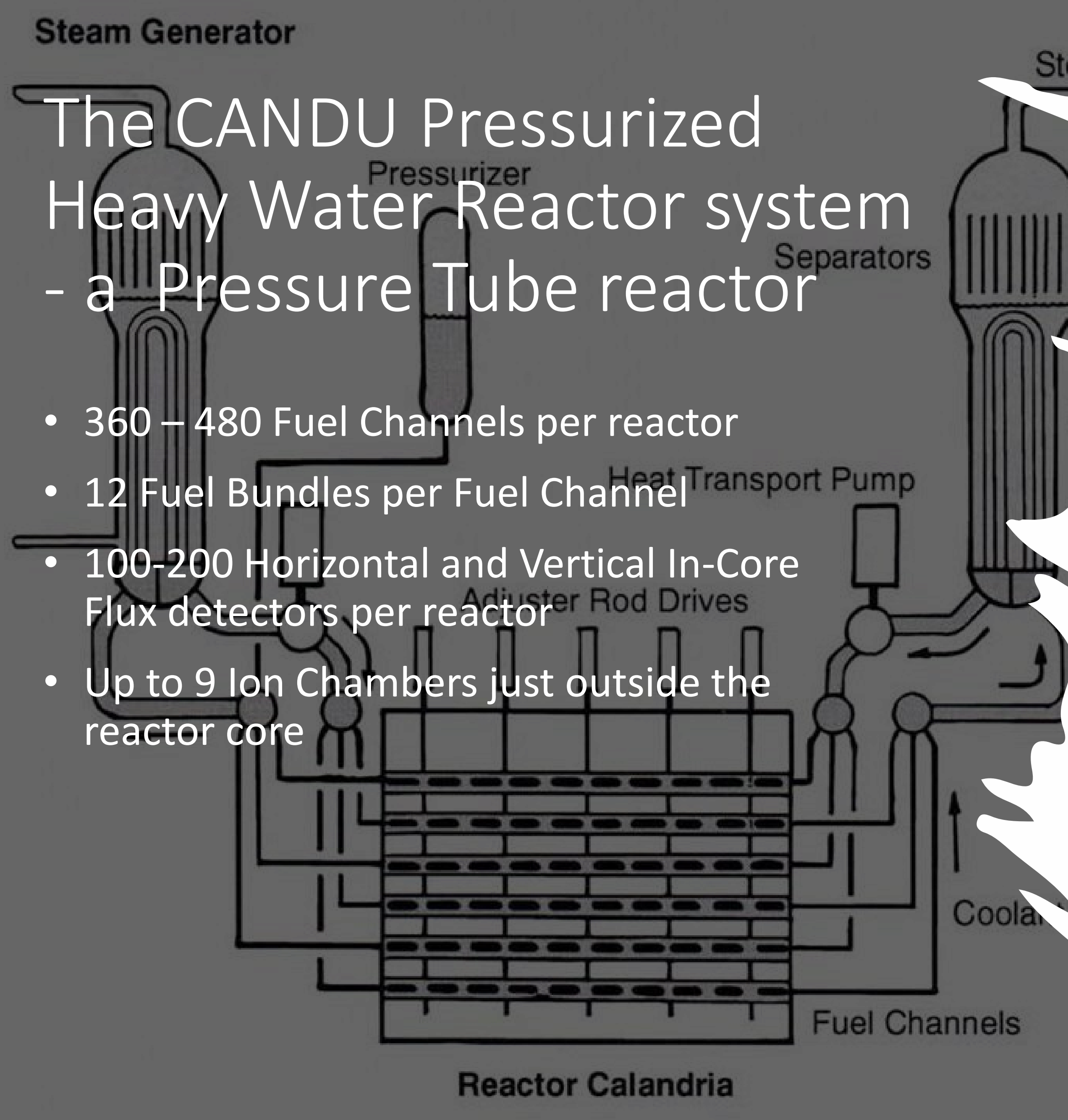
153-120000-001-000

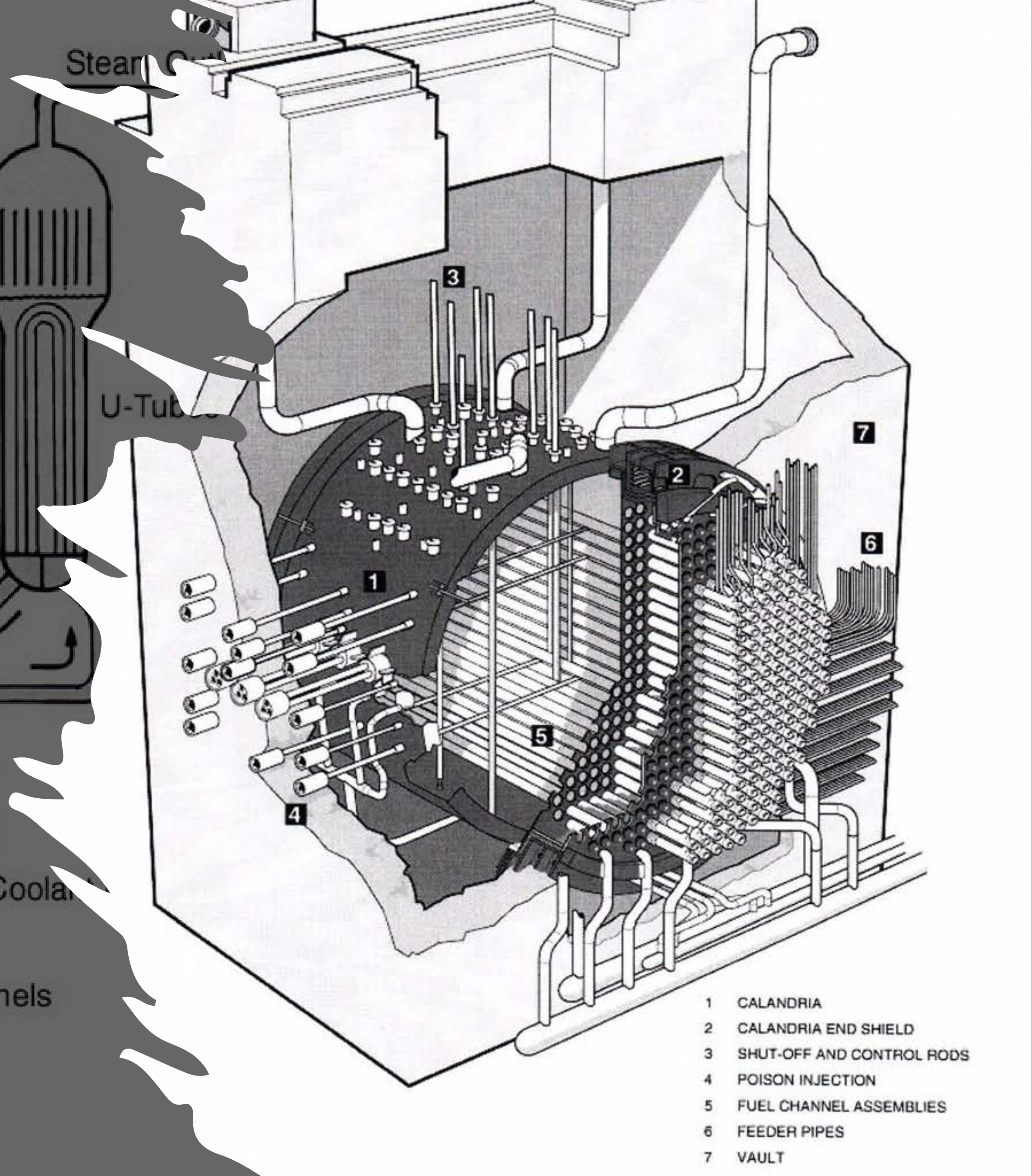


Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

The CANDU Pressurized Heavy Water Reactor system - a Pressure Tube reactor

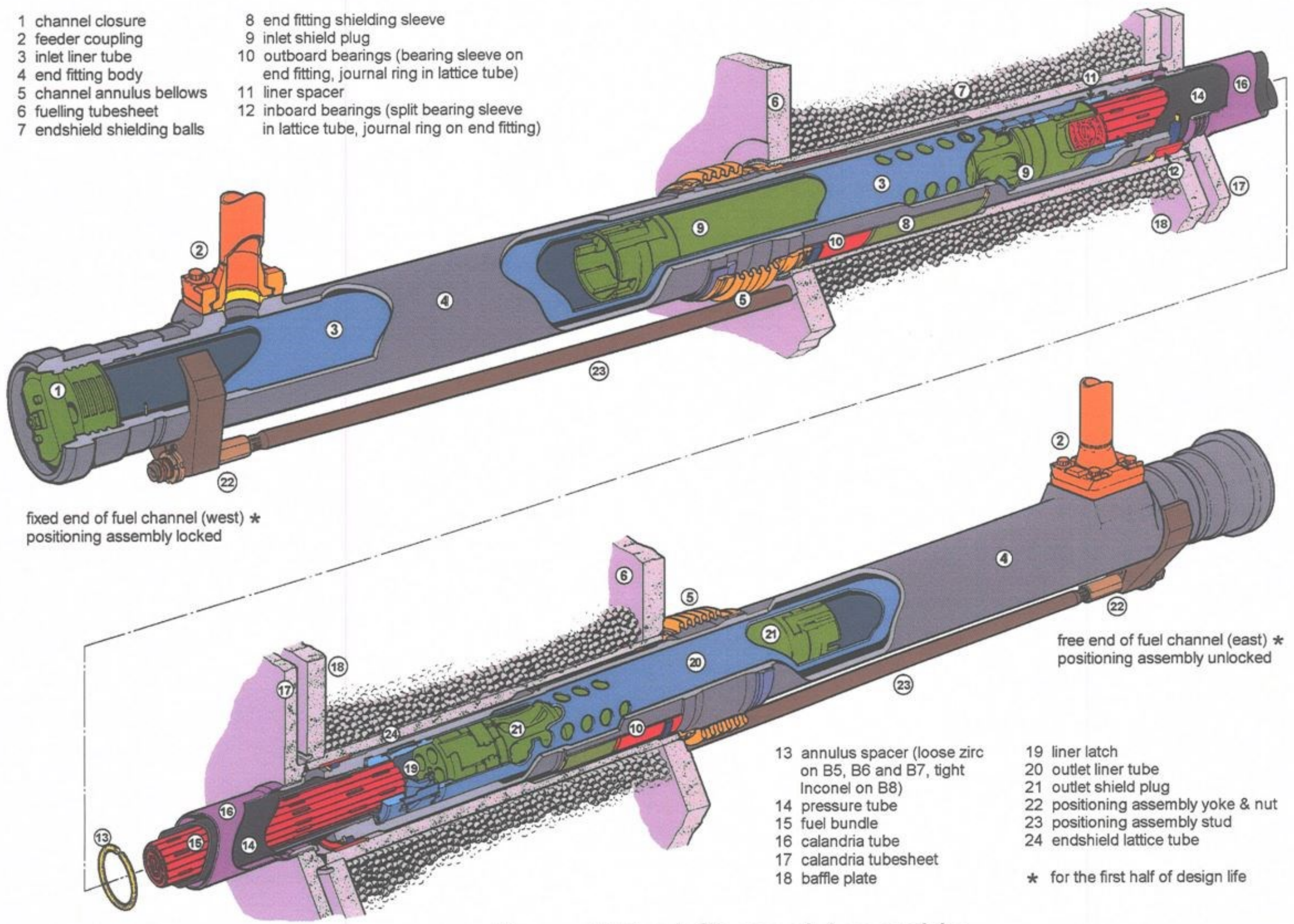
- 360 – 480 Fuel Channels per reactor
- 12 Fuel Bundles per Fuel Channel
- 100-200 Horizontal and Vertical In-Core Flux detectors per reactor
- Up to 9 Ion Chambers just outside the reactor core





CANDU Fuel Channels aging and degradation – currently monitored by inspections during outages

- FC Material irradiation - increased elastic modulus
- Pressure Tube diametrical creep
- Pressure Tube axial elongation
- Pressure Tube / Fuel Channel sag
- Pressure Tube hydriding (embrittlement)
- Pressure Tube-Calandria Tube spacer material degradation (may lead to PT-CT contact)
- Pressure Tube – Calandria Tube spacer mechanical failure or movement (may lead to PT-CT contact)
- End-Fitting support degradation

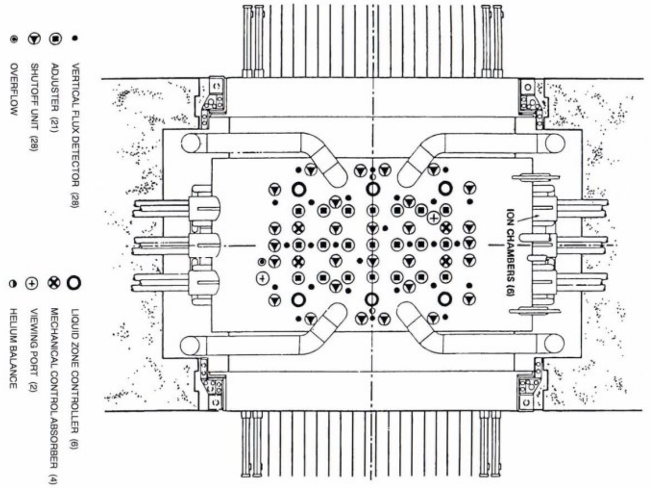


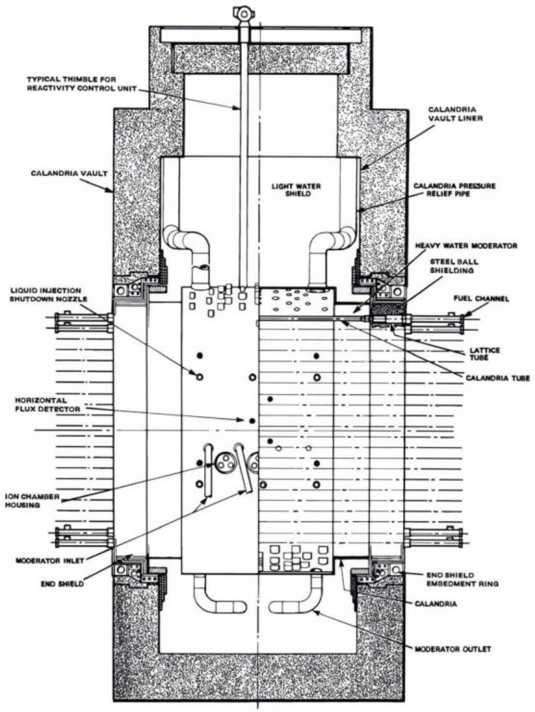
Bruce B Fuel Channel Assembly

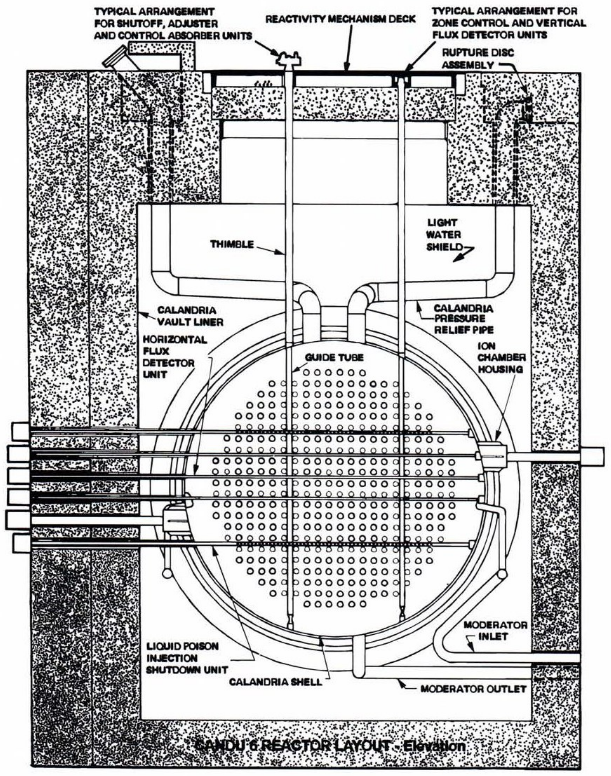
Can CANDU Fuel Channel aging be monitored by Neutron Noise Analysis?

Neutron Flux in CANDU monitored by In-Core Flux Detectors (ICFDs) and Ion Chambers (ICs)

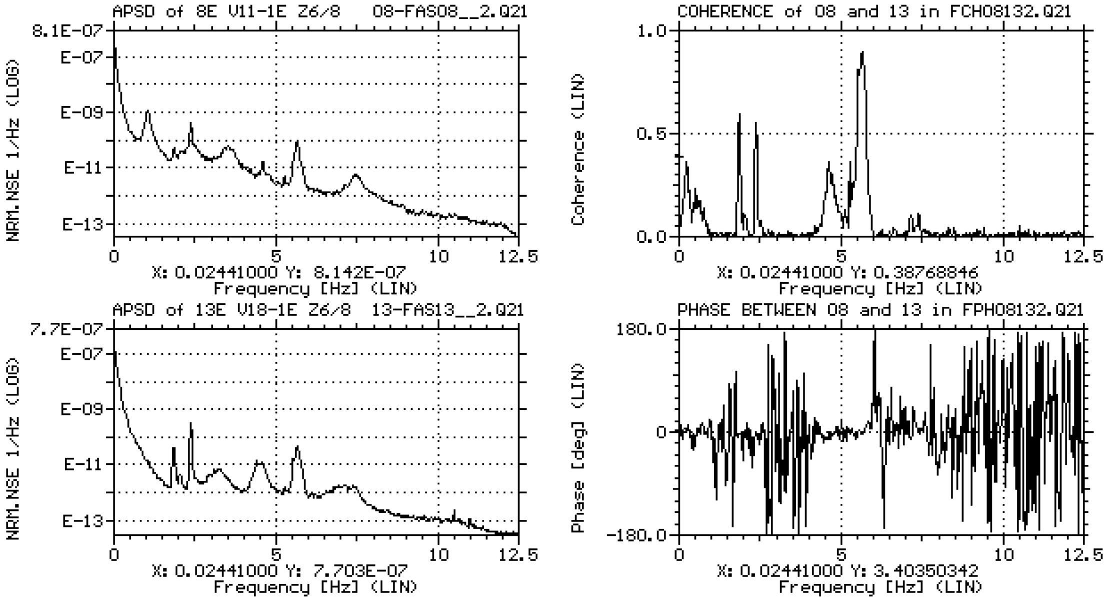
- Regional Overpower Protection (ROP) and Zone Control (ZC) ICFDs are ~ 1m (3 lattice pitches long); 90% – 105% prompt
- Up to 58 vertical and 42 horizontal ROP ICFDs per CANDU
- Up to 28 ZC ICFDs per CANDU
- Spatial control Vanadium (V) ICFDs are ~ 30 cm (1 lattice pitch) long; 9% prompt
- Up to 102 V ICFDs per CANDU-6
- Up to 3 ICs each for Reactor Regulating system, Shutdown system 1 and Shutdown system 2.

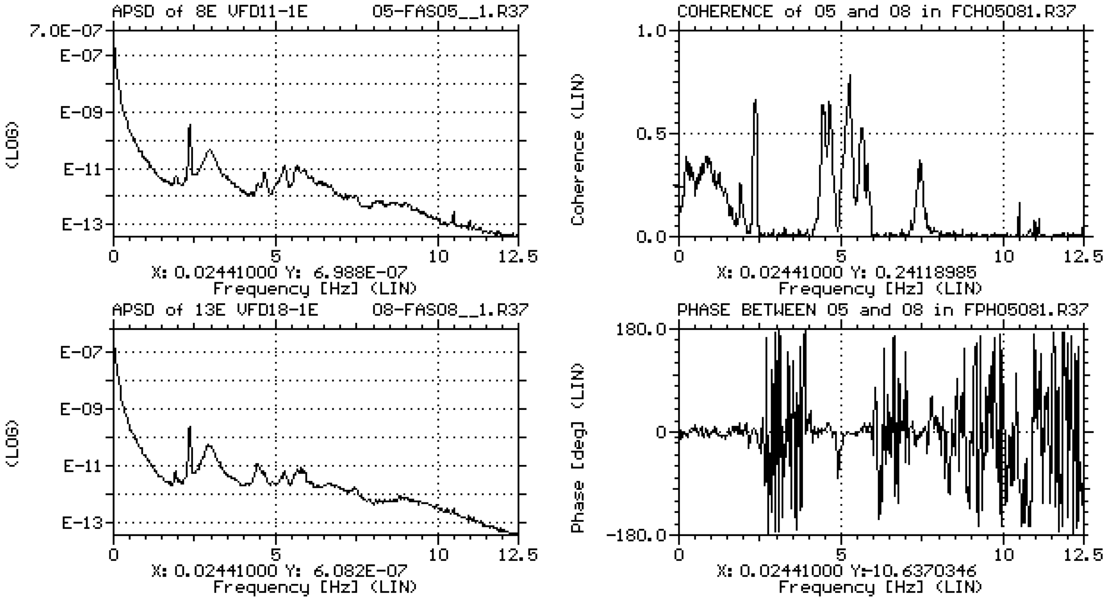






Auto-Power Spectral Densities (APSDs), Coherence and Phase of 2 vertical ROP ICFDs axially separated along common set of 6 Fuel Channels



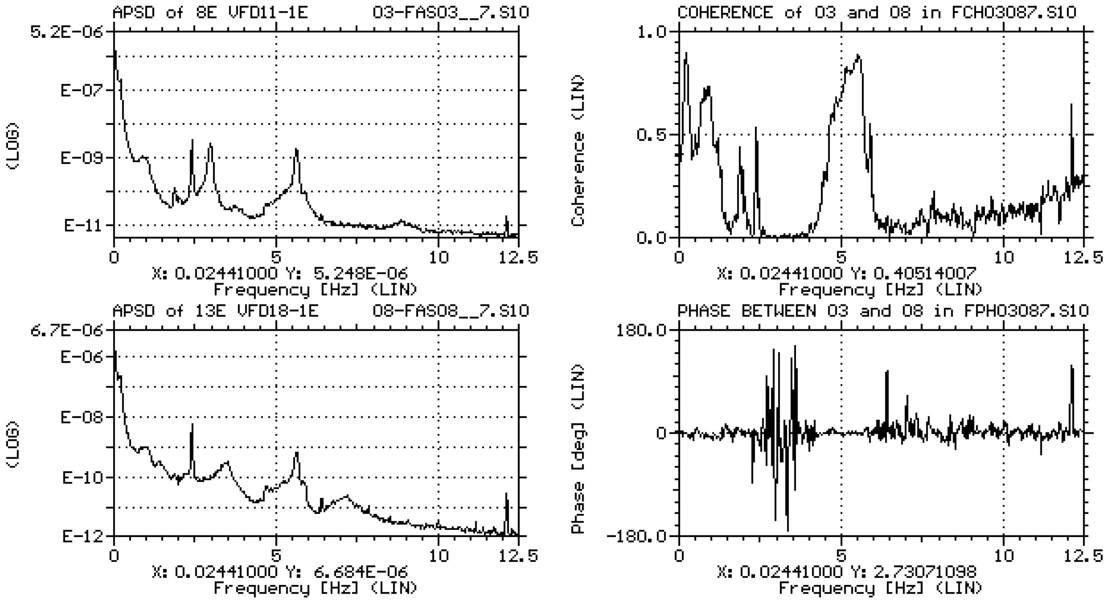


Darlington Unit 1: 2 coherence peaks at 4.6 and 5.6 Hz with zero phase

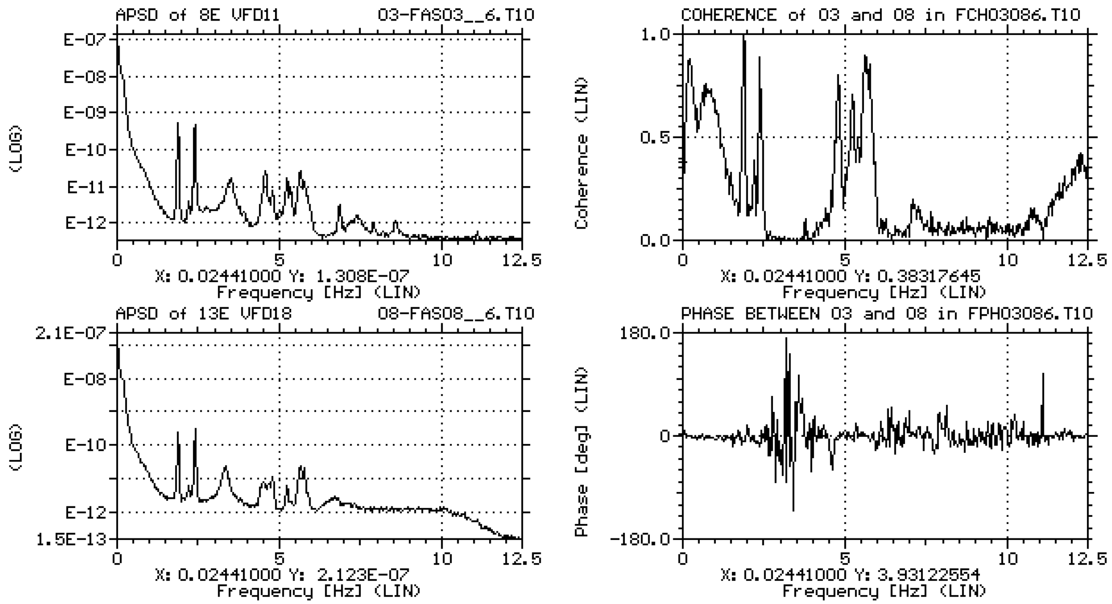
Darlington Unit 2: 5 coherence peaks between 4 and 6 Hz with zero phase

From: O. Glöckler, D. F. Cooke, G. J. Czuppon, and K. K. Kapoor, "Monitoring the Mechanical Vibration of In-Core Flux Detector Tubes and Fuel Channels in CANDU Reactors via Flux Noise Analysis," Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC & HMIT, 2000 ANS/ENS International Meeting, Washington DC, November 13-16, 2000

Auto-Power Spectral Densities (APSDs), Coherence and Phase of 2 vertical ROP ICFDs axially separated along common set of 6 Fuel Channels



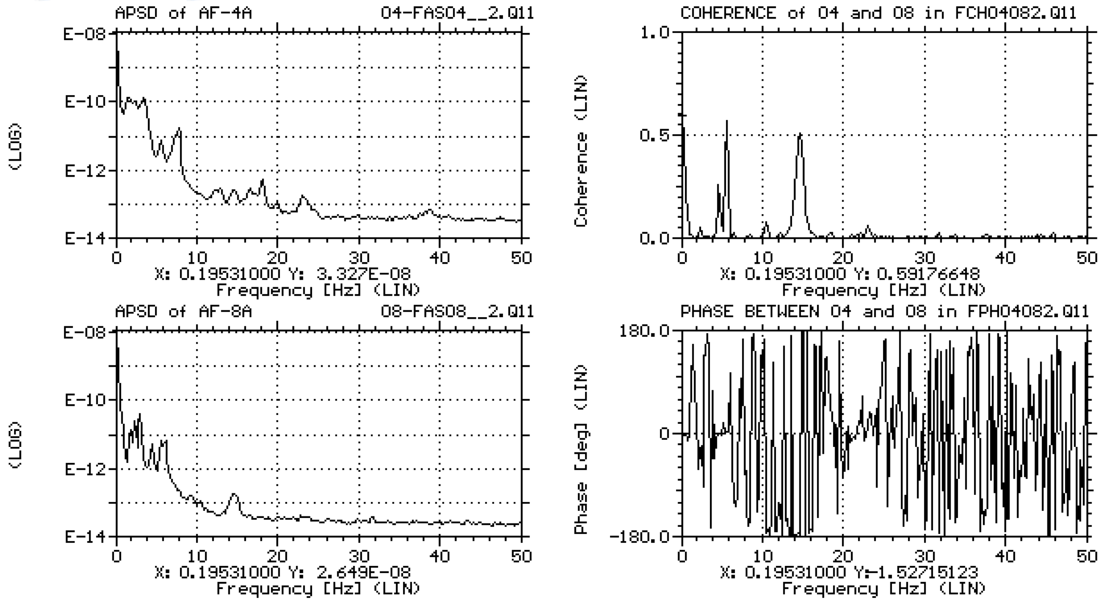
Darlington Unit 3: Merged coherence peak centered at 5.5 Hz with zero phase

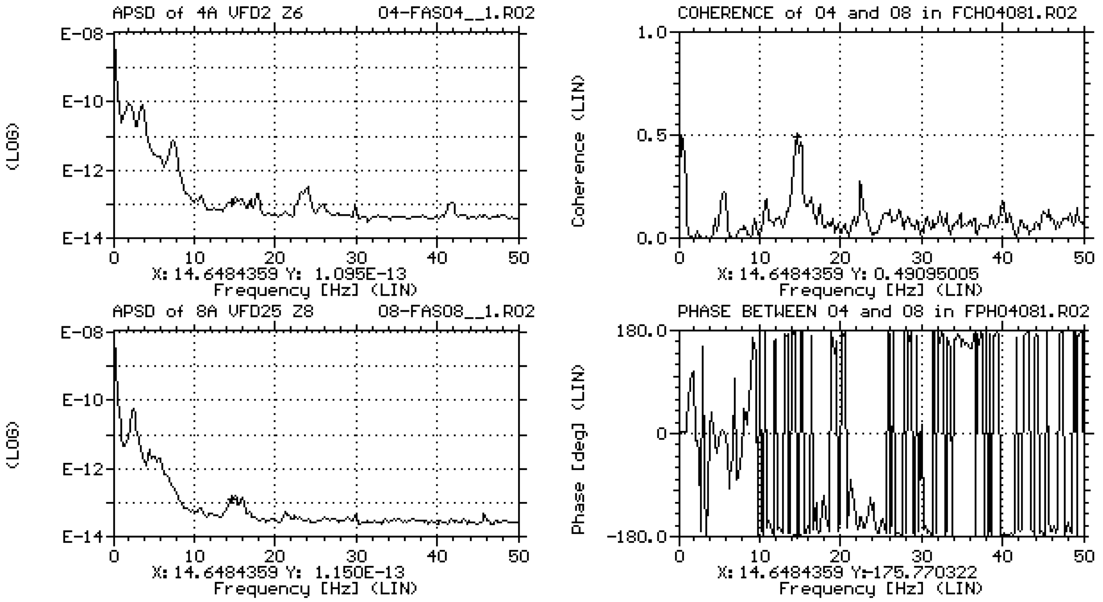


Darlington Unit 4: Multiple coherence peaks between 4.5 and 6 Hz with zero phase

From: O. Glöckler, D. F. Cooke, G. J. Czuppon, and K. K. Kapoor, "Monitoring the Mechanical Vibration of In-Core Flux Detector Tubes and Fuel Channels in CANDU Reactors via Flux Noise Analysis," Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC & HMIT, 2000 ANS/ENS International Meeting, Washington DC, November 13-16, 2000

Auto-Power Spectral Densities (APSDs), Coherence and Phase of 2 vertical ZC ICFDs axially separated along common set of 6 Fuel Channels



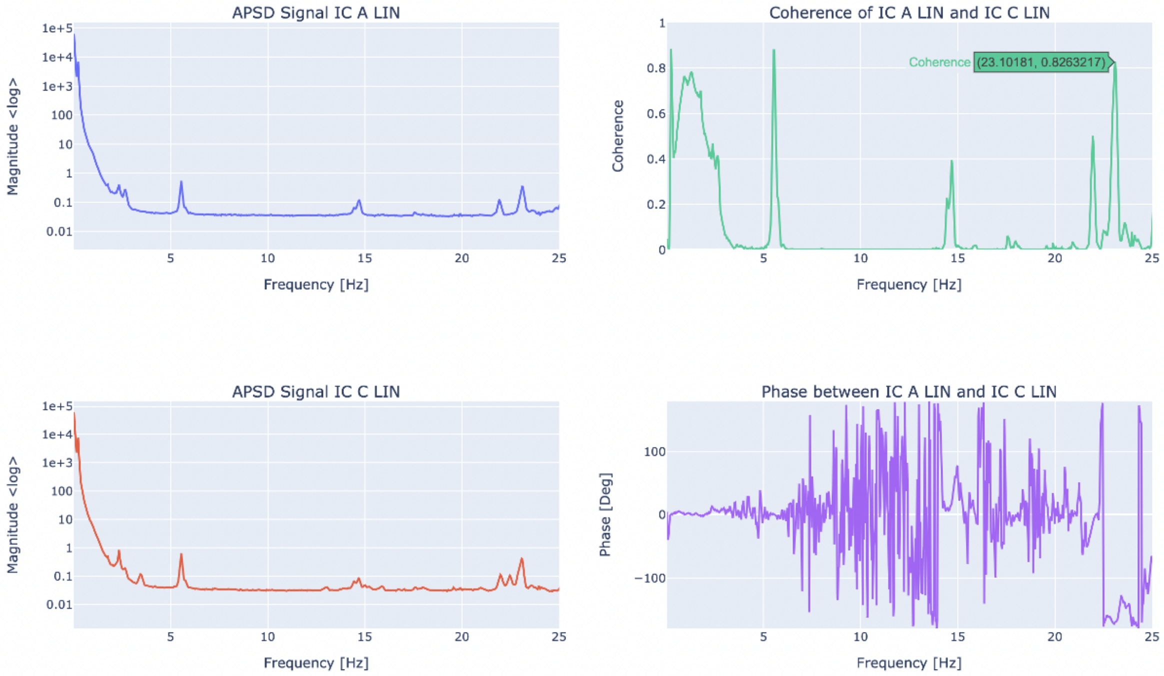


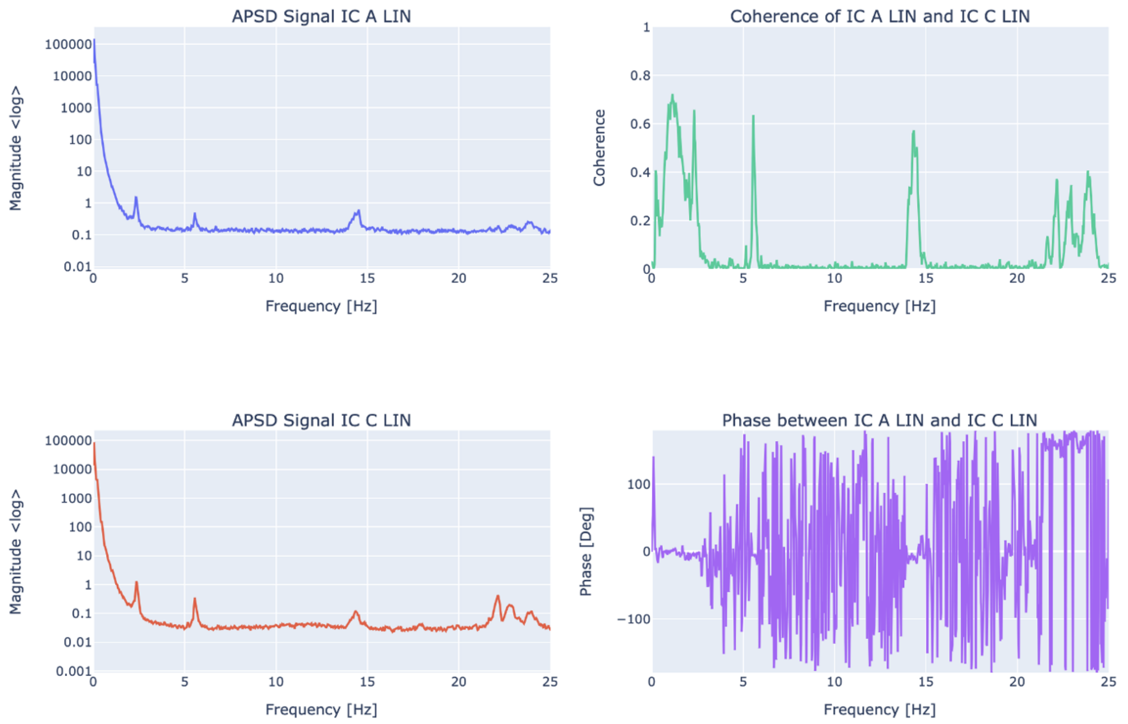
Darlington Unit 1: Coherence peaks at ~5 Hz (0 phase) and 15 Hz (180 phase)

Darlington Unit 2: Coherence peaks at 5 Hz (0 phase); 15 Hz (180 phase) and 22 Hz (180 phase)

From: O. Glöckler, D. F. Cooke, G. J. Czuppon, and K. K. Kapoor, "Monitoring the Mechanical Vibration of In-Core Flux Detector Tubes and Fuel Channels in CANDU Reactors via Flux Noise Analysis," Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC & HMIT, 2000 ANS/ENS International Meeting, Washington DC, November 13-16, 2000

Auto-Power Spectral Densities (APSDs), Coherence and Phase of 2 ICs axially separated on same side of reactor





Darlington Unit 3 (2020): Coherence peaks at ~5.5 Hz (0 phase) ;14.5 Hz (0 phase) and 22-23 Hz (180 phase)

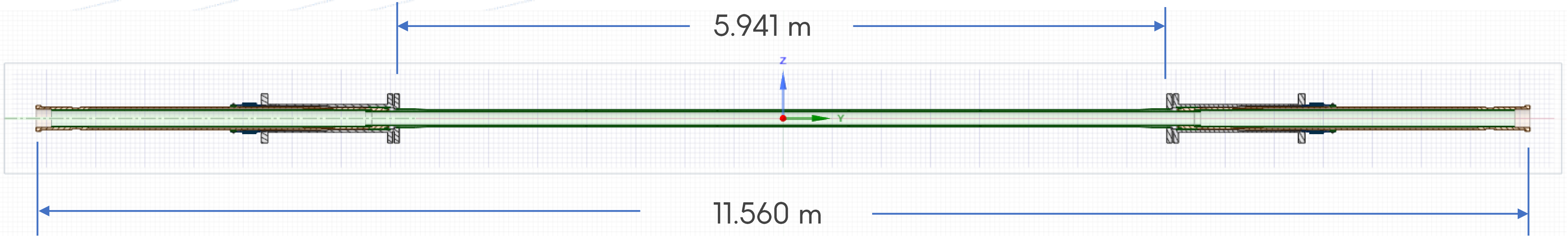
Darlington Unit 4 (2021): Coherence peaks at ~5.5 Hz (0 phase) ;14.5 Hz (0 phase) and 21-24 Hz (180 phase)

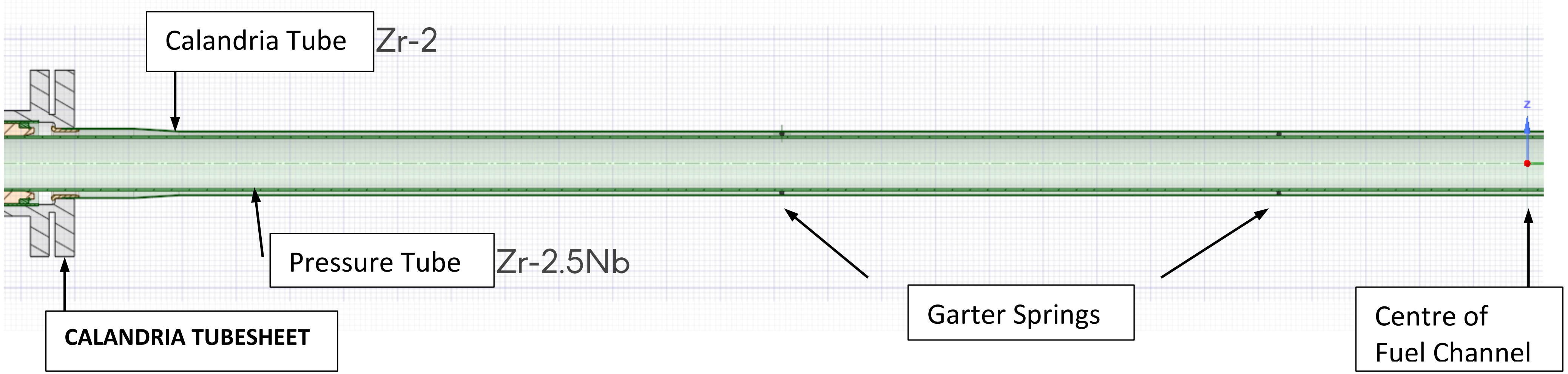
Summary of Neutron Noise Observations

- Appearance of coherence peaks in ICFDs and ICs near common Fuel Channels
- Phases depend on location of ICFDs with respect to Fuel Channel deformation
- Peaks clustered around frequencies of :
  - 4.5-6 Hz (1st vibrational mode?)
  - 14.5-15.5 Hz (2nd vibrational mode?)
  - 21-24 Hz (3rd vibrational mode?)
- Peak widths ~0.1 Hz @ 5 Hz (~2% resolution / separation)
- Spread of coherence peak frequencies corresponding to different Fuel Channels (even for replicated units in same station)

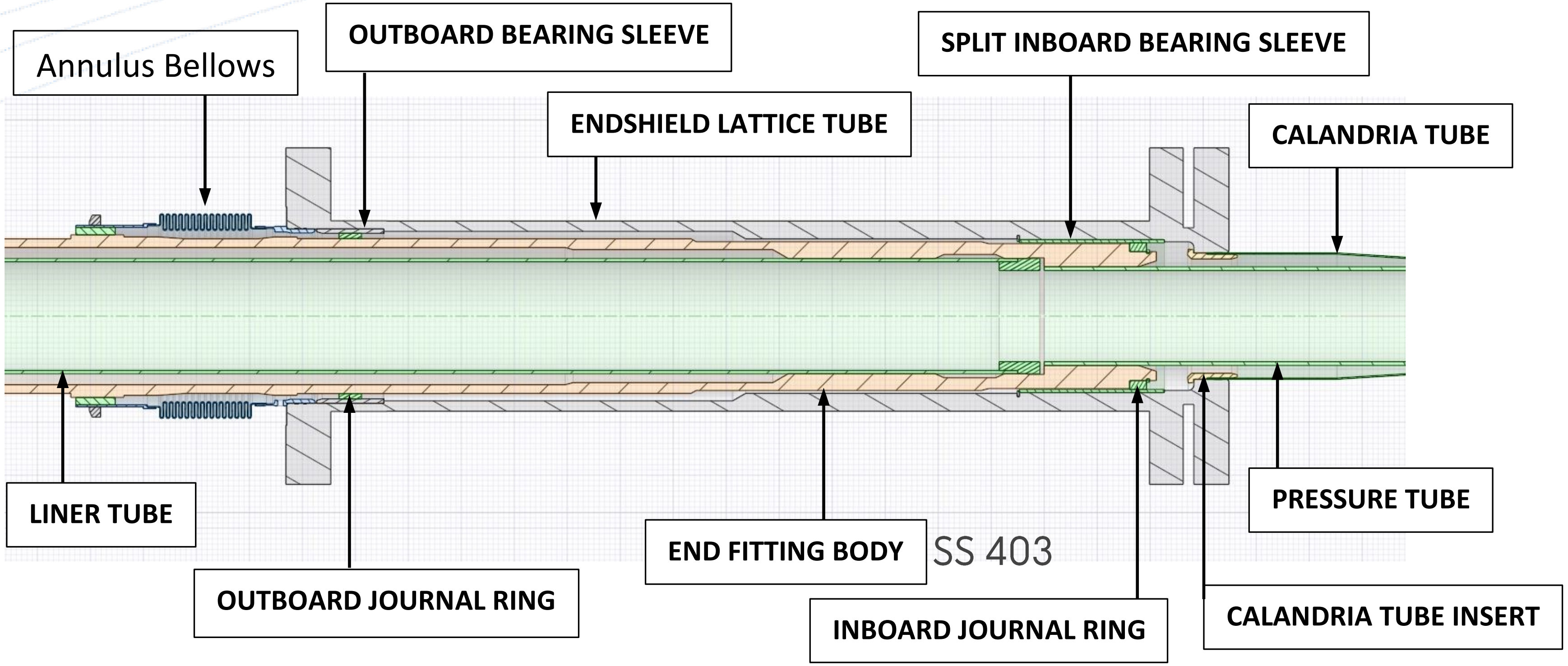
Modeling Aging and Degradation Effects on Fuel Channel Vibrations

Development of Fuel Channel Model (ANSYS)





Details of the Endshield and End Fitting Assembly



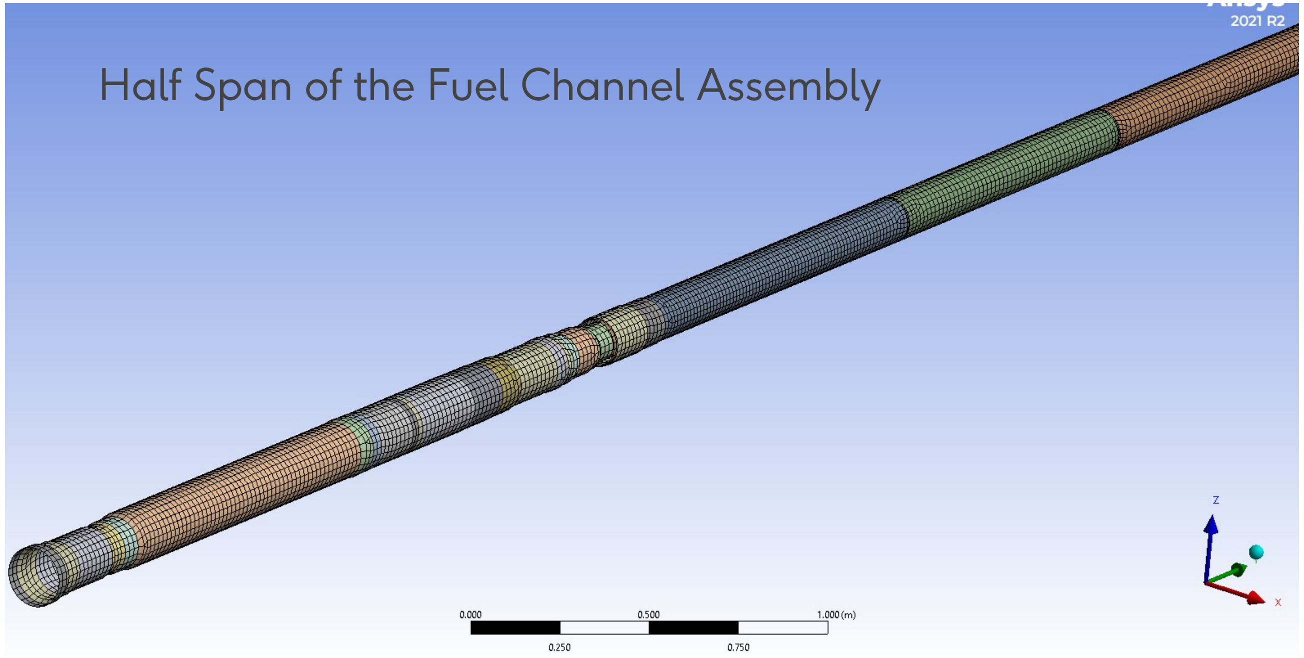
Material Properties and mass of components

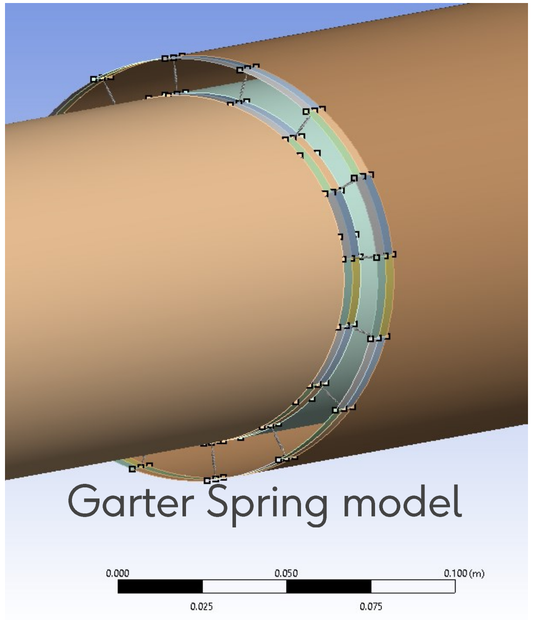
Material	Density	Young's Modulus	Poisson Ratio
Type 403 SS End Fitting	7779 kg/m^3	201 GPa (nom.) 181 GPa (300°C)	0.252 (nom.) 0.283 (300°C)
Zr-2.5wt.%Nb Pressure Tube	6520 kg/m^3	94.6 GPa (nom.) 74.7 GPa (300°C)	0.389 (nom.) 0.361 (300°C)
Zr-2 Calandria Tube	6500 kg/m^3	94.8 GPa (nom.) 90.4 GPa (80°C)	0.378 (nom.) 0.370 (80°C)

- Mass of fuel bundles, coolant, shield plugs, etc. are accounted for by adding it to the mass of the structural elements: e.g., Pressure Tube includes mass of Coolant, Fuel Bundles (12 x 24 kg).
- The End Fittings incorporate the mass of Shield Plugs (2 x 78.5 kg), Liner Tubes, Closure Plugs, Coolant.
- The Calandria Tube includes the dynamic effects from the surrounding FC dynamics and moderator.

Finite Element Model Development

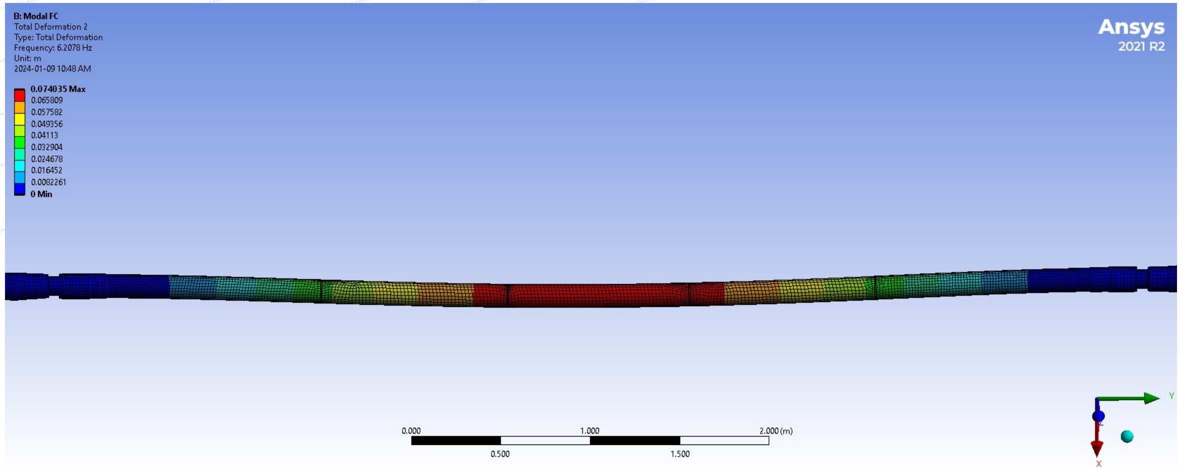
- Used “Shell Elements” – thin membranes to replace long cylinders with thin undeformed walls
- Finite Shell Element meshing of Fuel Channel Assembly: element size is 8 mm & 10 mm
- Total ~114,000 elements
- Garter Springs (Spacers) separate the PT and CT at 4 locations along the FC and their effect is modeled using radial spring elements connecting the PT to CT.



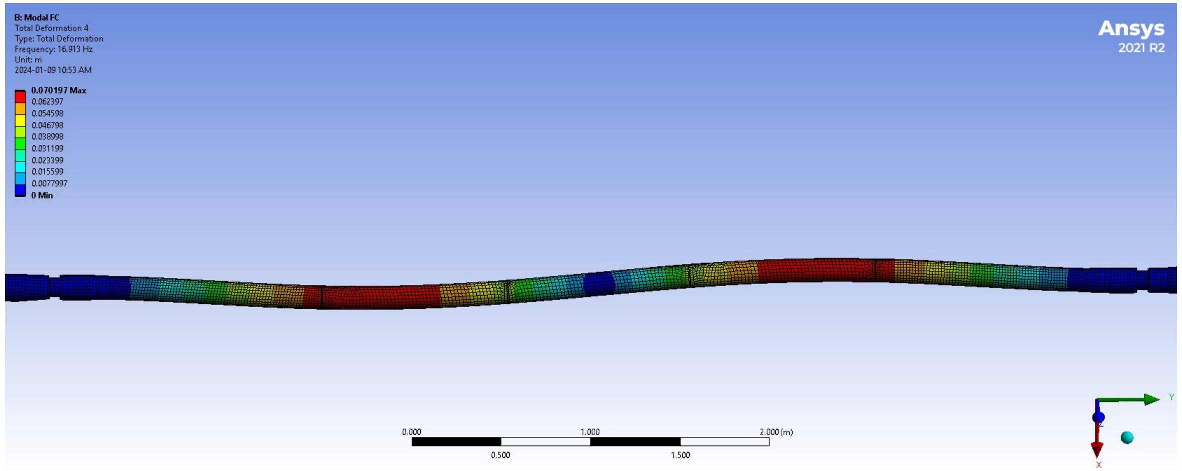


Main Modes of Fuel Channel Vibration

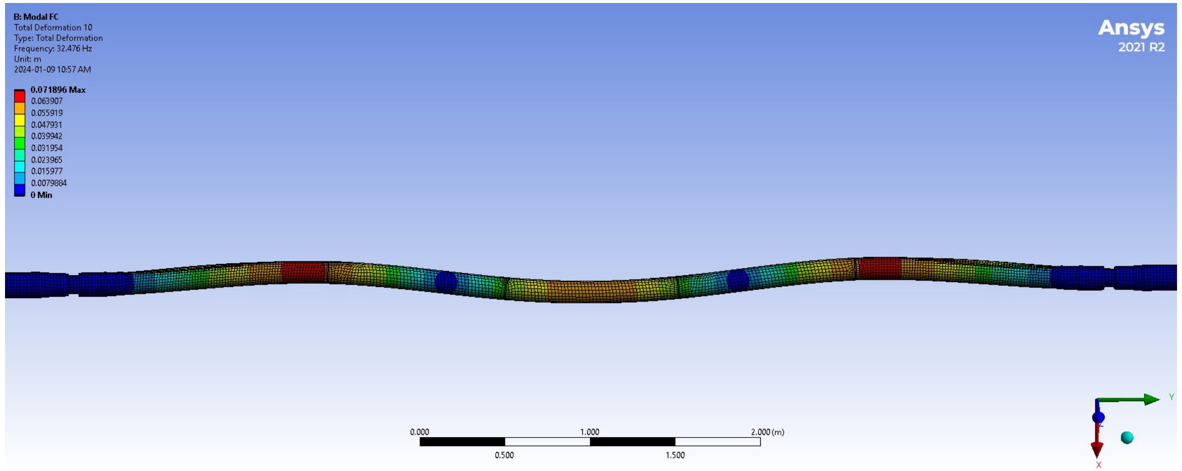
First Mode: ~5.5 Hz



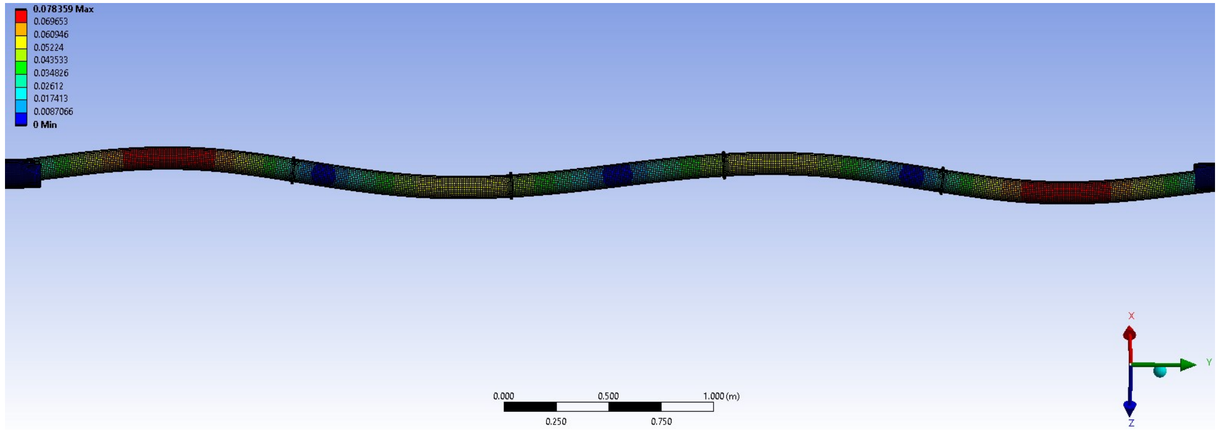
Second Mode: ~15 Hz



Third Mode: ~29 Hz

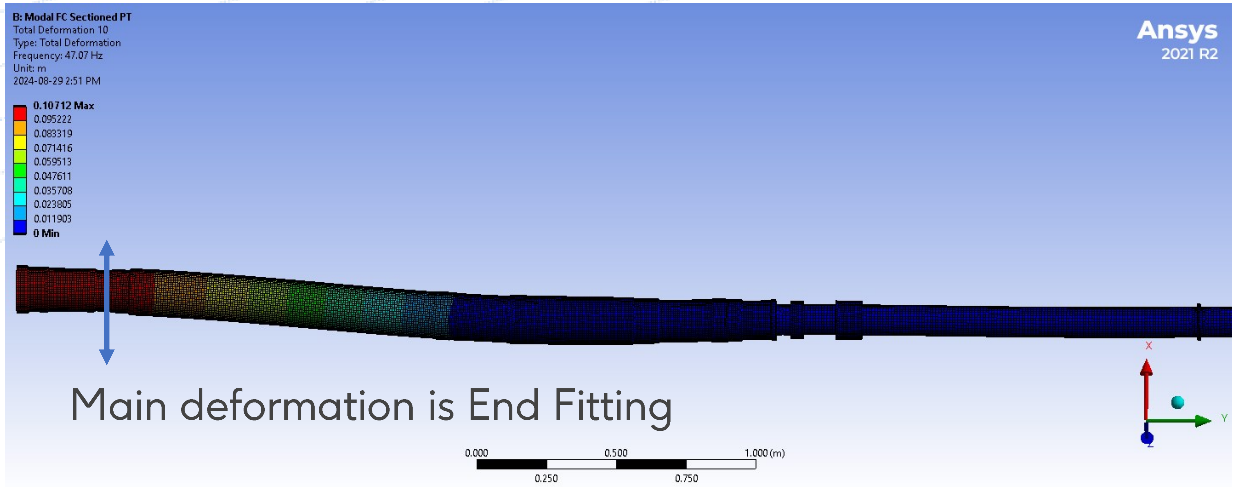


Fourth Mode: ~45 Hz



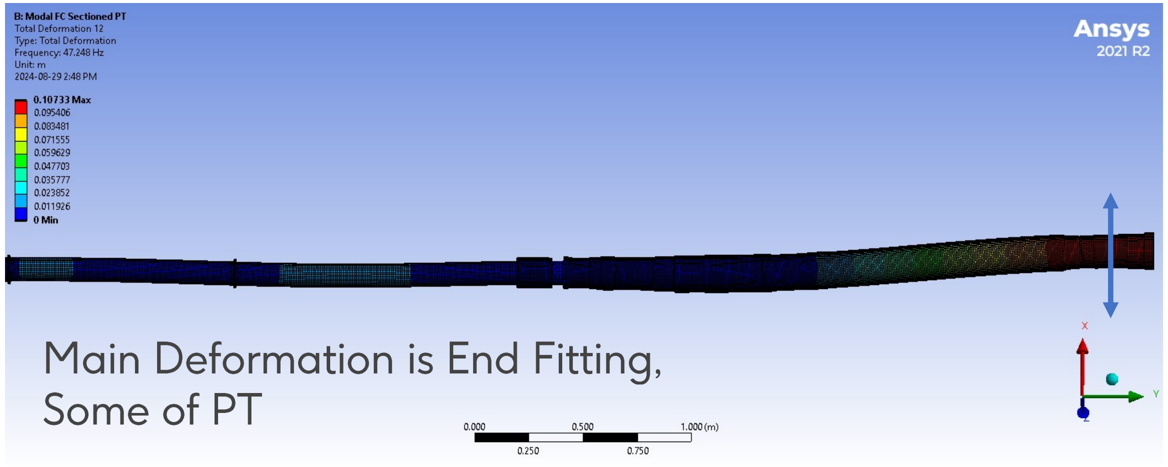
Additional Modes of Fuel Channel Vibration

Fifth Mode: ~47 Hz



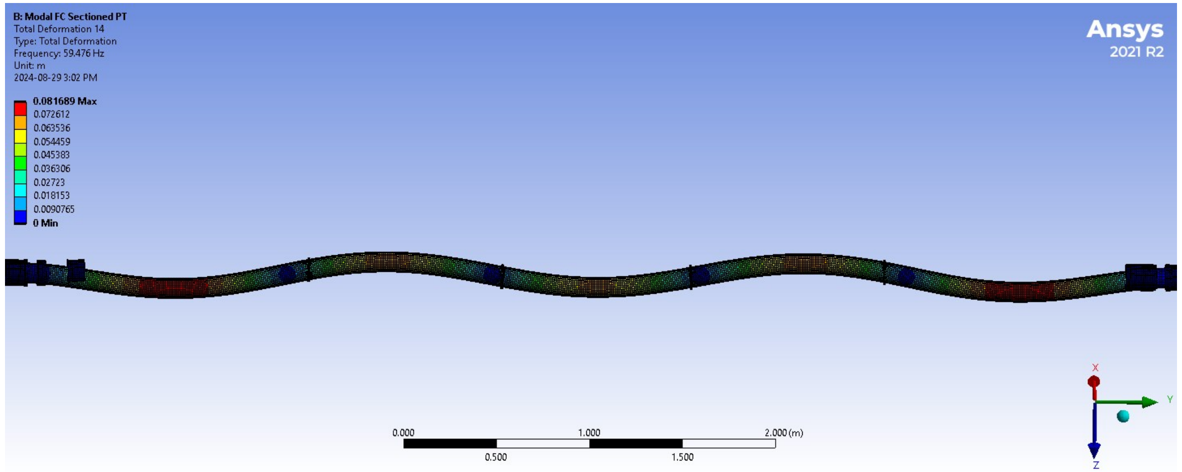
Main deformation is End Fitting

Sixth Mode: ~47.2 Hz



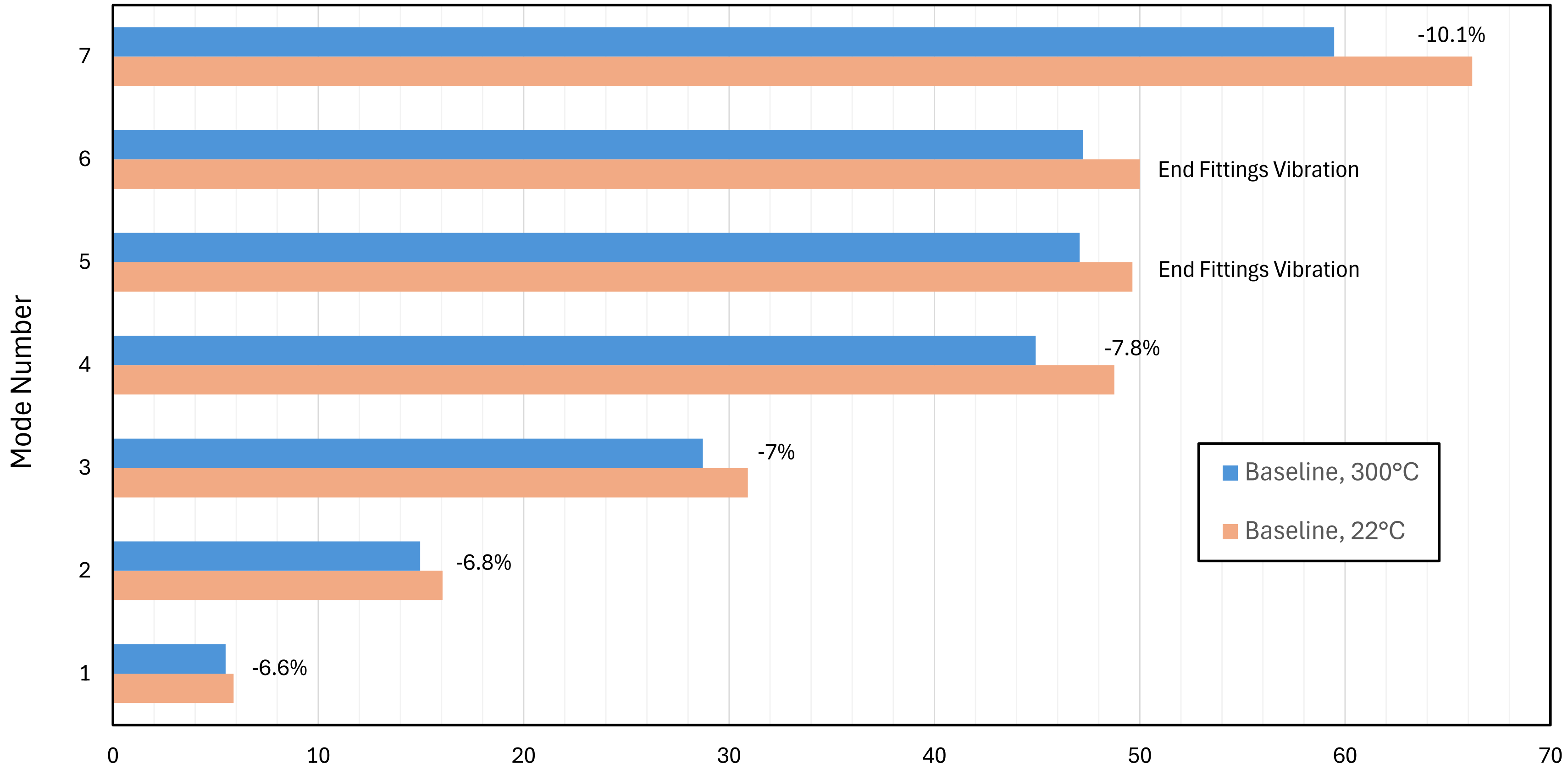
Main Deformation is End Fitting,
Some of PT

Seventh Mode: ~59.4 Hz



Changes in vibration frequencies from separate effects of aging and degradation

Main Vibration Modes at Ambient and Operating Temperature



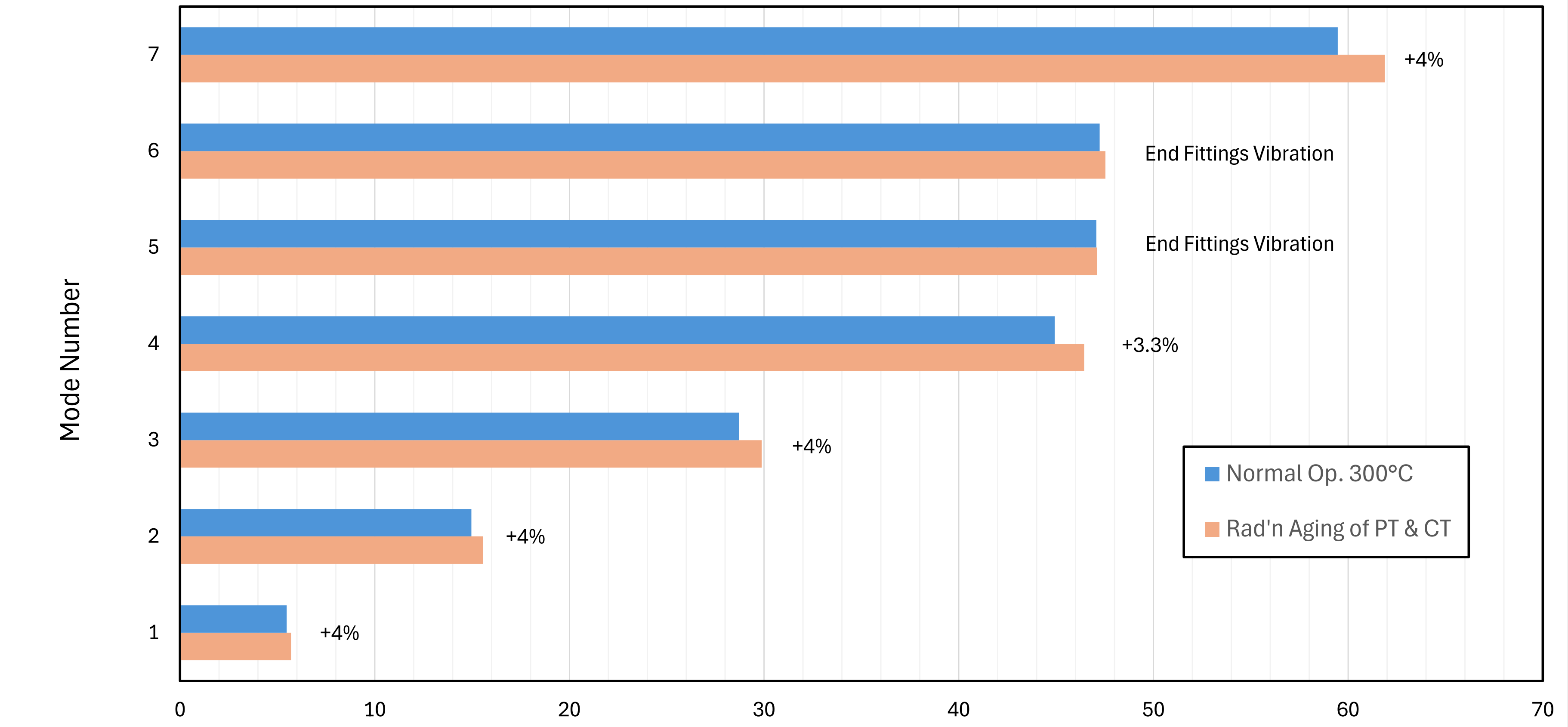
	1	2	3	4	5	6	7
Baseline, 300°C	5.48	14.96	28.72	44.93	47.07	47.24	59.47
Baseline, 22°C	5.87	16.05	30.91	48.76	49.64	50	66.19

Vibration Frequency, Hz

Operating temperature increase causes decrease in modal frequencies

- The computed modal frequencies compare favourably with those from similar studies.

Radiation Aging of PT and CT



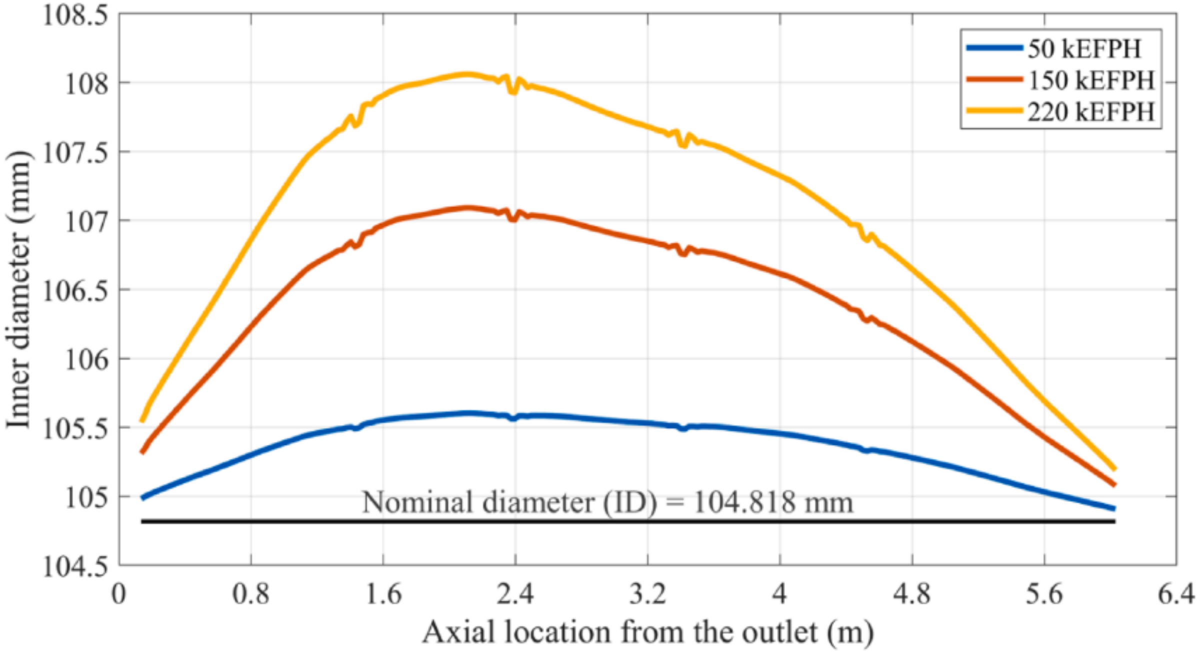
	1	2	3	4	5	6	7
Normal Op. 300°C	5.48	14.96	28.72	44.93	47.07	47.24	59.47
Rad'n Aging of PT & CT	5.70	15.57	29.88	46.44	47.10	47.53	61.88

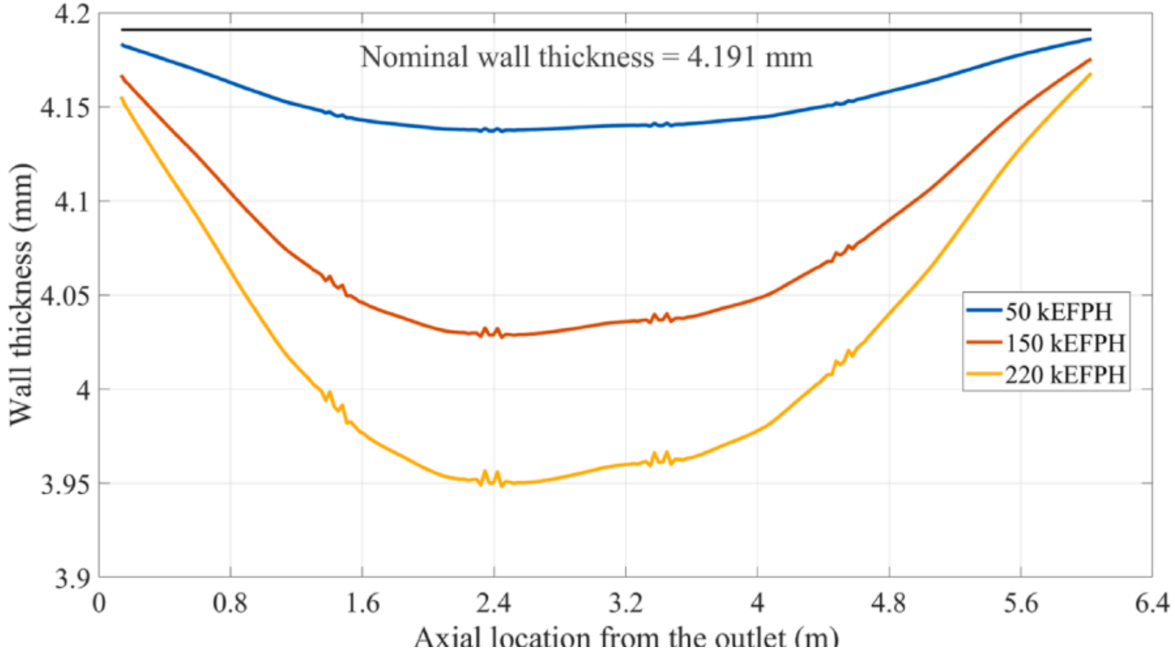
Vibration Frequency, Hz

- Irradiation to 15 KEFPH causes Young's modulus to increase by 8.4%.

Increasing material irradiation (aging) causes increase in modal frequencies

Pressure Tube Diametral Creep

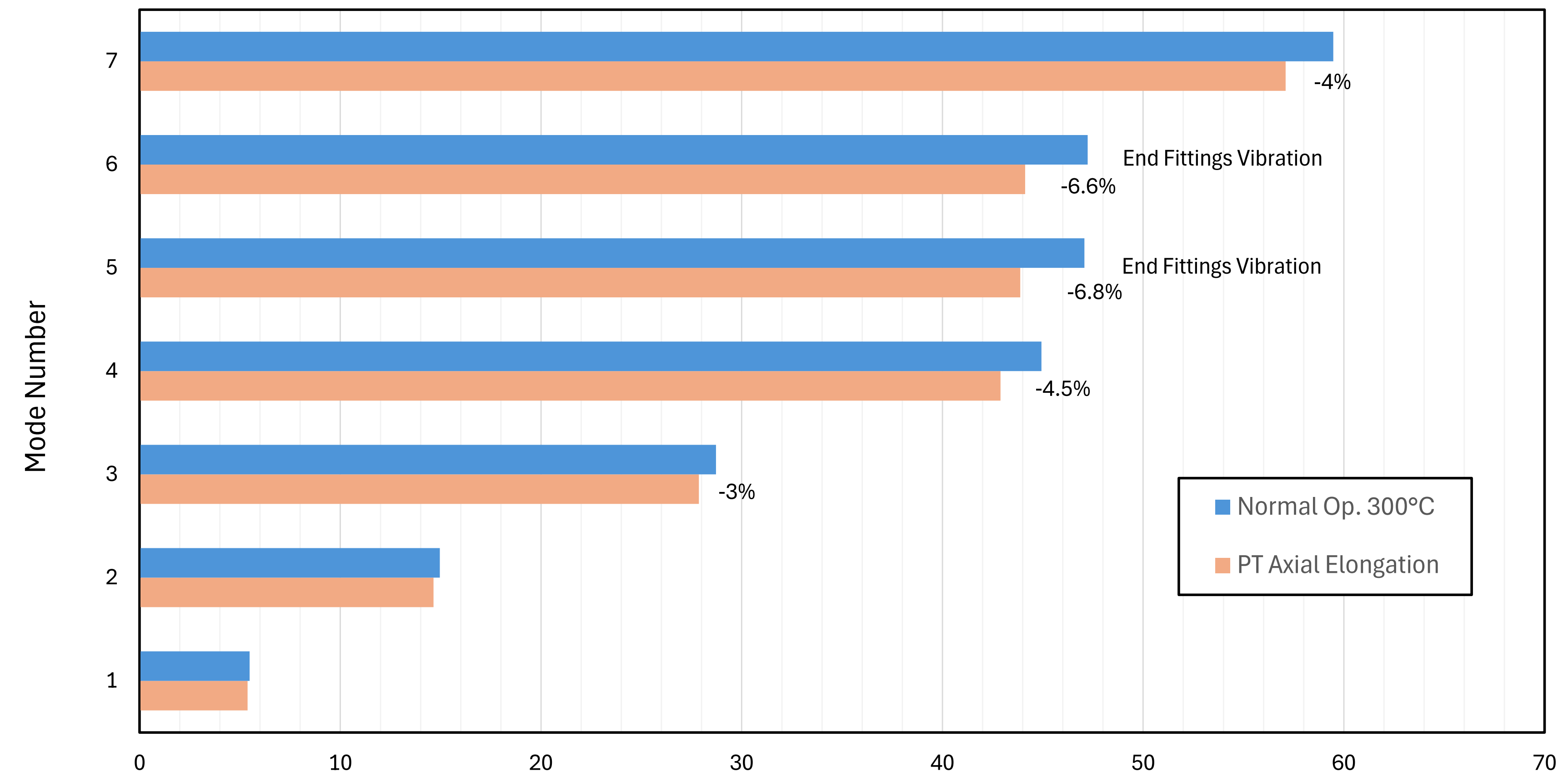




Source: Prabhu S.R., et al., "A Surrogate Model for the 3D Prediction of In-Service Deformation in CANDU Fuel Channels", Nucl. Eng. Des., Vol. 369, 2020.

EFPH is effective full power hours

Effect of Diametral Creep & Elongation of Pressure Tube on Modal Frequencies

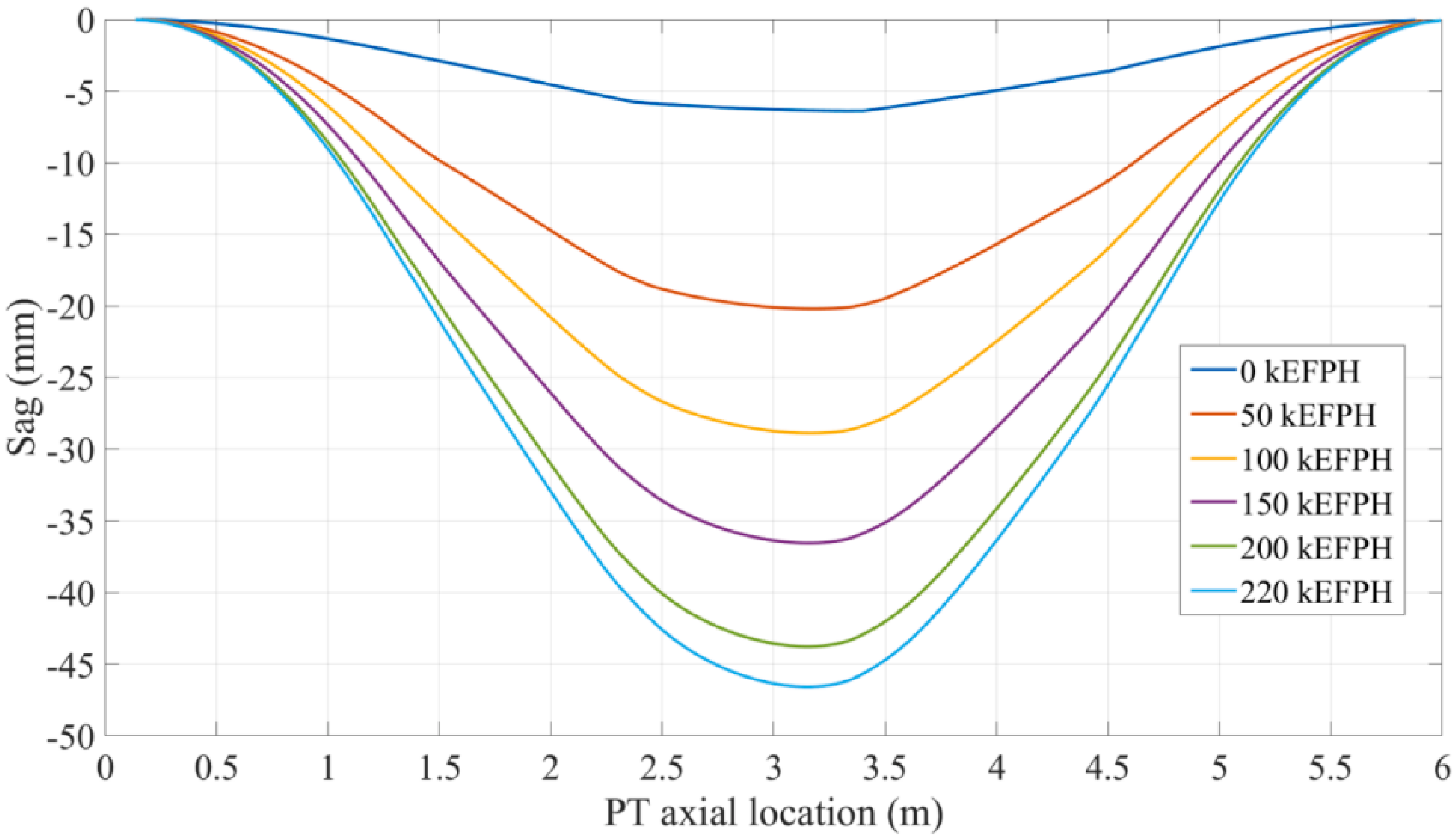


	1	2	3	4	5	6	7
Normal Op. 300°C	5.48	14.96	28.72	44.93	47.07	47.24	59.47
PT Axial Elongation	5.38	14.64	27.86	42.89	43.88	44.12	57.10

Diametrical creep increases and elongation decreases modal frequencies

- PT Axial Elongation by 4 Inches (10.2 cm) Each End
- There is negligible increase in mode frequency due to diametral creep.
- There is a general lowering of modal frequencies that is significant for Mode 2 and higher due to elongation.

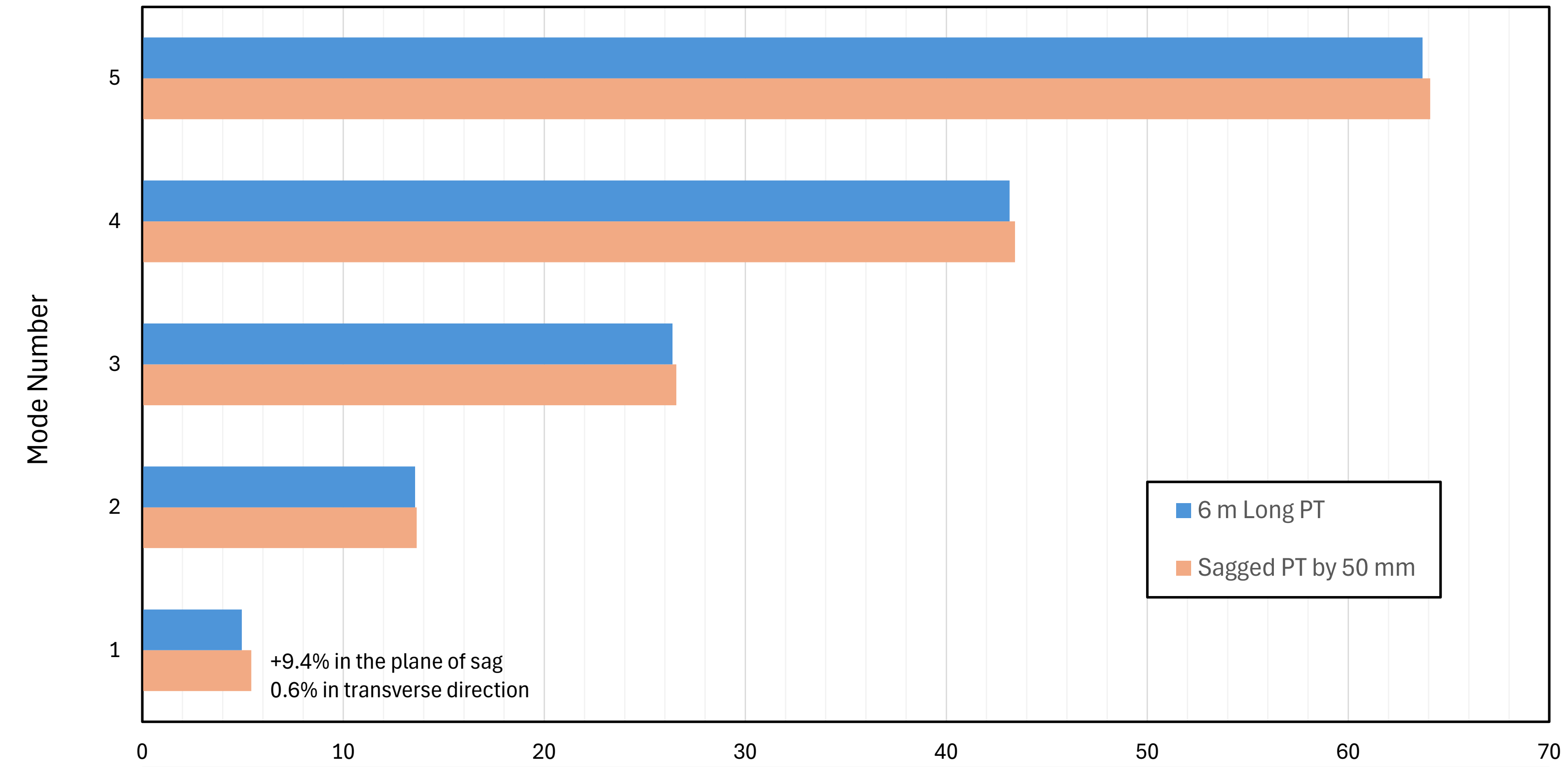
Pressure Tube Sag



Source: Prabhu S.R., et al., "A Surrogate Model for the 3D Prediction of In-Service Deformation in CANDU Fuel Channels", Nucl. Eng. Des., Vol. 369, 2020.

EFPH is effective full power hours

Effect of Sag on Modal Frequencies for a 6 m Long Pressure Tube



	1	2	3	4	5
6 m Long PT	4.95	13.57	26.38	43.15	63.69
Sagged PT by 50 mm	5.418	13.65	26.57	43.42	64.08

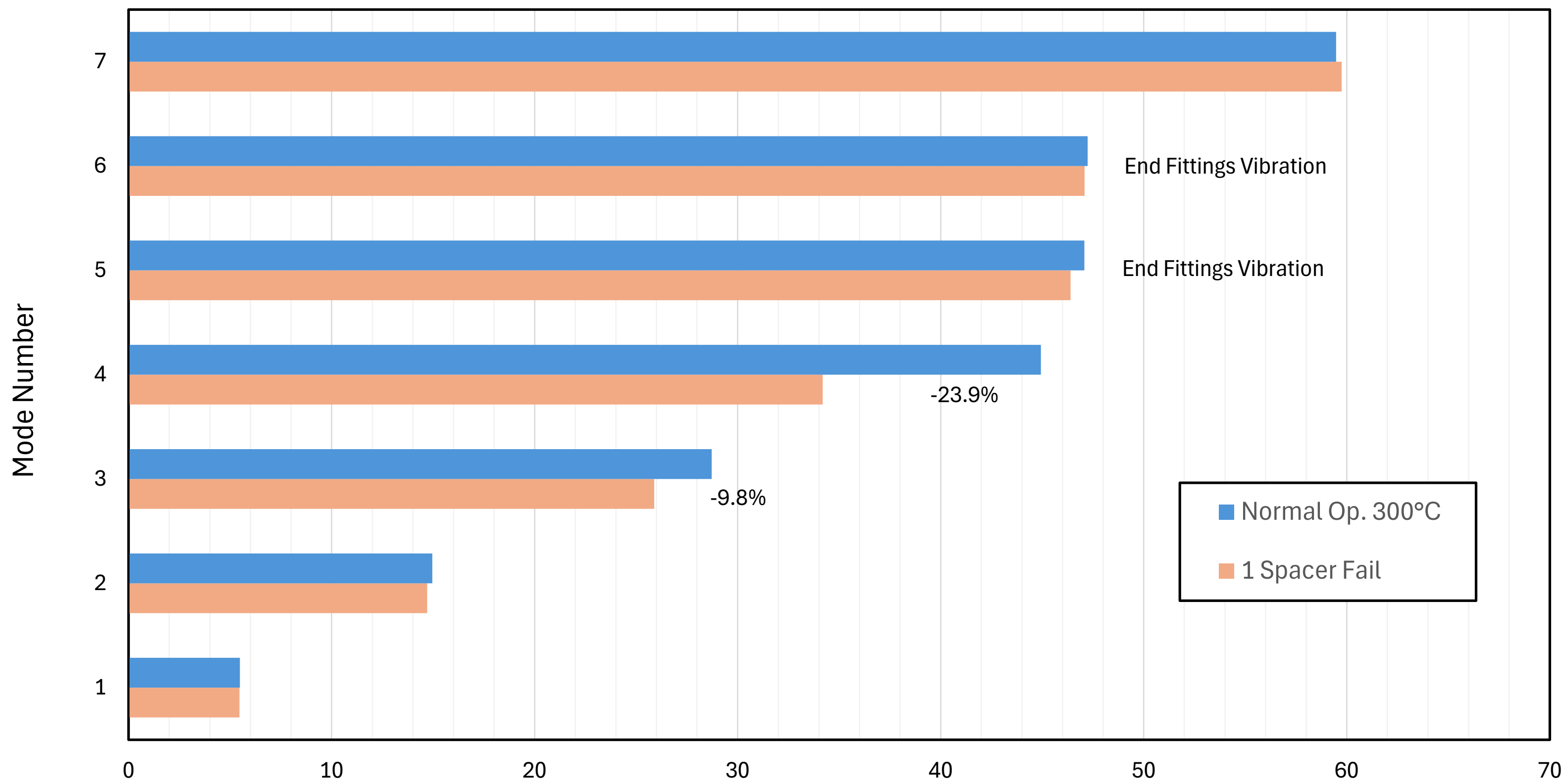
Vibration Frequency, Hz

- Maximum Imposed Sag 50 mm (at centre of PT)
- Sag causes very small increase in the modal frequencies
- the frequency of the first mode in the plane of sag differs by ~0.5 Hz from the transverse mode (beats?)

Summary of aging effects

- Separate aging effects (material irradiation, diametrical creep, axial elongation, sag) have competing effects – increase and decrease - on Fuel Channel vibration mode frequencies.
- Since FC components undergo a range of aging effects, this may contribute to the "normal" spread in modal frequencies observed in neutron noise signals
- First time that the effects of aging on Fuel Channel vibration modes have been modeled – still learning.

Effect of One Garter Spring (PT-CT spacer) Failing Next to End Fitting

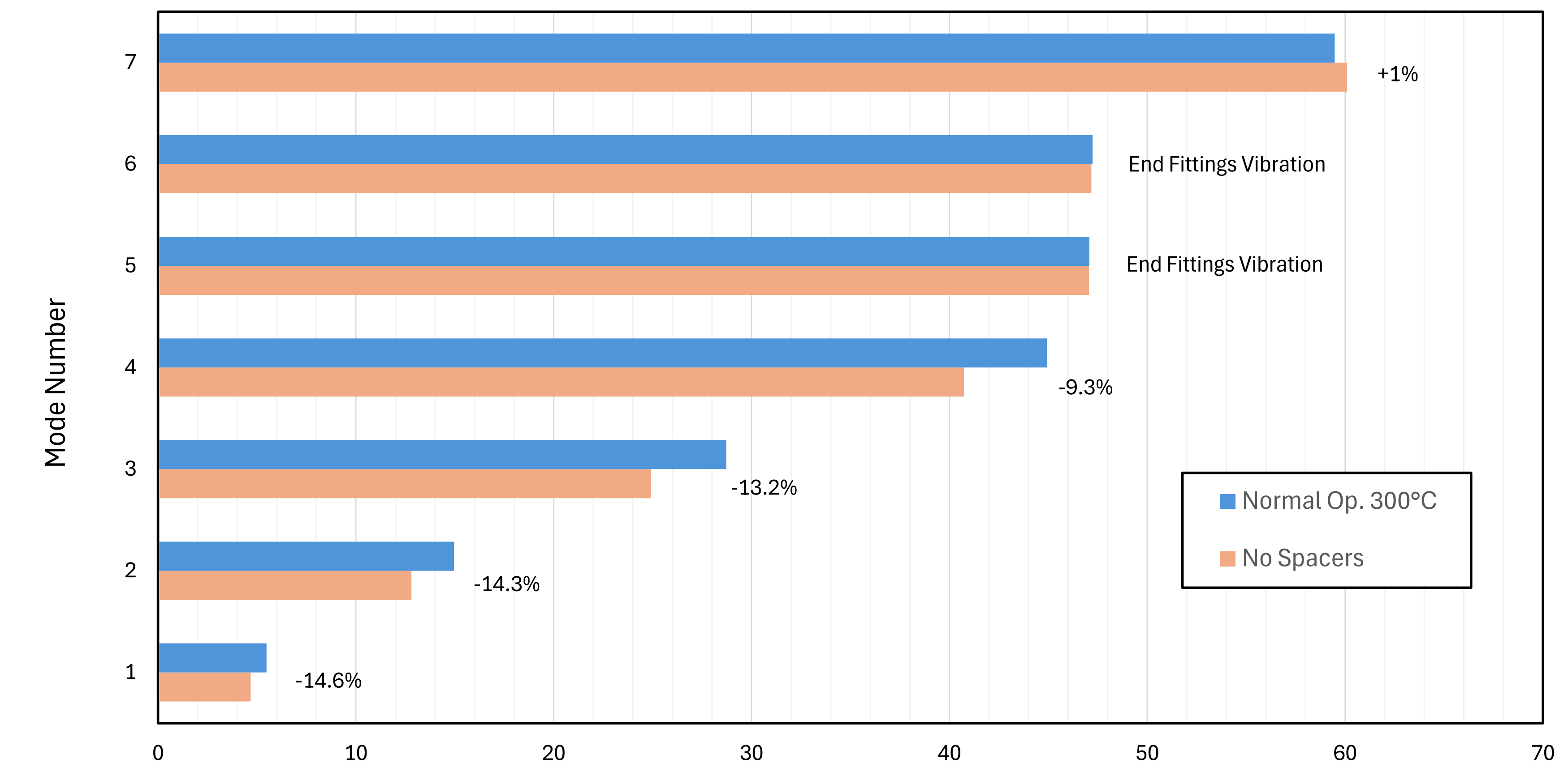


	1	2	3	4	5	6	7
Normal Op. 300°C	5.48	14.96	28.72	44.93	47.07	47.24	59.47
1 Spacer Fail	5.46	14.7	25.89	34.19	46.39	47.08	59.75

Vibration Frequency, Hz

- The 3rd mode frequency noticeably decreased
- A new 4th mode emerged which reflects the loss of stiffness in the FC at the first spacer location.
- A new 5th mode appears and involves more EF deformation

Effect of Removing Garter Springs (~0 spring stiffness)

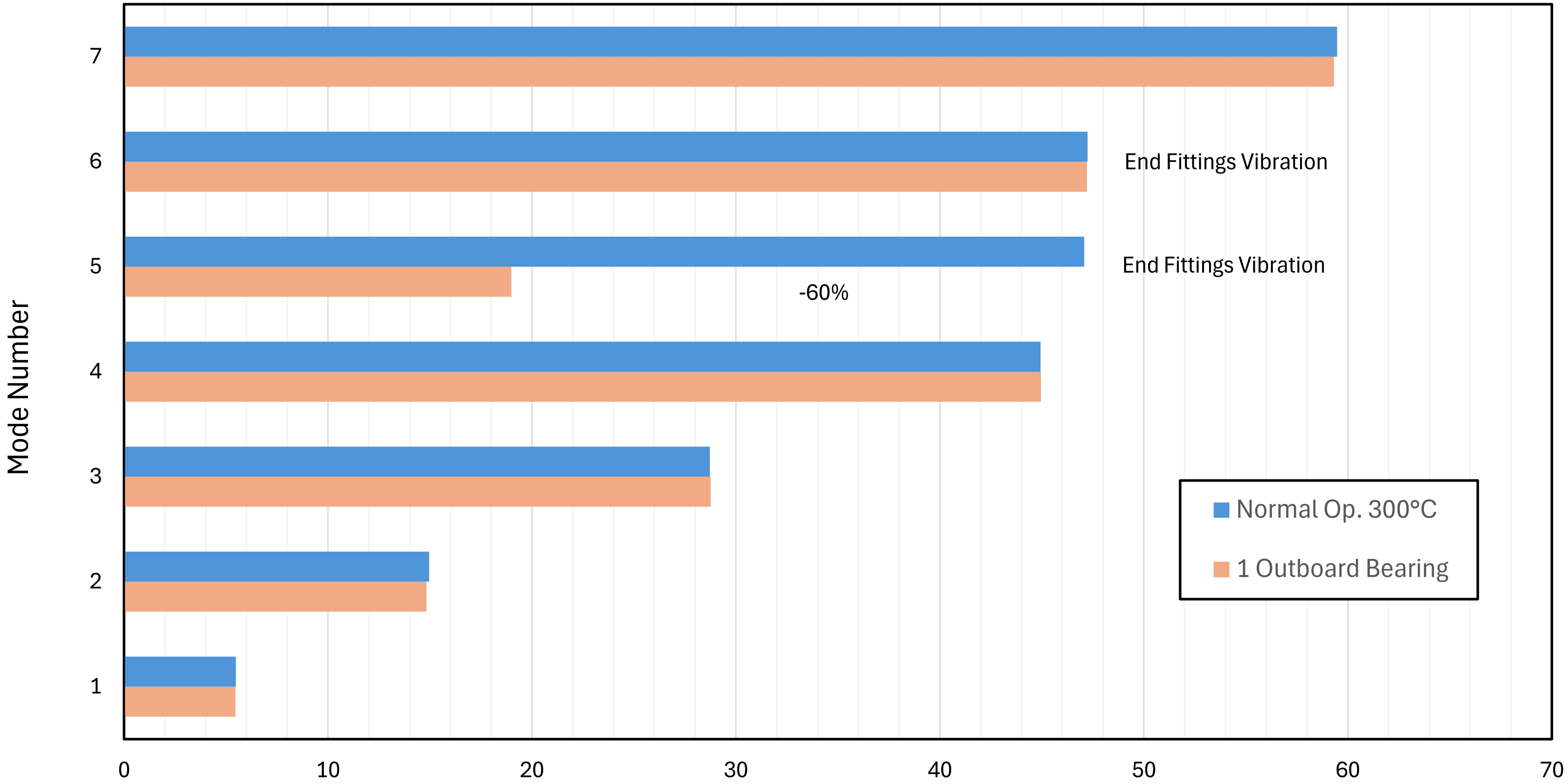


	1	2	3	4	5	6	7
Normal Op. 300°C	5.48	14.96	28.72	44.93	47.07	47.24	59.47
No Spacers	4.68	12.81	24.91	40.73	47.05	47.18	60.1

Vibration Frequency, Hz

- Decoupling the PT and CT results in separate modes of vibration;
- Noticeable decreases in the first 4 modal frequencies - due to a decrease in FC stiffness
- CT deforming independent from the PT (the CT is not supporting the PT).

Effect of Unconstrained Radial Movement of EF at One Outboard Bearing

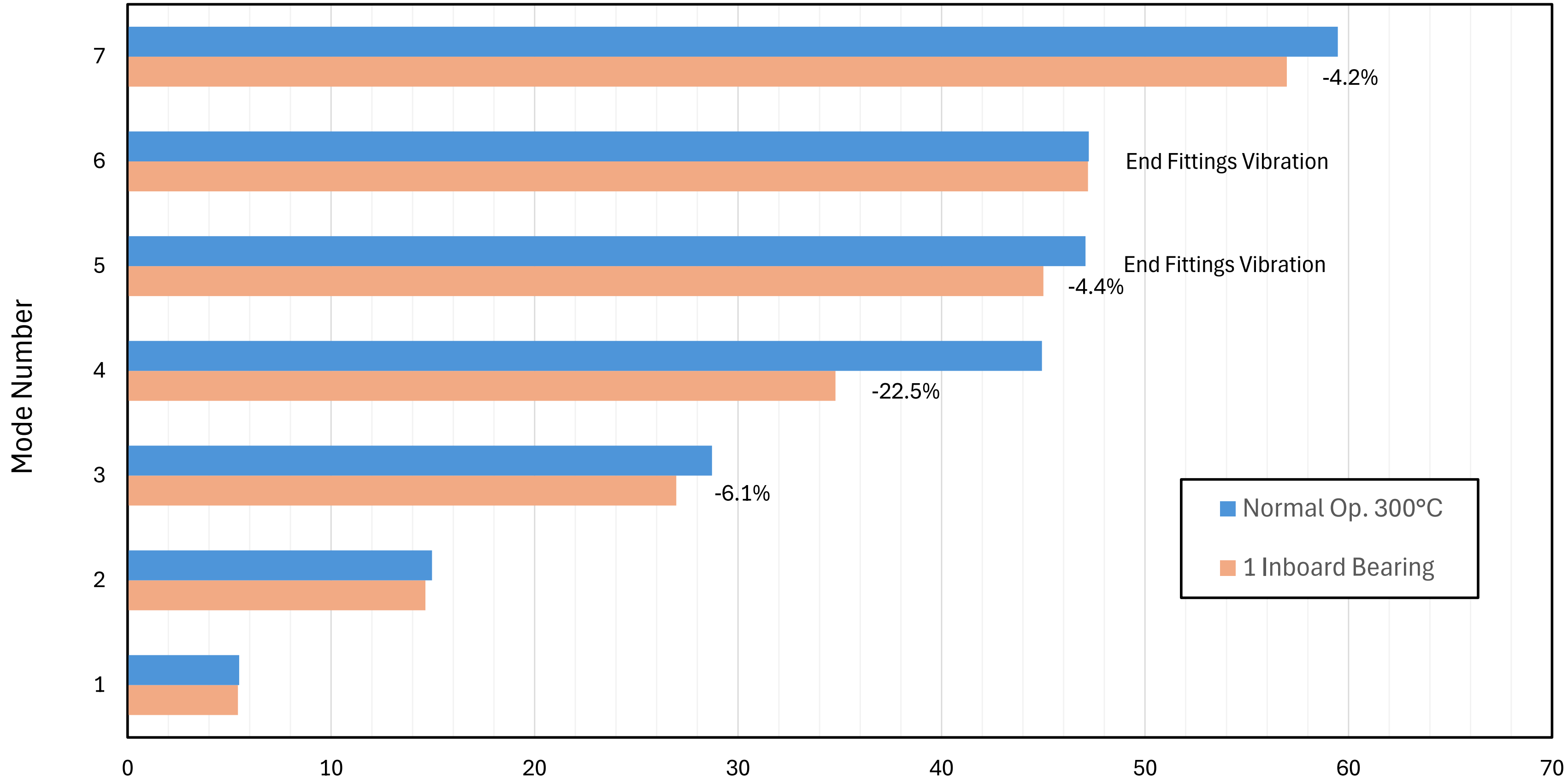


	1	2	3	4	5	6	7
Normal Op. 300°C	5.48	14.96	28.72	44.93	47.07	47.24	59.47
1 Outboard Bearing	5.46	14.83	28.76	44.95	18.99	47.21	59.32

Vibration Frequency, Hz

- A new 3rd mode frequency emerged due to deformation of the end fitting alone, caused by removal of the outboard bearing support.

Effect of Unconstrained Radial Movement of EF at One Inboard Bearing



	1	2	3	4	5	6	7
Normal Op. 300°C	5.48	14.96	28.72	44.93	47.07	47.24	59.47
1 Inboard Bearing	5.42	14.63	26.96	34.79	45	47.2	56.97

Vibration Frequency, Hz

- The frequency of the 3rd mode decreased
- a 4th mode frequency emerged similar to the 3rd.
- effectively lengthened the unsupported span of the fuel channel (PT, CT) and end fitting on one end (unsymmetric).

Conclusions and Future Direction

- A Finite Shell Element model of a CANDU Fuel Channel (FC) was developed based on design dimensions and shown to produce modal frequencies comparable to previous Finite Element Analysis (FEA) model studies and to data obtained from station neutron noise signals.
- Sensitivity of the FC model baseline frequencies to: changes in garter spring stiffness, partial voiding of the coolant on the downstream end of the Pressure Tube (PT), coolant density gradient, diametral creep, sag, all indicate negligible change to the natural frequencies of the fuel channel assembly.
- Sensitivity of the baseline modal frequencies to effects such as material property degradation, PT elongation, loose inboard bearing supports, failed/crushed garter spring, all show potential for the FEA model to provide health monitoring characteristics of a fuel channel through the use of neutron noise signals.
- PT to Calandria Tube (CT) contact during operation continues to be a concern; implementing this fault scenario into the model could provide an important capability.
- Assigning observed frequency peaks to individual FCs, tracking changes in modal frequencies and obtaining 100% coverage for all FCs are challenges for application of noise analysis.

Thank You