Nuclear Energy Agency

NEA/CSNI/R(2020)2

Unclassified **English text only**

13 February 2023

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

Evaluation of Design and Monitoring Requirements for Vibrations in Safety-Related Fluid Systems

This document is available in PDF format only.

JT03512231

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) addresses Nuclear Energy Agency (NEA) programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

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List of abbreviations and acronyms

ALMS	Acoustic leak monitoring system
ASME	American Society of Mechanical Engineers
BWR	Boiling water reactor
CAPS	CSNI activity proposal sheet
CB	Core barrel
CRDM	Control rod drive mechanism
CS	Carbon steel
CSNI	Committee on the Safety of Nuclear Installations
CV	Chemical volume control
CVAP	Comprehensive vibration assessment programme
DSR	Dutch safety requirements
ECT	Eddy Current Testing
EDF	Électricité de France
EFPY	Effective full power years
ENSI	Swiss Federal Nuclear Safety Inspectorate
EPZ	Elektriciteits-Productiemaatschappij Zuid-Nederland (Electricity Production Company, South Netherlands, the Netherlands)
FIV	Flow-induced vibration
HPCS	High Pressure Core Spray
IAGE	Integrity and ageing of components and structures
I&C	Instrumentation and Control
IRI	Incomplete rod insertion
ISI	In-service inspection
IVMS	Internal vibration monitoring system (Japan)
JSME	The Japan Society of Mechanical Engineers
KCB	Kerncentrale Borssele
KTA	Kerntechnischer Ausschuss (German Nuclear Safety Standards Commission)
LPMS	Loose parts monitoring system
LTO	Long-term operation
LUA	Lead use assemblies
NEA	Nuclear Energy Agency
NIMS	NSSS integrity monitoring system
NRA	The Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission
NRI	Nuclear Research Institute (Řež, Czech Republic)
NSSS	Nuclear steam supply system
NTD A.S.I.	Normative technical documentation of association of mechanical engineers

OECD	Organisation for Economic Co-operation and Development
PHWR	Pressurised heavy-water reactor
PLR	Primary loop recirculation
PSDS	Piping System Design Specification
PVT	Piping verification test
PWR	Pressurised water reactor
RCC_M	Design and construction rules for mechanical components of PWR nuclear islands (France)
RCP	Reactor coolant pump
RCS	Reactor Coolant System
RCPVMS	Reactor coolant pump vibration monitoring system
RFO	Refuelling outage
RG	Regulatory guide
RMS	Root mean square
RPV	Reactor pressure vessel
SSM	Swedish Radiation Safety Authority
STUK	Finnish Radiation and Nuclear Safety Authority
WGIAGE	Working Group on Integrity and Ageing of Components and Structures (NEA)

Executive summary

In order to reach a better understanding of countries' different approaches to the evaluation of vibrations detected in piping systems and components, the NEA Committee on the Safety of Nuclear Installations (CSNI) Working Group on Integrity and Ageing of Components and Structures (WGIAGE) initiated work focused on the vibrations of reactor internals and small piping connected to the primary piping. The requirements for managing vibrations in safety-related fluid systems were explored by means of a questionnaire, which has three main areas: design requirements, vibration monitoring and reactor pressure vessel (RPV) vibrations. The questions focused on vibration screening criteria, design requirements, proactive vibration programme controls, and the associated regulatory requirements for safety-related fluid systems and their components. The entire piping and component lifespan was addressed in the questionnaire, including design and construction, pre-operational monitoring programmes, and surveillance during operation. Operating experience with vibration-induced failures and mitigation of the most problematic vibration issues was also shared. Specific differences among the countries in defining functional safety relations and piping classification were taken into account during the evaluation. Information was also collected on fuel vibration issues, internal reactor parts and primary piping.

The following conclusions were made based on the analysis of the answers of 11 countries to the questionnaire:

- Operating vibrations of fluid systems and structures are a real problem at nuclear power plants. Vibrations must be given constant attention throughout the operation of the power plant, as the vibration level may change due to ageing and plant modifications. Acceptable and clear screening criteria for operating vibrations are essential for the safe operation of power plants. Conservative criteria for vibrations make it necessary to take measures even if vibrations do not endanger safe operation. On the other hand, relaxed screening criteria lead to equipment damage and other consequences of accidents. Based on experiences of member countries, many vibration issues are avoided through adequate design solutions and suitable requirements and criteria for trial run tests.

- The biggest differences among the participating countries are in their screening vibration criteria. Most participating countries use the US standard American Society of Mechanical Engineers (ASME) OM Part 3 values for vibrations. These values seem to be very conservative with respect to the real situation in nuclear power plants and therefore some countries have developed their own criteria.

- As a good practice, there is regular measurement of operating vibrations of pump bearings when they are switched on. In particular, this applies to safety-related systems. Incorporating this measurement into the operational control programme significantly improves the safety of pipeline systems that are important for the operation and safe shutdown of units in case of abnormal and emergency conditions.

- Some countries report the implementation of very complex monitoring and diagnostic systems for operating vibrations in the components of the primary circuit and all participating countries had implemented a diagnostic system for the main reactor coolant pump.

The lack of a special requirement from the authority to carry out regular monitoring of operational vibrations during the operation of nuclear power plants is an important finding of the survey.

Based on the assessment of the answers of 11 countries, the following recommendations could be made:

1. It is useful to incorporate applied and practice-validated screening vibration criteria into applied nuclear power plant standards. More detailed requirements for the evaluation of operational vibrations during the design and construction phase of nuclear power plants could help avoid situations in which piping systems or their parts exhibit their natural frequency or a frequency close to it. The latter is known as the pump excitation frequency.
2. Adequate industry requirements for the measurement of operational vibrations during trial (commissioning) operation and for regular monitoring of vibrations during operation should be established for use in nuclear power plant projects. Measurement and recording of operating vibrations to a large extent during commissioning and trial tests will aid in the recognition of exceptional situations and reduce the risk of damage during later operation. The definition of requirements for vibration analysis will also address the responsibility for operating vibrations at the same time.
3. Regular monitoring of operating vibrations with clear and practice-validated vibration screening and comparison criteria should be adopted to increase the safety of nuclear power plant operation. A diagnostic system for the vibrations of the main reactor coolant pump together with a diagnostic system for the vibrations of RPV internals would represent a minimum level of measurements needed for vibration analysis. Most participating countries use neutron flux detectors to identify RPV frequency spectra, which would be a very good practice for RPV internals or fuel vibration.

The recommendations are topics of discussions in the WGIAGE and in upcoming international workshops or expert groups. The analyses of trends in vibration failures and their safety margins based on operating experiences collected in international databases could be a focus for future work.

1. Background

Vibration issues in piping systems can occur during commissioning of a new plant, after power uprate or after major equipment replacement. Therefore, typically, each country has adopted separate requirements related to operability and functional capability. This complicates the licensing processes for long-term operation of nuclear plants and causes uncertainty about the actual safety system performance and margins in postulated accidents and design extension conditions. It is very useful to collect and summarise the requirements for ensuring operability and functional capability of mechanical safety system components in each country and to evaluate national differences among requirements on vibration issues.

Piping vibration problems are a reality in piping systems at nuclear power plants. Utilities and operators are extremely sensitive to the integrity risks because of the significant consequences associated with releases from ruptured piping. Vibration can cause reliability problems in equipment and fatigue failure of piping systems and small branch connections, including relief lines, instrumentation ports, nozzles, drains and valves. Vibration of rotating machinery is also a reliability issue.

Hence, it is important to monitor vibration levels during operation to assure that they are not a safety concern. One major question is at what level do pipe vibrations become severe and what parameter(s) should be measured. It is the objective of many standards and operation rules in each country to provide simple rules of thumb to nuclear power plant engineers, engineers evaluating vibration, and managers for evaluating the severity of the vibration issues with piping systems.

2. Introduction

Experience indicates that operational vibration can strongly increase the degradation of safety-related systems. Excessive piping vibration is a major cause of leaks, fatigue failures and high noise, and frequently of non-regular shutdowns of nuclear power plants. Statistics show that vibratory fatigue is the dominant failure mechanism for safety-related systems of small-diameter piping. The vibrational behaviour of fluid power systems is a very important issue regarding the lifetime of piping systems and components. Vibration of process plant piping can be a significant risk to asset integrity and safety.

Vibrations in hydraulic systems may be induced by fluid flows as well as by mechanical sources of vibration. Components of fluid systems, such as pumps, valves, chokes and shutters, generate pulsation of fluid flow– flow-induced vibration. Additionally, pressure-reducing devices in fluid systems can generate great acoustic energy that excites the pipe shell vibration modes. This acoustic-induced vibration leads to fatigue failure in the process piping or nearby small bore connections and generates broadband sound radiation in the range of 500 Hz to 2 000 Hz. On the other hand, vibrations in the system can be induced by unbalanced and misaligned rotating parts of the drive system, as well as by time-variable forces and moments acting upon the hydraulic system components. Vibrations of hydraulic pipes can be caused by factors associated with fluid flow or due to mechanical excitations. Vibrating elements, such as hydraulic pumps, as well as vibration of the supporting structure, can become sources of kinematic excitations. Vibration propagation is facilitated by a rigid connection between the frame, system components, inter-connecting pipes and hoses.

Pressure boundary design codes provide rules to ensure structural integrity of passive system components but do not address operability and functional capability requirements of mechanical components in the event of an accident. Because most of the piping design codes do not address the vibration issues in a design, their damaging effect is normally ignored during the design stage, and simple static analysis without attention to vibration is often performed on piping systems. Nonetheless, it has been observed that vibration causes many problems in operating power plants that should be solved during the design phase. The majority of the damaging effects of vibration can be mitigated if proper design philosophy is taken up while designing the system.

It is useful to have a screening rule for evaluation of piping vibration in order to determine whether it is potentially harmful (could lead to damage or fatigue failure) or simply a nuisance that can be accepted without doing a more detailed assessment or anything to mitigate it. It seems that velocity is in fact the best measurement for assessing the level of dynamic stress in a piping system because, for an elastic system, velocity is proportional to dynamic stress. This can be developed from an understanding that vibration is a transfer between potential and kinetic energy.

Vibration fatigue is the dominant failure mechanism for safety-related small-diameter (<25…50 mm) piping. The failure of safety-related Instrumentation and Control (I&C) system piping may cause spurious or false safety signals and result in plant level transients. Operating experience has indicated that effects of acoustic resonance and flow-induced vibration in fluid systems may have a severe impact on degradation of safety-related systems.

Vibration in process piping systems is a significant integrity issue and excessive piping vibration can cause real problems in nuclear power plants. The most common effects of operating vibrations are loosening of threaded connections, leaking flanges, pipes being knocked off of their supports, fretting and damage to pipe supports, excessive noise in compartments and, in extreme cases, pipe failure. Generally, such vibration problems cause long periods of shutdown of nuclear power plants.

Practice at power plants shows it is difficult to recognise, assess and solve problems with operating vibration of piping systems until damage to piping systems or their parts occurs. However, it is desirable to prevent damage to piping systems due to operational vibrations and to detect risks of failure of piping systems before damage occurs. It is necessary to know when vibration is excessive, evaluate the margins against defined safety limits and to decide when a change in vibration level is a problem.

Correct management of this issue at operational stages can result in a substantial improvement in the integrity issues of fluid systems in nuclear power plants.

This report collects information on different approaches to solving the problems of operating vibration in all participating countries and describes differences in requirements for acceptable operating vibration.

As a first step of the activity, a questionnaire was prepared by the proposing organisation. The questionnaire was reviewed by the NEA Working Group on Integrity and Ageing of Components and Structures (WGIAGE) metal subgroup and sent to all participating countries. The responses to the questionnaire were prepared in Word documents. The answers from ten countries were collected into this report and used as the basis for its preparation.

3. Objective

The main activity was summarising design and monitoring requirements in member countries and providing recommendations on good practices in managing operational vibration in safety-related fluid systems.

The objectives of this activity were to gather information from all countries on the following areas:

- design requirements for vibration assessment of piping systems;
- authority requirements for vibration issues;
- operation screening criteria for vibration of piping systems;
- monitoring of vibration during operation;
- experience with RPV vibration.

To fulfil the above objectives, the following milestones were established:

1. preparation of a questionnaire (by the leading organisation, the Institute of Applied Mechanics Brno, Czech Republic);
2. answers to the questionnaire (from all countries);
3. preparation of a report compiling the answers and a summary analysis of the different approaches and rationales behind them (by the leading organisation);
4. discussion of the rationales and pros and cons of the different approaches (among all countries);
5. determination of whether further work is needed through basic research, bibliography analysis, etc. (by all countries).

4. Questionnaire

The questionnaire was prepared by the leading organisation, the Institute of Applied Mechanics Brno (Czech Republic), and it was sent to all delegates of the Nuclear Energy Agency (NEA) Working Group on Integrity and Ageing of Components and Structures (WGIAGE) metal subgroup and the main group through the WGIAGE's Secretariat. The answers to the questionnaire were received in 2016 and updated in 2017. Some previous results were presented and updated at the metal subgroup meetings in 2016. The questionnaire is included as Annex A of this report. Three main topics in the questionnaire were considered:

- **Design requirements.** The objective of this part is to collect information on each country's standards, regulatory or other requirements on vibration analysis and evaluation in the period of design of equipment and piping systems. Defining the requirements for operating vibrations is very important. The plant operator and supplier very often discuss who is responsible for operating vibration on piping systems. Therefore, it is desirable to collect information on standard requirements or other directives in order to define the responsibility and requirement for analysis of operational vibration at the pipeline design stage and during first period of operation.
- **Monitoring vibration.** The objective of this part is to collect information on the standards and/or regulatory or other requirements of periodic piping system vibration monitoring during operation in each country. The questions were focused on the summary of information on the safe level of operational vibrations and on the description of the implemented vibration monitoring systems in the most important nuclear power plant fluid systems.
- **RPV vibration issue.** The objective of this part is to collect information about RPV internal vibration issues and methodologies of solutions for them in each country. The questions were focused on sharing the information about this specific issue. The questions were prepared with the co-operation of NRI Řež.

Eleven countries answered the questionnaire – Belgium, the Czech Republic, Finland, France, Germany, India, Japan, Korea, the Netherlands, Sweden and Switzerland. Though the United States did not answer this questionnaire, the analysis in the report includes some information on US requirements, codes and standards. Information in this report is based on public sources and use of US standards in national rules of other countries. Certain information on the fatigue vibration events is also available in the CSNI report "NEA CODAP Project Topical Report on Basic Principles of Collecting and Evaluating Operating Experience Data on Metallic Passive Components" (NEA, 2019).

5. Analysis of the answers by items

5.1. Answers to questions related to design requirements

Question 1:

Do you have any requirements on vibration analysis of piping systems in design stage in your design standard?

Answers of participating countries:

Belgium:

Yes. Belgium follows the ASME code Section III for the design of the piping systems. According to the articles NB-3622.3, NC-3622.3 and ND-3622.3: *"Piping shall be arranged and supported so that vibration will be minimised. The designer shall be responsible, by design and by observation under start-up or initial service conditions, for ensuring that vibration of piping systems is within acceptable levels."* There are no specific requirements on the methodology.

Czech Republic:

Yes, in the Czech national standard NTD A.S.I. Section III, Design, Chapter 12, Article 12.2.

In the design stage, for the following frequency ratios it is assumed that resonance will not occur:

a) In the region of the first three modes of vibration:

$$f_n / f_{err} \leq 0{,}7 \; ; \qquad 1{,}3 \leq f_n / f_{err},$$

where:

f_n	Eigenvalues of a given mode, n = 1, 2, 3. [Hz]
f_{err}	Exciting frequency [Hz]

b) In the region of higher vibration modes under the action of high frequency exciting vibrations:

$$f_n/f_{err} \leq 0{,}9 \; ; \qquad 1{,}1 \leq f_n/f_{err} \; ,$$

where f_n Eigenvalues of high frequency vibration modes.

Finland:

No answer

France:

Nothing in the French code RCC-M, the French design standard.

Germany:

According to KTA 3201, Part 2, Section 7.8, a fatigue analysis shall be made depending on the type of component (DN > 50) to avoid fatigue failure due to cyclic loading. The bases for fatigue evaluation are the design fatigue curves based on tests carried out in ambient air. Permitted fatigue analysis methods include simplified fatigue evaluation (clause 7.8.2), elastic fatigue analysis (clause 7.8.3), simplified elastic-plastic fatigue analysis (clause 7.8.4) and general elastic-plastic fatigue analysis.

Specific requirements for a fatigue analysis of piping systems (including DN ≤ 50 piping) are defined in section 8.4 and may be used in lieu of the analysis methods dealt with in clauses 7.8.3 and 7.8.4.

India:

During design stage, the first few modes of piping vibration for important piping systems (as calculated from detailed Eigen mode analysis) are checked for possible resonance with connected rotating/reciprocating equipment to preclude the chances of excitation and subsequent resonance from these sources.

Japan:

In the NRA Ordinance on Technical Standards for Commercial Power Reactors Facilities, article 19 "Prevention of damage due to flow-induced vibration, etc." stipulates:

> Fuel assemblies, reflectors, core support structures and thermal shields, as well as the vessels, pipes, pumps and valves relating to the primary cooling system shall be constructed in such a way that they are not damaged by flow-induced vibration resulting from circulation, boiling or other behaviour of the primary coolant or secondary coolant, or by temperature fluctuations resulting from the mixing of fluids with different temperatures or other behaviour of the primary coolant or secondary coolant.

According to the Regulatory Guide of NRA Ordinance on Technical Standards for Commercial Power Reactor Facilities that describes the interpretation of the above ordinance, the following analysis methods must be applied:

- PVB-3600 in JSME S NC1-2005 or 2012 "Code for nuclear power generation facilities –Rules on design and construction for nuclear power plants-" for bending area of steam generator tubing;
- JSME S012 "Guideline for evaluation of flow-induced vibration of a cylindrical structure in a pipe";
- JSME S017 "Guideline for evaluation of high-cycle thermal fatigue of a pipe".

Korea:

General requirements: ASME Boiler and Pressure Vessel Code Section III NX-3622.3 Piping shall be arranged and supported so that vibration will be minimised. The designer shall be responsible, by design and by observation under start-up or initial service conditions, for ensuring that vibration of piping systems is within acceptable levels.

In general, piping systems are not analysed for steady-state vibration loads. However, portions of the CV (chemical volume control) system piping are known to be subject to pressure pulsation loads as defined in the CV system Piping System Design Specification (PSDS), which will be accounted for during design phase.

The frequency and amplitude of the pressure pulse due to the auxiliary charging pump operation is defined in the technical specifications for CV system and CV system PSDS.

Piping is analysed for steady-state vibration loads using the stress analysis programme.

Netherlands:

There is one nuclear power plant in operation in the Netherlands. This is the Siemens/KWU PWR type Borssele Nuclear Power Station (KCB). Borssele Nuclear Power Station has no (specific) requirements regarding vibration measurements of piping. Borssele Nuclear Power Station has requirements and uses guides for vibration monitoring of certain rotating equipment.

For nuclear safety-relevant piping, a German (KWU) standard is used: *Verlegerichtlinie*. Based on the loading (including earthquake loading) this guide gives requirements for the maximum distance between supports.

The Netherlands uses as specific standards: ISO 7919-2 and 10816-1, -2, -3 and -7 for rotating equipment.

Sweden:

The Swedish Radiation Safety Authority (SSM) has no specific regulations for vibration analysis in piping systems. Design limits for operation vibrations are addressed in the basic provisions stated in SSMFS 2008:13, Chapter 2, Section 1: "In order to be commissioned, a mechanical component must have been designed, manufactured, installed and inspected so as to maintain safety in connection with all events up to and including the event class 'unlikely events'."

Also, according to SSMFS 2008:13, Chapter 3, Section 3: "Components deemed as potentially being exposed to damaging vibration loads should be suitably monitored in order to check that these loads do not reach levels posing a risk of rapid fatigue crack growth."

Switzerland:

General ASME requirements are applied. Components must meet the stress and fatigue limits of ASME BPVC Section III.

Analysis of answers to question 1

- Belgium, Germany, Japan, Korea, the Netherlands, Sweden and Switzerland indicate only the general requirements on vibrations in accord with used national or international standards.
- Japan, Korea, Germany and Sweden indicate additional documents to the standard with requirements on the stress analysis of operational vibrations.
- France does not indicate any requirements.
- The Czech Republic and India indicate standard requirements in design stage of piping systems on vibration analysis on the base of the known excitation and Eigen frequency.

Question 2:

Do you have any requirements on vibration analysis of piping systems in pre-service (trial) operation stage in your design standard?

Answers of participating countries:

Belgium:

Yes. These are part of the same requirements for the analysis (implementation of adequate pipe supports) at the design stage. See the answer to question 1.

Czech Republic:

Yes, the Czech national standard NTD A.S.I. Section III, Design, Chapter 12, Article 12.3. pre-service and in-service includes the following requirements:

- An investigation should be carried out of the vibration effects caused by changes from design during assembly or from the identification of previously unknown exciting forces.
- For quantitative vibration assessment, the following parameters are used: stress, acceleration, velocity and displacement. The vibration parameters should be determined both for nominal or for transient modes, including start-up and shutdown of the unit.
- Places of measurement are chosen on the basis of a preliminary theoretical analysis of the vibrations of equipment, piping and their supports.
- By using quantitative vibrations data, it is necessary to show that parts of the equipment, piping and their supports will not be working in modes with impulse vibrations and with increased wear due to vibration.
- For the elimination of modes with impulse vibrations of structural components of a single type united into groups, the following condition must be fulfilled:
  - $A < 0.5\ (l - d)$
- For arbitrary components located at a distance L, the condition of analogy in shape is used:
  - $|a1| + |a2| < L$,
- where

A:	maximum amplitude of displacement in vibration mode, mm,
d:	part dimension, mm,
L:	distance, mm,
l:	motion with largest displacement d, mm,
a1, a2:	shift amplitudes of corresponding vibrating components.

- In the verification strength analysis of cyclic loading taking account of vibrations, real parameters of vibration are determined, including the basic spectrum frequencies and characterisation of the vibration process.
- For the measurement and recording of vibration analysis parameters, it is necessary to use measuring devices with a maximum frequency in the working range of 12 kHz. It is recommended to use measuring devices with maximum tolerance of up to ±5%. When devices with higher tolerance are used, it is necessary to add the tolerance to the measured value.

Finland:

In the context of commissioning, power up-rates and other major modifications, a pre-operational and initial start-up vibration testing programme shall be conducted. General requirements are given in the new regulatory guide YVL E.4. ASME OM Code-1998 Part 3 has been the reference standard for the primary circuit, and currently VDI 3842 is increasingly applied to other important piping.

The regulatory authority STUK and authorised inspecting organisations oversee these activities and ascertain that adequate attention is given to piping vibrations. Enhanced inspections and measurements have been required as necessary.

France:

EDF uses a technical guide called GT n°36

Germany:

According to KTA 3201, Part 4, Section 9.2:

> …the vibration behaviour of the components of the primary coolant system shall be measured during the first commissioning of the plant. This shall also consider representative small lines. The results shall be evaluated with regard to the analysis of cyclic strength and shall be used as comparative basis for operational vibration monitoring. In case of a series of plants with the same design, a reduced measurement programme is allowed for the follow-up plants compared to the first plant of this series.
>
> The instrumentation for measuring the vibrations during commissioning should be chosen such that these measurements can also be performed during operation of the nuclear power plant. The decision shall be made whether or not vibration monitoring is required during plant operation, taking into consideration the results of the vibration measurements during commissioning in conjunction with a substantiation based on calculation as well as operational experience gained with comparable plants.

India:

During the pre-service and trial operation stage, vibrations of important (safety-related) piping systems are measured and evaluated with acceptance standards and values. For this, the piping vibration velocities are compared with the acceptable value obtained as per the ASME/ANSI OM standard.

Japan:

Yes. The requirements described in the answer to Question 1 are also applicable to pre-service (trial) operation stage.

Korea:

Piping systems are analysed for steady-state vibration loads if the measured maximum displacement exceeds the acceptance criteria (quoted in ASME OM Part 3) during start-up of the plant.

Commissioning requirements: (US NRC RG 1.68)

The integrity verification test of piping systems in nuclear power plants, also referred to as piping verification test (PVT), is a series of tests that checks the movement of the piping system to ensure it behaves as designed during hot functional and power ascension tests in initial tests. In other words, the piping verification test verifies the adequacy of safety-related and important piping systems by confirming the compliance of the installed condition of the piping and pipe supports with design, and by checking measured pipe movement due to vibration and thermal expansion against allowable design limits.

Netherlands:

No answer

Sweden:

See answer to Q1.

Switzerland:

No specific requirements

Analysis of answers to question 2

- Belgium, Japan and Sweden do not have any requirements on vibration analysis during the first period of plant operation. The countries indicate the same general requirements on vibration as for design of piping systems.
- Korea indicates the application of US NRC RG 1.68 requirements for the first period of plant operation and the use of ASME OM Part 3 criteria on vibrations.
- The Czech Republic, Finland, Germany and India indicate standard or guide requirements on vibration analysis during plant trial operation.
- France and Switzerland do not indicate any requirements.

5.2. Answers to questions related to monitoring vibration

Question 3:

Have you recorded an unscheduled shutdown of units due to operating vibration in your country during the last ten years?

Answers of participating countries:

Belgium:

Yes. Here are some examples:

- In 2014, in Doel 3, high vibrations in a small piping led to its rupture. The piping support was not adequate. Note that the incident occurred during shutdown of the unit, so this incident did not lead to an unscheduled shutdown.
- In 2016, in Doel 3, vibrations in two small pipes for I&C (tubing) connected to the feedwater system led to some damage on the pipes, and the two pipes ruptured during a transient probably due to a water hammer effect. This incident was concurrent with an unscheduled shutdown, without being its cause. The piping supports were not adequate.

Czech Republic:

Yes, shutdowns of units and the reason for shutdowns of nuclear power plants were recorded in the Czech Republic.

Both power plants (Temelín and Dukovany) were shut down due to higher operating vibrations in the turbine bearings after blade modernisation. The units were shut down due to increased vibration of the turbine oil coolant pipe of bearings too.

Outside, failures of piping hangers were detected several times in the period 2012 to 2015. The failures occurred during shutdown of the units, so they did not lead to an unscheduled shutdown.

Vortex shading with combination acoustic resonance was detected on the main steam line in the safety valve area.

Finland:

No answer

France:

There was no shutdown strictly due to vibration but a few shutdowns appeared due to leakages caused by vibration fatigue.

Germany:

One unscheduled unit shutdown was registered in Germany during the stated period. The affected unit was a PWR. The unscheduled shutdown was triggered by a rupture of a DN15 relief line in the residual heat removal system due to operating vibration.

India:

In Indian pressurised heavy-water reactors (PHWRs), no unplanned shutdown of units was encountered in the last ten years specifically due to vibrations.

Japan:

No such event has been reported to the regulatory authority.

Korea:

Yes, shutdowns of Kori 3, 4 nuclear power reactors were recorded.

Both power plants were shut down manually due to high-cycle fatigue failure of small bore socket welded pipe joints of steam generator drain line.

Netherlands:

No answer

Sweden:

Yes, but SSM do not know the number of shutdowns. Shutdowns were caused, for example, by vibrations in the main steam lines (due to modernisation and power uprate) and vibrations in turbine systems (due to turbine exchange).

Switzerland:

- Operating vibration in non-safety-related fluid systems occurred during the commissioning of a new generator and restart was delayed.
- Vibrations at a drain nozzle in the PWR system induced an unscheduled shutdown of a PWR plant during emergency supply tests.

Analysis of answers to question 3

- All countries, except India, indicate problems with piping vibration, usually on small diameter. The problem of operating vibrations in piping systems is a frequent issue at power plants that needs to be regularly monitored and analysed.

Question 4:

Did you solve the issue of operating vibration on fluid piping systems in your country during the last ten years?

Answers of participating countries:

Belgium:

Vibrational fatigue, see answer to question 5.

Czech Republic:

Yes. It was necessary to solve vibration in main steam lines where vortex shedding with acoustic resonance was detected.

Higher vibrations were detected in active emergency cooling systems. Basic vibration screening criteria had to be determined first (level 1). Consequently, issues were solved in piping systems where vibrations were over the screening criteria. Individual criteria were determined for each piping system that showed vibrations above the screening criteria (level 2) on base of fatigue analysis. Piping systems that had higher vibrations than individual criteria (level 2) were re-designed or reconstructed. Reconstructions included new supports, new anchorage of piping or pumps, new piping geometry (change of nature frequencies), new hangers, etc.

Finland:

No answer

France:

EDF carried out a large campaign of measurements of vibration levels in some parts of fluid piping systems relevant for the safety in order to detect any “abnormal” level of vibrations due to cavitation phenomenon, resonance phenomenon in relation to pumps. When an abnormal level of vibration was monitored, an action was undertaken by EDF to reduce the vibration. Similarly, dye penetrant tests and visual examinations were also performed to check the absence of fatigue-induced cracks.

Germany:

Operating vibration was not a general issue in German nuclear power plants throughout the last ten years. The above-mentioned event (question 3) turned out to be a specific singular problem in the affected unit.

The operating vibration of the affected relief line was caused by chattering of an overflow valve during a test run of the safety injection pump. This led to a vibratory excitation of the relief line resulting in a rupture of the pipe.

It is assumed that the valves ahead of the overflow valves were not closed. It was not explicitly specified in the operating manual that the valve ahead of the overflow valve has to be closed during test run of the safety injection pump. There was only a note that the valves are to be set according to the operating manual when actuating the valves.

Accordingly, the problem was fixed by improving the procedure for the test run of the safety injection pump.

India:

Not encountered during the last ten years.

Japan:

No such event has been reported to the regulatory authority.

Korea:

The failure of small bore socket welded pipe joints of steam generator drain line of Kori3 nuclear power reactor has initiated due to a fabrication defect. Vibrational fatigue is the main failure mechanism for this event.

Netherlands:

No answer

Sweden:

Yes, for example the (acoustic) vibrations in the main steam lines (system 311) were caused by a standing wave in one of the isolation valves. The operator managed to manipulate the flow in such a way that the vibrations stopped.

Switzerland:

a) Reportable vibration events in small-diameter pipes (HPCS) of a BWR were solved. Some pipe sections were replaced and weld design and pipe supports were optimised. Additionally, operational measures were installed (e.g. venting of safety valves). A temporary installed monitoring system confirmed afterwards a significant reduction in pipe vibrations. Later, high vibration levels were observed again during a system test. Further improvements are ongoing.

b) High vibrations in pipes and supports of the PRW system were mitigated by design modification and partly replacement. Some years later, vibrations were observed again. The root cause is highly complex and still not fully understood due to the interaction within the pipe system. After further design modification and replacement of some pipes and supports a significant reduction in pipe vibrations was achieved.

c) High vibrations at components of a check valve were observed and solved by the regular maintenance procedure.

Analysis of answers to question 4

- All countries, except India and Japan, indicate any problems with piping vibration, usually on small diameter piping.
- The Czech Republic and France indicate a significant programme of vibration measurements on piping systems related to safety and measures to reduce the piping vibration.
- Korea indicate a problem with the socket welds of small bore pipes, a common problem in nuclear power plants.

Question 5:

Have you established a periodic operation programme of visual inspections or operational measurements to monitor the development of operational vibration of piping systems over time in units in your country?

Answers of participating countries:

Belgium:

The licensee has established a periodic inspection programme for all Class 1 small bore piping systems with diameter <1" connected to Class 1 large bore circuits (150 items per unit). The inspection frequency is about every ten years in order to detect effects of vibrational fatigue.

The primary piping adjacent to the reactor coolant pump is also subjected to visual inspection.

Following the international return of experience, one-time inspections have been carried out on all Class 1 small pipes of all Belgian nuclear power plants between 1997 and 2006. More recently, following the return of experience in Doel 3, one-time inspections and vibration measurements have been carried out on several (not necessarily Class 1) small pipings of Doel 3 and Doel 4.

Czech Republic:

Regular measurement of operating vibrations in pump bearings for all safety-relevant systems in the inspection programme is carried out. Operating vibrations are measured each time the pumps are switched on. The bearing vibration trend is recorded and evaluated once a year.

Regular measurement of operating vibrations in the inspection programme for safety-relevant piping systems was included (temporarily during vibration solution), where operating vibrations were variables when starting various pumps. Based on a long-term measurement, the pipeline system was re-designed.

Regular measurement of operating vibrations in turbine bearings in the inspection programme was included.

A regular evaluation of RPV vibration was done at the Temelín Nuclear Power Plant. RPV vibrations are measured using four accelerometers located on the RPV top head. Pressure sensors are installed on each cold line and one sensor on the hot leg on unit 2. Pressure pulsations generated by the main circulation pumps and frequencies of the acoustic standing waves in primary circuit have been detected.

However, there is no regular programme to measure operating vibrations or to regularly inspect hangers on piping systems. Usually, vibration control is performed only after the event.

Finland:

No answer

France:

Dye penetrant tests and visual examinations are performed every cycle to check the absence of fatigue-induced cracks on small-diameter piping that present excessive vibration according to the threshold retained.

Germany:

See answer to question 6 below.

India:

There is a well-established online vibration measurement program/system for important components like turbine, generator, primary pumps, moderator pumps, etc. Vibrations are generally measured and transmitted to a central location for logging, annunciating, tripping and trend monitoring. For piping systems, an indirect method of evaluating deterioration due to vibrations is in place through an in-service inspection programme, where the weld joints of important piping systems are examined visually and/or volumetrically at periodic intervals ranging from two years to six years or more, to capture any deleterious effect of vibrations or other degrading mechanisms.

Japan:

There is no regulatory requirement for such monitoring of vibration in piping systems.

Korea:

Licensees have installed on-line vibration monitoring systems on RCP, CCWP, ESWP, MG set, TBN, COP, TBCCWP, BFWP, MFWP, CWP, TBOCWP, IA Comp, etc.

And regular measurement of operating vibrations on pump bearings for all safety-relevant systems in the inspection programme was carried out. Operating vibrations are measured each time the pumps are switched on. The bearing vibration trend is recorded and evaluated.

There is no monitoring requirement for operational vibration of all safety-related piping during normal operation.

Netherlands:

According to the Siemens/KWU piping specifications (RE-L3377), vibration has to be considered in case of load specifications, which include dynamic loading. In the past, this was done for some pipe systems.

The specification also mentions considering vibration or amplitude monitoring for the commissioning of piping systems. This was done for some piping systems.

Borssele Nuclear Power Station performs vibration monitoring on the main steam line to be sure of the adequate performance of the flow metres in this line. This is done for trending purposes.

In recent years, vibration monitoring has been performed on piping parts of the control volume piping to monitor the occurrence of cavitation.

In the internal EPZ Maintenance guideline WNW-UR-007, all rotating equipment >25 kW, besides turbine/generator-set and YD main coolant pumps, that is being monitored is listed. Vibration monitoring is being done according to:

- ISO 7919-2: Turbine/Generator - rotating parts (shafts);
- ISO 10816-2: Turbine/Generator - non-rotating parts (bearing houses);
- ISO 10816-3: Electric motors, fans, gear boxes;
- ISO 10816-7: Pumps;
- The Turbine/Generator has an online monitoring system;
- The other rotating equipment is being monitored in a 4-weekly schedule;
- The seawater pumps are being monitored on a 2-weekly basis, because the impeller of these vertical pumps is deep under water, which complicates the monitoring.

Sweden:

SSM has no specific regulations for periodic inspections of vibrations in piping systems. However, periodic inspections are addressed generally in SSMFS 2008:13, Chapter 3, Section 3, which states that:

> All mechanical components must be continuously checked, examined and monitored to ensure leak tightness and to ensure that no other signs of damaging impact have arisen. Mechanical components assigned to inspection groups A and B must also be subjected to in-service inspections. Components in spaces accessible during operation should normally be visually inspected on a continuous basis, whereas other components and systems should be visually inspected in connection with the regular scheduled outages. Such visual inspections should involve devoting particular attention to components that may have been negatively affected by vibrations.

Pipes and supports are inspected visually during outage. Pipes and supports in inspection groups A and B are also included in periodic inspection programmes. Furthermore, pipe supports (snubbers) in inspection groups A and B are included in periodic testing programmes.

Switzerland:

There are no specific regulations for periodic inspections of vibrations in piping systems. Periodic inspections are addressed generally. The general objective is to prevent or mitigate any relevant vibrations and not to monitor them.

Analysis of answers to question 5

- France indicates penetrant test and visual examinations are carried out at every operation cycle.
- Belgium, the Czech Republic, the Netherlands, Sweden and Switzerland have no specific regulations for periodic inspections of vibrations in piping systems but some of the piping systems or supports are included in regular inspection programmes.
- The Czech Republic, Korea and the Netherlands added regular operating vibration measurements of pump bearings to the periodic inspection programme every time the pumps are switched on. It is one of the most effective measures to reduce potential sources of vibration.
- India notes there is a systematic vibration measurement program/system for important components like turbine, generator, primary pumps, moderator pumps, etc.

Question 6:

Please briefly describe how you monitor the level of vibration of piping systems in units in your country?

Answers of participating countries:

Belgium:

There is no systematic monitoring of vibration in piping systems in Belgian nuclear power plants.

Czech Republic:

Only velocity of vibration is assessed in regular vibration measurements. All vibration limits were determined for velocity of vibration in mm.s-1. Acceleration is used for special measurement only.

The power spectral density is evaluated from measured signals on the RPV and the trends are evaluated.

Finland:

ASME OM Code-1998 Part 3 and VDI 3842 are used. A national standard, PSK 5712 (in Finnish), has been applied to non-nuclear piping. Also, the design rules and stress analyses, conducted as per ASME Section III, RCC-M and others, are effective in limiting vibratory levels in specified transient operating situations (turbine/pump trips, blowdowns, etc.) for which stress limits are designated or the dynamic response must not jeopardise active parts like valves and their actuators. For normal operation, analysis is not feasible since the excitation (turbulence, etc.) is seldom quantitatively known. However, resonances due to coincident natural and rotational frequencies shall be avoided by proper design. This is a regulatory requirement.

The limit for measured velocity is the most well-established since it correlates with bending stresses and often yields the flattest frequency spectrum. Deflection is important in visual monitoring, and acceleration could be useful in transient situations or if the impact on active components has yet to be discovered. For impulse piping, the deflection is often large and easy to observe while attaching or holding measurement instrumentation may be difficult.

The definition shall follow the applicable standard. ASME OM Code-1998 Part 3 presents criteria in terms of peak velocities while VDI 3842 uses the root mean square (RMS). The RMS would be an intrinsic choice for truly random vibration under wide-band excitation (turbulence, etc.) or transient situations where several loading phenomena coincide. In some random (and transient) vibrations the noisy periods are time-wise distinct and then the timing and length of the observation period may be crucial.

France:

There is no continuous monitoring of piping systems.

Germany:

Primary coolant system of PWR:

Vibration is monitored by means of permanently installed vibration sensors. The monitoring aims to detect changes in the vibration behaviour at representative locations of the primary coolant system. The installed system allows for vibration monitoring at any time, but in practice it may be performed discontinuously. The regulations require at least two measurements for each refuelling cycle. One of these measurements is required directly after refuelling and one before the next refuelling, with the plant being in steady-state operation.

BWR piping systems, pressure and activity retaining components of systems outside the primary circuit of PWRs:

Monitoring for vibrations is carried out via plant walk-throughs in regular intervals specified by the operator. This monitoring covers the in-service inspection of small-diameter pipes in the range smaller than or equal to DN 50 not required for the response of safety systems. The scope of the monitoring is to be specified in a unit-specific manner.

In the case of particular occurrences (e.g. damage to pipes on account of vibrations) as well as in the case of new knowledge gained, special instrumentation (e.g. measuring vibrations or strains) and monitoring of the individual measurement parameters are required.

India:

Piping vibrations are measured in important piping systems during the pre-operational stage at specific points of piping (away from supports) where amplification is expected. The parameter recorded is vibration velocity (mm/sec, 0 to peak or peak to peak or the RMS, depending on the instrument's available feature). This measurement is done using a hand-held vibration meter, duly calibrated. The measured values are evaluated with acceptance standards/values obtained as per the ASME/ANSI OM standard.

Japan:

There is no regulatory requirement for such monitoring of vibration in piping systems.

In the case of an electric utility:

Periodic monitors of the vibration model are not performed for piping; however, temporal monitors have been performed in order to identify the source of the vibration due to crack occurrence in small-diameter piping.

Korea:

An allowable vibration displacement limit formula is quoted in ASME OM Part 3, vibration testing of piping systems. Displacements of piping for steady-state vibration are measured by a vibration meter or accelerometer. Dynamic responses are monitored for transient vibration by VT.

Netherlands:

For surveillance purposes, the vibration analysis of safety-relevant pumps is performed in accordance with the ASME OM code.

This is described in the specific guideline. KCB uses displacement for rotors (turbine/generator and shaft main coolant pump).

For other components, velocity is used (ISO 10186 alarm levels only use velocity). Acceleration is used in monitoring and analyses but not for alarm level.

Sweden:

No answer

Switzerland:

If necessary, velocities are measured and recorded, but other methods can also be applied.

Analysis of answers to question 6

- India uses the velocity measurement (mm/sec) 0 to peak or peak to peak or the RMS, depending on the instrument availability.
- The Czech Republic and Switzerland prefer velocity measurement but measurement of other variables (displacement or acceleration) can be applied in special cases.
- Finland and the Netherlands use all three variables (velocity, displacement and acceleration). The measured value is given by measurement on a specific equipment.
- Belgium and Finland use two standards (ASME OM-3 and VDI-3842) to determine vibration criteria.
- Korea uses ASME OM Part 3; OM lists the limits for all three variables – displacement, velocity and acceleration.

Question 7:

Have you established screening criteria for a safe level of operational vibration when there is no need to perform any action on the piping systems in your country?

Answers of participating countries:

Belgium:

There is a procedure based on acceptance criteria (sources of criteria e.g. ASME OM-3 or VDI-3842) depending on the pipe material, considering a limitation of the peak speed due to vibrations measured on pipe systems.

Czech Republic:

There are two safety screening criteria: 12 mm/s for seismic piping systems and 9 mm/s for non-seismic piping systems. Both values are the RMS.

Operating vibrations begin to resolve if the measured velocity values exceed screening criteria.

Finland:

ASME OM Code-1998 Part 3 and VDI 3842 give applicable vibration limits. Using ASME OM principles, even project-specific limits have been derived by means of modal analysis techniques. These rely on the correlation between the observed vibration level and the induced bending stresses, for which the limiting value follows from fatigue analysis in terms of the number of cycles.

An alternative approach, specific to the German Break preclusion approach, has been suggested in the ongoing EPR construction project (Olkiluoto 3), where only the relative changes in vibratory and static displacement behaviour would be used as an early warning of incipient failures in the primary circuit. So far, it is believed that the absolute vibration level should also be observed based on criteria set for the components' integrity and operability.

ASME OM Code-1998 Part 3 presents a clear grouping, from one through three, for applicable vibration monitoring methods and criteria. In group 2, a simple velocity criterion may be established, 12.5 mm/s being a conservative rule of thumb for most piping, while in group 3, a qualified inspector's visual observation may be enough. In group 1, higher screening criteria can be demonstrated by means of stress analysis. The presence of mass and stress concentrations generally lower the criteria while, for long straight pipe spans, several tens of millimetres per second could be justified.

In projects, general screening criteria have also been presented in case of VDI 3842 application. Its criteria are frequency-dependent, e.g. 40 mm/s would still be allowable for a typical frequency of 20 Hz.

France:

An RMS velocity threshold of 12 mm/s was set. The theoretical basis of this criterion is the same as that of ASME ANSI-OM3, but the criterion was established considering different input data.

Germany:

The decision whether or not vibration monitoring is required during plant operation shall be made by taking into consideration the results of the vibration measurements during commissioning in conjunction with a substantiation based on calculation as well as operational experience gained with comparable plants (see question 2).

During operation, changes in the vibration behaviour may cause changes in the monitored features (e.g. peak frequency, peak amplitude or peak shape). Attention thresholds are defined for the relevant monitored features based on the experience of other comparable units, structural dynamic calculations and experimental analyses. If the attention thresholds are exceeded, further action is required.

India:

Yes, a vibration screening criterion exists based on the acceptable value obtained as per the ASME/ANSI OM standard. A value of 12.5 mm/sec (0 to peak) is considered a screening velocity below which no corrective action or further action needs to be taken.

Japan:

No screening criteria has been established at the NRA.

In the case of an electric utility:

Periodic monitoring of the vibration model is not performed for piping.

Korea:

The allowable vibration displacement limit formula that is used is quoted in ASME OM Part 3, vibration testing of piping systems. Since the parameters of the formula are different for each measurement position, the allowable vibration displacement limit varies depending on the measurement position.

It also depends on the type of piping materials. Generally, the limits are 22 mm/s for stainless steel pipes and 12.7 mm/s for CS pipes according to ASME OM Part 3.

Netherlands:

KCB has design limits for operation vibration of certain rotating equipment. Monitoring of rotating equipment RMS, 0 to peak and peak to peak is used for vibration. All three are used to be able to detect early damage in bearings or gears. An example of limits and criteria for pumps can be found in ISO 10816-3/7.

For the turbine/generator the limits are mentioned in ISO 7919-2 and 10816-2.

In the guidelines, displacement is mentioned in peak to peak, velocity in RMS. For analyses, all three parameters are used. For example, the 0 to peak/RMS (CREST factor) is used as an early warning for upcoming bearing damage without increase of the RMS.

Sweden:

SSM has no established screening criteria in the provisions. The Swedish philosophy is that vibrations can be neglected if the value of KI is smaller than the threshold value ΔK_{th}.

Furthermore, the operators have used a screening criteria of 15 mm/s (0-peak) for stainless steel (SS) and 10 mm/s (0-peak) for carbon steel (CS) in Swedish BWRs. These criteria were considered to give an adequate margin to fatigue damage and were based on mechanical and dynamic analyses. Moreover, 15 mm/s for SS and 10 mm/s for CS are close to the screening criteria in ASME OM-S/G (0.5 IPS = 12.5 mm) that is practised today.

If the screening criteria or ΔK_{th} is exceeded, actions are required. These actions include installation of dampers, support, etc.

Switzerland:

According to Swiss regulatory guideline ENSI-B01, components must be considered fatigue relevant, if they are affected by elevated stress levels induced by vibrations. There are no general screening criteria defined by the regulator.

ASME OM, Div. 2, Part 3 (12.7 mm/s) can be used for the acceptance criteria. In one case, German guideline VDI-3842 was applied.

Analysis of answers to question 7

- All indicated threshold values are for velocity.
- Finland, India, Korea and Switzerland use ASME OM Part 3. It means the screening criteria are peak values. The used screening peak threshold value is 12.5 mm/s.
- Sweden indicates screening criteria similar to ASME OM Part 3 and uses peak values, too. For stainless steels, the peak value 15 mm/s is used, for CSs 10 mm/s is used.
- Korea has peak values of 22 mm/s for stainless steels pipes and 12.7 mm/s for CS pipes.
- France indicates an RMS threshold value of 12 mm/s.
- Belgium compares the results of vibration measurements with acceptance criteria (e.g. in ASME OM Part3 or in VDI-3842) for different materials.
- The Czech Republic uses RMS velocity threshold values developed on the base stress and fatigue analysis: 12 mm/s for seismic piping systems and 9 mm/s for non-seismic piping systems.
- Japan does not have screening criteria in the regulation.
- There is a divergence between used threshed values (RMS/peak). It is a topic for discussion.

Question 8:

Have you installed any monitoring system for operational vibration measurement on any piping systems or other component in your country?

Answers of participating countries:

Belgium:

A monitoring system has been installed in the reactor coolant pump. Following experience at Doel 3, one-time inspections and vibration measurements have also been carried out on several (not necessarily Class 1) small piping (≤ 1") at Doel 3 and Doel 4.

Czech Republic:

Diagnostic monitoring vibration systems were installed during the construction of the Temelín Nuclear Power Plant:

- RPV (four sensors on plate cover).
- All reactor coolant pump (RCP) - three sensors on the shaft.
- Three sensors on the feed water system distribution inside steam generator (SG) (on one SG only).
- Four sensors on each SG for acoustic emission (sensors can be re-designed to vibration measurement).
- Each main steam line and feed water line has two acoustic emission sensors.

- Main coolant piping system has monitoring of free particles.
- Sensors of the pressure pulsations generated by the main circulation pumps on each cold leg (four sensors) and one sensor on the hot leg of the power plant.

Monitoring systems during the resolution of vibration issues:

- Twenty strain gauges were installed on the main steam line for continual vibration measurement. Measurement was five years in operation.
- Accelerometers were installed for turbine bearings (two years in operation).
- Tip Timing diagnostic monitoring system for turbine blade vibration measurement was installed (in-service).

Finland:

In Finnish regulatory practice, the primary circuit shall be provided with permanent (continuous) vibration monitoring systems. For other important systems, vibrations are regularly observed during in-service testing and other operational surveillance according to the licensee's plant procedures.

The inspections and measurements under item 1 are expected to encompass safety-related impulse piping. Already in the regulatory review and inspections of design and commissioning, considerable attention is given to adequate support and avoiding transfer of resonant vibrations from adjoining components or common supports. For non-accessible components, visual monitoring by TV cameras has proved efficient and sometimes caused a forced outage to undertake the corrective actions needed.

France:

A system monitors vibrations in reactor coolant pumps.

Germany:

In all German PWRs, the vibration behaviour of the primary coolant circuit is monitored by means of a permanently installed vibration monitoring system, which meets the requirements of DIN 25475-2. Accordingly:

- Absolute motion of the RPV is monitored via four seismic vibration sensors that are distributed uniformly on the circumference of the RPV closure head flange.
- Motion of the main coolant lines relative to the containment is monitored by means of inductive displacement sensors that are installed at the elbows at the suction side of the main coolant pumps (eight sensors) and between the RPV and SG (eight sensors).
- Pressure fluctuations of the primary coolant are monitored by means of piezoelectric pressure sensors in four inlet lines (cold leg) and one discharge line (hot leg).

Partially, a shaft vibration measurement for the main coolant pumps was included in the monitoring programme. For this purpose, two shaft vibration pick-ups were installed above the shaft seal casing to detect the vibration behaviour of the shaft relative to the casing.

India:

On-line piping vibration system has not been installed in the country's units. However, there is a well-established online vibration measurement programme/system for important components like turbine, generator, primary pumps and moderator pumps.

Japan:

It depends on the utility since there is no regulatory requirement for such monitoring systems.

In the case of an electric utility:

Periodic monitoring of the vibration model is not performed for piping. For rotating equipment such as pumps or fans, condition monitoring including vibration measurements is periodically conducted using a portable measuring instrument. Online vibration measurements are also conducted for major components such as primary loop recirculation (PLR) pumps, main turbines or feedwater/condensate pumps, for which both vibration velocity and acceleration are measured along three dimensions. Installation areas are determined in response to the structures of components. Screening criteria are determined in reference to ISO 10816-1, 10816-3, 7919-1, etc.

Korea: Vibration monitoring systems were installed for rotating machines during nuclear power plant construction. Vibration monitoring systems were also installed to solve vibration issues.

There is no monitoring requirement for operational vibration of all safety-related piping. The piping system is monitored if there are problems or operating experiences.

Netherlands:

Yes, as identified in the Dutch nuclear safety guideline NVR-NS-G-2.6, paragraph 9.18:

> "surveillance of other items
>
> 9.18. Other items that should be subject to surveillance are those that, if they were to fail, would be likely to give rise to or contribute to unsafe conditions or accident conditions.
>
> - high energy piping and associated piping restraints;
> - structural supports (stack stay wires, pipe supports)."

For hangers and supports of high energy piping systems, Borssele Nuclear Power Station has a periodic inspection programme.

Borssele Nuclear Power Station performs vibration monitoring on the main steam line to be sure of the adequate performance of the flow meters in this line. This is done for trending purposes.

In recent years, vibration monitoring is performed on piping parts of the control volume piping to monitor the occurrence of cavitation.

In the internal EPZ Maintenance guideline WNW-UR-007 all rotating equipment >25 kW, besides turbine/generator-set and (YD-system) main coolant pumps, are listed as being monitored.

Sweden:

Yes, some operators have systems (e.g. Vibroview) to monitor vibrations in real time. Systems and components known to have "problems" with vibrations (e.g. 311, 313, pumps) are usually equipped with accelerometers and strain gauges.

Switzerland:

In one PWR plant a permanent vibration monitoring system is installed at the primary loop; in other plants no regular monitoring systems are applied.

Vibration monitoring systems were temporarily installed at several pipe systems in order to prove the benefit of a performed design modification or for root cause analysis.

Analysis of answers to question 8

- All participants report the installation of vibration measurements on the primary coolant pumps.
- Most participants report the installation of vibration measurements on rotating machines and pumps.
- The Czech Republic, Finland and Germany have the same vibration diagnostic system on the RPV and primary loops.

Question 9:

Were requirements for periodic inspection of vibration in piping systems or other components issued by the regulator authority in your country?

Answers of participating countries:

Belgium:

No.

Czech Republic:

No.

Finland:

YVL guides contain general requirements about the vibration activities. Also, these activities and the applicable requirements and plant procedures are reviewed by STUK and the authorised inspecting organisation as required.

France:

EDF uses a technical guide for vibration tests on safety-relevant pumps, the so-called GT32.

Germany:

Yes, appropriate requirements were issued in the "Safety Requirements for Nuclear Power Plants". Beside this regulation issued by the authority, the KTA safety standards KTA 3201.4, KTA 3211.4 and KTA 3204 contain more specific requirements. Although the KTA safety standards are not legally binding, their development process and level of detail mean they have an extensive effect in practice.

India:

No.

Japan:

No.

Korea:

No.

Netherlands:

The previously mentioned guide (NVR-NS-G-2.16) is part of the licence of Borssele Nuclear Power Station. The regulator is currently developing a new regulation for a new build of nuclear power plants, the so-called Dutch safety requirements (DSR). The DSR also addresses the topic of vibrations.

Sweden:

SSM has no specific regulations for periodic inspections of vibrations in piping systems. However, periodic inspections are addressed generally in SSMFS 2008:13, 3 Chapter Section 3. See question 5.

Switzerland:

No.

Analysis of answers to question 9

- Only Finland, Germany, the Netherlands and Sweden indicate regulatory authority documents with general requirements on vibration issue.
- Other countries do not have any regulatory authority documents on vibration issues.

5.3. Answers to questions related to RPV vibration issue

Question 10:

Did you solve the issue of operational vibration of the reactor internals or vibration of fuel in your country?

Answers of participating countries:

Belgium:

Yes. Baffle jetting occurred in Tihange 1. The issue was solved by performing an up flow conversion, which reduces the pressure differential.

Czech Republic:

Yes, operating vibrations were solved during the trial operation and during the first operational campaigns using new fuel on Temelín Nuclear Power Plant. Individual measured frequencies were identified and the success of corrective actions was evaluated. Corrective actions were done on RPV internals.

This problem no longer occurs.

Finland:

No answer

France:

No.

Germany:

Operational vibration of fuel elements was/is not a generic issue in German nuclear power plants.

Operational vibration was a direct cause of minor incidents involving spacer-edge fretting and edge-rod fretting observed in German PWRs. However, the root cause of these events was excessive bowing of the affected fuel elements. Remedial measures included a design change of the affected fuel element types with the aim to increase the lateral stiffness and enlarging the sliding surfaces of the spacer edges.

For RPV internals it shall be proved during the construction phase that they are capable of withstanding the permanent or temporary vibration loadings during the reactor service life (see KTA 3204). Acceptability of operational vibrations may be demonstrated by experimental measures or via an appropriate stress analysis. Throughout the last 20 years no systematic failures of reactor internals were observed. The root causes of isolated events involving operational vibration were fixed by appropriate measures.

India:

As most of the units are of PHWR type, no issues related to vibration of reactor internals have been encountered in the last decade.

Japan:

A. Reactor internals

Events for reactor internals are as follows:

- Dropout of high pressure core spray sparger nozzle at Shimane unit 2, March 2006.
- Rupture and crack of jet pump sensing line tube at Tokai-Daini, November 2006.
- Crack in the steam dryer at Tokai-Daini, September 2009.
- Crack for steam dryer at Tsuruga unit 1, October 2009.
- Rupture of jet pump sensing line tube at Kashiwazaki-Kariwa unit 2, March 2010.
- Rupture of in-core temperature measurement conduit tube at Tomari unit 3, 2012.
- Rupture of in-core temperature measurement conduit tube at Turuga unit 2, 2014.
- Deformation and rupture of moisture separator anti-vibration bar at Hamaoka unit 3, November 2014.

The causes of these events were related to factors including crack initiation and development due to flow vibration, high-cycle fatigue and vibration induced during water jet peening work. To prevent the recurrence of such events, it was decided where appropriate to:

- fix such parts with a mechanical clamp to prevent resonance due to its character frequency;

- revise related manuals to add parameters to be confirmed during pump operation;
- remove such cracks and conduct repairs to reduce stress concentration;
- evaluate the effects of small cracks on the function and structural integrity of such components to make a judgement of continued service;
- apply pipe sleeve repairs to such parts or install rupture protection reinforcement devices;
- add support devices to improve stiffness property for such piping;
- conduct fatigue evaluation of adjacent pipes and pipes similar to the affected pipe to confirm structural integrity;
- not restore the affected portion into service.

B. Fuel assemblies and fuel rods

The following events regarding fuel assemblies and fuel rods were experienced;

- fuel rod clad damage involving foreign materials in Kashiwazaki-Kariwa unit 7, July 2009;
- fuel rod clad fretting damage involving foreign materials in Kashiwazaki-Kariwa unit 7, September 2010.

The possible cause of these events was considered to be debris fretting that vibration of foreign materials captured inside fuel assembly, induced by coolant flow; it contributed to damage of fuel clad surrounding the foreign materials and a pinhole was induced.

As the countermeasures for these events, replacement to a new type of fuel assembly with foreign material filter were conducted. Furthermore, as countermeasures for reduction of leaked fuel due to foreign materials, various measures were applied to prevent foreign materials from getting trapped in fuel assemblies, including cleaning inside the reactor and prohibiting the use of wire-brush and wire-buff inside controlled areas.

Korea:

Yes, there were fuel failures due to fuel assembly vibration many years ago. The issue was resolved by replacing the failed fuel assemblies with new fuel assemblies. This issue no longer occurs.

Netherlands:

No answer

Sweden:

No answer

Switzerland:

The Swiss regulation (ENSI directive G-20) demands that hydraulic-induced vibrations be minimised for the reactor core. Cyclical loads have to be limited to prevent fatigue-induced failures of fuel and control assemblies. Corresponding verifications have to be provided when a new fuel or control assembly type is introduced.

Vibration-induced fuel failures have not been detected in Swiss plants during recent years.

To prevent fuel failures by baffle jetting, the baffle bolts that fix the baffle plates were replaced as a precaution in a Swiss PWR in 2010. The reason was the discovery of degradations in foreign plants.

Analysis of answers to question 10

- The Czech Republic, Germany and Korea have experience with vibration of fuel elements from the first campaigns of nuclear power plant operation. Operational vibration of fuel elements is not a current issue in these countries.
- Belgium and Switzerland have experience with baffle jetting. During baffle jetting, part of coolant bypass flow is directed through of the baffle gaps towards the core. The baffle gaps are opened due to vibration in the core.
- Japan indicates many vibration issues on the RPV. Japan have significant experience with this issue.

Question 11:

Is a diagnostic system for vibration measurement of the RPV and connected main cooling piping systems installed on all units in your country?

Answers of participating countries:

Belgium:

No.

Czech Republic:

A vibration monitoring (diagnostic) system was installed at Temelín Nuclear Power Plant (not at Dukovany Nuclear Power Station), comprising:

- RPV (four sensors on plate cover);
- four sensors of the pressure pulsations generated by the RCP on each cold leg and one sensor on the hot leg;
- all RCP (three sensors on shaft);
- three sensors on the feed water system distribution inside SG (on one SG only);
- four sensors on each SG for acoustic emission (sensors can be re-designed for vibration measurement).

Each main steam line and feed water line has two acoustic emission sensors.

The main cooling piping system has monitoring of free particles inside the primary pressure circuit.

Finland:

No answer

France:

No.

Germany:

A diagnostic system for vibration measurement in the RPV and the connected main cooling piping system is installed in all German PWR units. A description of this system is given under question 8. Here, the four seismic vibration sensors that are distributed uniformly on the circumference of the RPV closure head flange are of particular importance because they can also detect the vibrations of the reactor internals. The information is obtained indirectly by measuring the vessel movement. With these methods, corresponding variables to be monitored shall be established.

An effective use of this system requires plant-specific reference measurements and a data basis for the assignment of signal components to the vibration behaviour of the monitored components.

According to KTA 3204, at least three measurements shall be performed during each fuel cycle. One of these measurements shall be performed immediately after refuelling and one prior to the next refuelling at steady-state operation of the nuclear facility.

Currently, there is no similar method available for BWRs.

India:

Due to the difference in the design of PHWR units compared to PWRs, the reactor is not a pressure vessel and has very low velocity fluid inside it. There is no online vibration diagnostic system installed on primary piping. But as mentioned earlier, there is an elaborate in-service inspection programme to detect the material degradation due to vibrations or otherwise in primary and other important piping systems during periodic inspections. There is a well-defined in-service inspection (ISI) programme in place for all units, which is reviewed by the regulator.

Japan:

For example, a "predictor monitoring system" with many measurement data, including on vibrations, is installed in some nuclear power plants. However, NRA does not have detailed information since there is no regulatory requirement to install such systems.

Korea:

A vibration monitoring (diagnostic) system was installed on:

- RPV, which has a reactor internal vibration monitoring system (IVMS) utilising neutron flux signals.
- RCP, which has a reactor coolant pump vibration monitoring system (RCPVMS) with proximity probes and accelerometers around RCP shafts.

There is no vibration monitoring system on the SG or the main coolant piping.

However, the NIMS (NSSS Integrity Monitoring System), an integrated system that monitors the NSSS, is installed for:

- loose parts at natural collection zones (four to six sensors on up and down plate of the RPV, two to three sensors on primary and secondary sides plate of each Steam Generator, four sensors on casing plate of four RCPs) using Loose Parts Monitoring System (LPMS);

- coolant steam leakage and piping cracks at potential leak regions (19 sensors on the RPV, RCP, Steam Generator, PZR and RCS pipe) using Acoustic Leak Monitoring System (ALMS);
- vibration of the reactor core (core support barrel, fuel, etc.), with 12 ex-core neutron flux detectors on the RPV, using IVMS;
- reactor coolant pump and motor vibration levels, pump shaft displacement (orbits) and RPM (24 sensors in four RCPs) using Reactor Coolant Pump Vibration Monitoring System (RCPVMS).

Netherlands:

No answer

Sweden:

No answer

Switzerland:

Not in all units.

Analysis of answers to question 11

- The Czech Republic (Temelín Nuclear Power Plant only), Germany and Korea had installed a very complex vibration diagnostic measurement system on the RPV and connected main cooling piping system.
- All participants had installed a vibration diagnostic measurement system on RCP as a minimum.

Question 12:

Has an evaluation been performed of the measured signal of a vibration monitoring system to identify significant peaks in operational spectrum in the RPV and main cooling piping systems in your country?

Answers of participating countries:

Belgium:

No.

Czech Republic:

Yes, it was carried out on Temelín Nuclear Power Plant. Measured frequencies on the RPV cover were identified on base modal analysis of RPV internals, modal analysis of the main cooling piping system, CFD fluid analysis of loops, operating conditions, unit power, settings of valves, etc. Additional measurement of the neutron flux noise has been proposed for identification of frequencies in the RPV.

Finland:

No answer

France:

No.

Germany:

The significant peaks in the operational vibration spectrum of the RPV and main cooling piping system were identified during the initial reference measurement and characterised in terms of peak frequency, peak amplitude and peak shape. This information serves as a basis for the assessment of the vibration behaviour during operation as described in the answer to question 18 below.

After implementation of significant changes to the primary circuit, to the mode of operation of the reactor or changes to the monitoring equipment, a new reference measurement is to be carried out.

India:

Please refer to the reply to question 11 above.

Japan:

It is thought that Japanese utilities conduct detailed evaluations of vibration measurements they carry out. However, the NRA does not have detailed information since there is no regulatory requirement to install such a system.

Korea:

No. However, during the pre-core hot functional test at the construction and commissioning stage, the Comprehensive Vibration Assessment Program (CVAP) according to US NRC Regulatory Guide (USNRC RG) 1.20 is performed and evaluates that there would be no excessive vibration during normal operation.

Furthermore, various analyses and evaluations for alarm discriminations are performed on reference data, all captured and logged when alarms or abnormal signals occur in the four subsystems: LPMS, IVMS, ALMS and RCPVMS in NIMS (NSSS integrity monitoring system).

Netherlands:

No answer

Sweden:

No answer

Switzerland:

The evaluation of monitoring data is based on plant-specific criteria.

Analysis of answers to question 12

- The Czech Republic and Germany report the analysis and identification of resonance peaks in the frequency spectrum during the first operational campaigns.
- Other countries do not present this procedure, but provide the documents requesting this analysis. Thus, this analysis appears to have been carried out in all countries.

Question 13:

Do you use any other sensors for determination of RPV internals or fuel vibration?

Answers of participating countries:

Belgium:

No.

Czech Republic

Yes. Fuel vibrations are additionally diagnosed indirectly by evaluation of the neutron flux noise.

Finland:

No answer

France:

No.

Germany:

RPV internals or fuel vibrations are additionally diagnosed indirectly by evaluation of the neutron flux noise, which is monitored by the ex-core neutron flux detectors. The signals used for monitoring the vibrations are decoupled from the neutron flux measuring system in such a way that the frequency range required for the vibration monitoring is available.

India:

No.

Japan:

As mentioned above, the predictor monitoring system consists of many measurement sensors (pressure, temperature and so on) and their analysis system. However, the NRA does not have detailed information since there is no regulatory requirement to install such a system.

Korea:

Yes, ex-core neutron flux detectors are used to provide signals for reactor IVMS.

Netherlands:

No answer

Sweden:

No answer

Switzerland:

The neutron detector signals can indicate fuel vibrations.

Analysis of answers to question 13

- Neutron flux detectors are used for reactor IVMS by the Czech Republic, Germany, Korea and Switzerland.
- Using neutron flux detectors is a very good practice to monitor RPV internals or fuel vibration.

- Other participants do not know about the performance of this measurement at power stations or the measurement is not performed.

Question 14:

Did you solve the issue of acoustic resonance or flow-induced vibration on any fluid systems in your country?

Answers of participating countries:

Belgium:

No.

Czech Republic:

Yes, it was solved on the main steam pipe in safety s compartment on Temelín Nuclear Power Plant. The same problem was seen in Russia and Ukraine. The vortex shedding in the area of the branches to the SG safety valves created pressure pulsation. The pressure pulsation frequency due to vortex shedding was the same as the wavelength of the pipe to the one safety valve from the main steam line. Soon after the full unit power was reached, there was a near-resonance state at 45 Hz. The problem was solved after changing the piping geometry to the safety valve.

Finland:

No answer

France:

Flow-induced vibration is often due to improper design. Consequently, EDF recently wrote a design guide to avoid excessive vibrations.

Germany:

Acoustic resonance or flow-induced vibration are not and have not been a major issue in German nuclear power plants.

India:

No.

Japan:

Japanese nuclear power plants have some experiences of acoustic resonance or flow-induced vibration, and have solved them by changing the piping geometry and so on. The issues were then incorporated into the regulatory requirements.

Korea:

No.

Netherlands:

No answer

Sweden:

No answer

Switzerland:

So far, acoustic resonance has not been a relevant issue. See other vibration issues discussed above. Acoustic resonance and/or FIV phenomena were potentially involved in some of the issues listed under questions 3 and 4.

Analysis of answers to question 14

- Almost every participant has experience with acoustic resonance or flow-induced vibration in fluid systems.
- Acoustic resonance or flow-induced vibration in fluid systems is a serious problem in power plants.
- It is interesting to note that EDF recently wrote a design guide (internal document) on how to avoid excessive vibrations.

5.4. Answers to special questions related to RPV rod vibration issue

Question 15:

Did you solve the issue of control rod vibration in your country?

Answers of participating countries:

Belgium:

In the Belgian units, control rod vibration is not a significant issue. Wear of control rods and guide cards is followed in-service but no critical issue was detected. Surface hardening has been applied to the control rods. In addition, axial repositioning of the control rods is applied in order to make sure that wear is not always affecting the same location.

For the control rods that are outside the reactor core in normal operation, the extremities are subject to wear due to friction of the vibrating control rods. In some units, this wear has led to penetration of the control rod metal sheet in the area where the absorbing material is situated. In order to solve this issue, long plugs have been installed at the extremities of the control rods in order to make sure that wear does no longer affect the metal sheet but the solid plug only.

Czech Republic.

Control rod vibration is not currently an issue in the Czech Republic.

Finland:

No answer

France:

No.

Germany:

Control rod vibration was/is not an issue in German nuclear power plants.

India:

There was no incident of vibration of control rods reported in reactors as they encounter low flow and low velocities through or across them.

Japan:

Yes. The following events regarding control rods and control rod guide tubes were experienced in Japan:

- wear of control rod cluster guide cards at Tomari unit 1, June 2007;
- wear of control rod cluster guide tube support pin (nut and locking pin) at Tomari unit 1, January 2010;
- wear of control rod clad at Genkai unit 4, September 2010.

The causes of these events were related to small vibrations induced by coolant flow inside the reactors. The event concerning the control rod cluster guide was considered to be caused by wear between the control rod and guide card caused by control rod vibration induced by primary coolant flow in the reactor core.

Regarding countermeasures to prevent the recurrence of these events, the following necessary actions were taken:

- change in designs to improve abrasion resistance and integrity of such components;
- preparation of guidelines and manuals for inspection and maintenance;
- periodical inspections and replacements of such components in a scheduled and preventive manner.

Korea:

Yes.

Problem:

At full power operation, all control rods are in out position except for the power control rod. The rod is worn out because vibration is intensive on the spot of contact with guide card.

Improvement:

The rod position is changed periodically to reduce thinning (axial repositioning), and the power control rod is shuffled radially to disperse thinning at refuelling outage (RFO). Visual tests (every RFO) and ECT (every 3 RFOs) are conducted to check the thinning. The rod is replaced within 10 EFPY.

Netherlands:

No answer

Sweden:

No answer

Switzerland:

There was no such issue in Switzerland in recent years. There are regular inspections of control rods (see question 18).

Analysis of answers to question 15

- Three countries – Belgium, Japan and Korea – reported wearing of control rods due to friction. Improvements are described by these countries.
- Other participants do not have such problems now. Problems with wear have been resolved before.

Question 16:

In what manner was the issue of IRI (Incomplete rod insertion) predicted and solved in your country?

Answers of participating countries:

Belgium:

IRI may be due to deformation of fuel assemblies. In units with long fuel elements this issue is managed through appropriate design of the fuel elements (creep resistant material) and by preferably putting fresh, rigid fuel elements in the central part of the reactor core.

IRI may also be due to swelling of the absorbing material inside the control rods. In the Belgian units, the control rods are subjected to periodic inspections to detect swelling at an early stage in order to avoid IRI. Control rods used for power regulation are more prone to swelling since they are subjected to higher flux and fluence. Therefore, those control rods are only used for a limited number of fuel cycles.

Czech Republic:

Drop test time measurements is performed during each outage. IRI is not currently an issue.

Finland:

No answer

France:

To detect this issue, there are some drop test time measurements performed during outage.

Germany:

The few IRI-events that occurred in German PWRs were not related to vibration effects. Rather, they were caused by excessive bowing of a specific fuel element type characterised by a reduced lateral stiffness. Remedial measures included a design change of the affected fuel element type with the aim to increase the lateral stiffness.

India:

Not reported in reactors.

Japan:

Although the following event is not directly related to IRI, it relates to an incorrect signal of the rod position.

In November 2009, alarms signalled a power supply failure of the control rod drive mechanism (CRDM) as well as a difference between the control rod operation signal and the control rod position at Mihama unit 1. The cause for the event was contact failure due to insufficient insertion of the power cable connector of the CRDM and insufficient tightening of the nut, resulting in the gradual loosening of the nut by vibration, etc. accompanying operation or manipulation of the control rod.

Korea:

No, there was no IRI issue.

Netherlands:

No answer

Sweden:

IRI due to control rod vibrations has not been noted in Sweden. There have been several instances with assembly and box-bending, which also can lead to IRI. On a few occasions, increased control rod insertion times were noted during inspection, but the insertion times were within the limits. In Sweden, thermal hydraulic conditions are usually more demanding than the risk of IRI due to bending.

Switzerland:

There was no IRI issue in Switzerland in recent years. Before the restart after the yearly outage, there are SCRAM time measurements in all plants to prove that the technical specifications are met.

Analysis of answers to question 16

- All participants present drop test time measurements for IRI detection. It is a good practice.
- Belgium, Germany and Japan described the causes of IRI.

Question 17:

Have you diagnosed core barrel oscillations in your country?

Answers of participating countries:

Belgium:

The neutron noise monitoring instrumentation could detect beam mode oscillations of the core barrel.

Czech Republic:

The following criteria have been established for the core barrel vibrations of all operating reactors (440 and 1 000 MW):

- evaluation of the high cyclic fatigue of the core barrel upper flange;
- assessment of the fretting wear in the contact of the lower part of the core basket (CB) and the RPV.

In both cases the lumped mass model of the reactors 440 and 1 000 MW have been developed. The excitation forces are assumed to be the pressure pulsations generated by the main circulation pumps from a blade rotational frequency of 24.8 Hz (VVER440 MW) and 16.667Hz (1 000 MW), respectively.

Finland:

No answer

France:

No.

Germany:

Core barrel oscillations may be diagnosed indirectly by evaluation of the neutron flux noise (monitored by ex-core neutron flux detectors) or absolute motion signals of the RPV. So far, no significant oscillations have been detected.

India:

Not reported in reactors.

Japan:

The NRA does not have information since there is no regulatory requirement to diagnose.

Korea:

Yes, the reactor IVMS utilising neutron flux signals is used to monitor any excessive vibration of reactor internals.

Netherlands:

No answer

Sweden:

No answer

Switzerland:

No, there is no information about such an issue.

Analysis of answers to question 17

- Core barrel oscillations may be diagnosed indirectly by evaluation of the neutron flux noise.
- Core barrel oscillation is not currently an issue in the participating countries.

Question 18:

Do you have any criteria to identify standard (or safe) vibrational behaviour of RPV, internals or fuel?

Answers of participating countries:

Belgium:

No criteria.

Czech Republic:

Yes, the following criteria have been established:

- For the upper flange of the CB, national models calculated the bending moments generated by the main circulation pumps. The criterion is the cumulative usage factor, which must be less than one.
- For the contact of the lower part of the CB and RPV the main designer established allowed values of the gap. The frictional forces between CB and RPV were determined based on experimental measurements. The force measurements were input into our numerical model of the reactor and the mass loss in contact was determined. As a result, the gap between CB and RPV was increased.

Finland:

No answer

France:

No.

Germany:

Based on the reference measurement carried out after the first-time steady-state power operation is reached, unit-specific attention thresholds are defined for the relevant monitored vibration features (e.g. peak frequency, peak amplitude or peak shape) of each component. During operation, changes in the vibration behaviour may cause changes in the monitored vibration features. The acquired data are compared in terms of frequency, peak shape and amplitude with the reference measurement. Deviations may indicate a changed vibration behaviour and thus an incipient damage. If the attention thresholds are exceeded, further action is required (e.g. trend monitoring, specific tests).

India:

Our reactors are not pressure vessels and no vibration problems have been encountered.

Japan:

No criterion has been established at the NRA.

Korea:

Yes, licensees perform the fuel assembly vibration test to get the fuel assembly vibration characteristics. Based on the test results, licensees confirm if there is any fuel assembly vibration.

Netherlands:

No answer

Sweden:

To identify vibrations in fuel, the common procedure is to regularly inspect fuel for signs of grid-to-rod fretting. No instance of any such occurrence has been reported to SSM in the past 20 years.

Switzerland:

When a new fuel or control assembly type is introduced at a Swiss plant, the regulation (ENSI directive G-20) demands the introduction at first of a limited number of lead use assemblies (LUA). During the outages, there are extensive LUA inspections to examine the behaviour according to the design. This includes vibrational issues (e.g. spacer fretting).

The regulation also demands regular inspections of normal reload fuel and control assemblies.

Analysis of answers to question 18

- The precise vibration limit for the RPV, internals or fuel is not stated.

6. Analysis of responses

6.1. Analysis of responses related to design requirements

The national or international standards currently used for nuclear power plants do not specify in any detail the requirements for the evaluation of operational vibrations at the project stage, as was confirmed by the majority of respondents. Only general requirements are implemented in these standards. For this reason, each country using these national or international standards has developed its own additional requirements for in-service vibration assessment. These requirements were created during the operation of power plants based on operating experience with vibrations.

The applied standards do not specify any requirements for the assessment of operating vibrations during trial operation. Also, they do not provide any normative requirements for preventive assessment of vibration during the trial operation and first operation periods.

Usually, there are no detailed requirements for the evaluation of operational vibrations in the national regulations. Therefore, possible requirements for the vibration at the project phase of a nuclear power plant as well as acceptance criteria for vibrations during the trial tests and operation phase of a nuclear power plant should be based on the requirements of the operator with discussions on the responsibilities of the technology supplier. Requirements and limits as well as safety margins for operational vibrations of the operating units are usually based on the lessons learnt on corrective maintenance and operating experiences of similar plant types.

6.2. Analysis of responses related to monitoring vibration

Standards focusing on operating vibrations are limited. However, there are some general standards and guidelines for measures and requirements for avoiding vibration problems. Most respondents report using the criteria listed in these two standards:

- ASME OM-SG-2007 standards and guides for operation and maintenance of nuclear power plants;
- ANSI/ASME Operation and Maintenance Standards/Guides Part-3, 1991, “Preoperational and Initial Startup Testing of Nuclear Power Plant Piping Systems” (OM-3).

Vibration requirements and guidelines are often given in vibration velocity, as vibration energy is closely connected to vibration velocity. All respondents report a speed unit for the vibration criterion. However, at lower frequencies, displacement may be of more interest. At frequencies up to 2-5 Hz, vibration requirements may be given in terms of displacement.

The respondents differ most in their screening vibration criteria. The most commonly used operating vibration criterion, referenced to the above standards, is a peak velocity of 12.7 mm/s. This is the peak, maximum measured velocity value of vibration (0-peak). Sometimes, operational vibration criteria are reported using RMS. Using the crest factor, which is the ratio between the peak and the effective value velocity, the RMS rate limit can be obtained. For pipelines, the crest factor of 3.5 is most often considered, in which case the RMS is approximately 3.6 mm/s. The peak value of 12.7 mm/s is considerably conservative and its application as a screening criterion is practically meaningless in this case. Whether an RMS criterion is exceeded can also be monitored by simple portable hand-held gauges, which are carried by power plant personnel.

However, based on the received answers, it can be assumed that the peak velocity criterion of 12.5 mm/s is, for many of the respondents, very conservative, and it is not used. Many respondents have created their own, less conservative operating vibration criteria, mostly based on the effective RMS vibration value. It seems that the RMS value is more representative than the peak value for steady-state vibration assessment and most of the vibration metres used during visual inspection report velocity in RMS.

The range of installed vibration monitoring systems at power plants varies from country to country. Most respondents have installed operating vibration monitoring systems on main circulation pumps and turbines. The scope of implemented systems at power plants is probably a result of the time of construction of individual power plants. However, some countries have implemented very complex operating vibration monitoring systems on other important components of the primary and secondary circuits.

All the respondents agree on the existence of no supervisory documents with requirements on operating vibrations. The answers of the respondents do not include any documents of the supervisory authorities that would require a regular assessment of operational vibrations during operation. The supervisory authorities do not control this mechanism of damage. It is therefore up to the operator how the vibration mechanism is monitored and evaluated, whether by predictive or corrective maintenance. Regular evaluation of operating vibrations brings many benefits. These include, in particular, increased serviceability, reduced unplanned shutdowns and failures, integrity of pressure equipment, and overall reduction of operational risk of equipment damage.

6.3. Analysis of responses related to RPV vibration issues

All the participating countries had problems with operating vibrations of the internal parts of the RPV. This issue appears to accompany the beginning of operation of each power plant. It has been successfully resolved in each of the surveyed countries during the first operational campaigns and is no longer a problem.

Neutron flux detectors are used in most of the countries surveyed. It appears that their employment as a vibration monitoring system for the inside of RPVs is a good and established practice. This may be very important information for participating countries that have not used the available measurement at this time.

7. Conclusions from the questionnaire

It is possible to draw the following conclusions based on the analysis of the answers to the questions sent to participating countries:

- Operating vibrations of fluid systems and structures are a real problem at nuclear power plants. Vibrations must be given constant attention throughout the operation of the power plant, as the vibration level may change with the operating time.
- Acceptable and clear screening criteria for operating vibrations are essential for the safe operation of power plants. Conservative criteria for vibration make it necessary to take measures even if vibrations do not endanger safe operation. On the other hand, relaxed screening criteria lead to equipment damage and accidents. Based on the experiences of member countries, many vibration issues recognised in early operation phase are avoided with adequate design solutions and with suitable requirements and criteria for trial run tests.
- The biggest differences among the participating countries are in their screening vibration criteria. Most participating countries use the US standard ASME OM Part 3, which prescribes a peak vibration speed of 12.7 mm/s. When comparing these values, the ASME requires an analysis of operational vibrations when the average RMS value reaches 3.6 mm/s (0.14 in/s). This value seems to be very conservative with respect to the real situation in power plants. Some countries using this standard have decided to create their own criteria. This is a point that should be further discussed.
- As a good practice, there is regular measurement of operating vibrations of pump bearings when they are switched on. In particular, this applies to safety-related systems. Incorporating this measurement into the operational control programme significantly improves the safety of pipeline systems that are important for the operation and safe shutdown of units in case of abnormal and emergency conditions.
- Some countries report the implementation of very complex monitoring and diagnostic systems for operating vibrations in the components of the primary circuit. This range of diagnostic systems meets the latest requirements of international agencies. All participating countries describe the implementation of a diagnostic system for the RCP, which can be considered a minimum requirement for diagnostic systems in relation to the vibrations of RPV internals.
- Most participating countries use neutron flux detectors to identify RPV frequency spectra. Using neutron flux detectors is a very good practice for RPV internals or fuel vibration.
- All participating countries consistently state that there is no special requirement of the authority to carry out regular monitoring of operational vibrations during the operation of power plants. There are only general requirements for safe operation in all countries. This is an important finding of the survey.

8. Recommendations

The three following recommendations can be made on the basis of the analysis of the received answers and their assessment.

1. To include in the nuclear power plant standards more detailed industry requirements for the evaluation of operational vibrations in the project phase, for the measurement of operational vibrations during trial (commissioning) operation, and for regular monitoring of vibrations during operation. Evaluating operational vibrations during a project phase will avoid situations in which piping systems or their parts exhibit their natural frequency or one near to the known pump excitation frequencies. Measurement of operating vibrations during trial operation will greatly reduce the risk of damage during later operation. The definition of requirements for vibration analysis will also address the responsibility for operating vibrations at the same time.
2. To incorporate applied and practice-validated screening vibration criteria into applied nuclear power plant standards. It would also be useful to include requirements, procedures and recommendations for the evaluation of operational vibrations measured during operation. Performing basic measurements to verify the level of operating vibrations is highly useful for safe operation.
3. Regular monitoring of operating vibrations with clear and practice-validated vibration screening criteria increases the safety of nuclear power plant operation.

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Annex A

Questionnaire

Evaluation of design and monitoring requirements for vibrations in safety-related fluid systems

Objective

To summarise the design and monitoring requirements of member states and provide recommendations on good practices in managing operational vibration in safety-related fluid systems.

Background

Vibration fatigue is the dominant failure mechanism for safety-related small-diameter (<25…50 mm) and medium-diameter (up to 100…150 mm) piping. The failure of such I&C system piping may cause spurious or false safety signals and result in plant level transients. Excessive vibration is also a potential safety issue for large-diameter piping. Operating experience has indicated that effects of acoustic resonance and flow-induced vibration in fluid systems may have a severe impact on degradation of safety-related systems.

The scope of the questionnaire

Three main topics are considered in the questionnaire:

1.Design requirements: the objective of this part is to collect standard, regulatory or other requirements on vibration analysis and evaluation in the period of design in each country.

2. Operational monitoring requirements: the objective of this part is to collect standard, regulatory or other requirements on periodic vibration monitoring during operation in each country.

3. RPV vibration issues: the objective of this part is to collect information about RPV internal vibration issues and methodologies of solutions for them in each country.

Questions on topics

A) Questions on design requirements

1) Have you any requirements on vibration analysis of piping systems in the design stage in your design standard?

If yes, please briefly describe the methodology of analysis and indicate standard articles.

2) Have you any requirements on vibration analysis of piping systems in the pre-service (trial) operation stage in your design standard?

If yes, please briefly describe the extent of requirements and indicate standard articles.

B) Questions on operational monitoring requirements

3) Have you recorded unscheduled shutdown of units due to operating vibration in your country in the last ten years?

If yes, please specify the number of unit shutdowns and their reasons.

4) Was an issue of operating vibration in any fluid piping system solved in your country in the last ten years?

If yes, please briefly indicate the system(s) and reason(s) for vibration.

5) Have you established a periodic operation programme of visual inspections or operational measurements to monitor the development of operational vibration of piping systems over time in units in your country?

If yes, please briefly describe the operation programme and indicate the period of this programme with respect to safety class or piping system.

6) Please briefly describe how you monitor the level of vibration of piping systems in units in your country.

Please indicate which variable you use to measure vibration (stress, acceleration, velocity or displacement).

7) Have you established screening criteria for a safe level of operational vibration at which there is no need to perform any action on a piping system in your country?

If yes, please indicate the level in your safety screening criteria (including units) and specify whether peak or RMS values are used.

8) Have you installed any monitoring system for operational vibration measurement on any piping system or other component in your country?

If yes, please describe the areas of installation and extent of measurement.

9) Have requirements for periodic inspection of vibration in piping systems or other components been issued by the regulating authority in your country?

If yes, please indicate the document.

C) Questions on RPV vibration issues

10) Has an issue of operational vibration of reactor internals or vibration of fuel been solved in your country?

If yes, please briefly describe this issue.

11) Is a diagnostic system for vibration measurement of the RPV and connected main cooling piping systems installed on all units in your country?

If yes, please briefly describe this system, with the positions of sensors and their limitations, and indicate a period of evaluation of this system.

12) Has there been performed an evaluation of the measured signal of a vibration monitoring system to identify significant peaks in the operational spectrum in the RPV and main cooling piping systems in your country?

If yes, please briefly describe the process.

13) Do you use any other sensors for determination of RPV internals or fuel vibration?

If yes, please briefly describe the system and its sensors, position and period of evaluation.

14) Has an issue of acoustic resonance or flow-induced vibration in any fluid system been solved in your country?

If yes, please describe this issue.

D) Special questions on RPV rod vibration issues

15) Has an issue of control rod vibration been solved in your country?

If yes, please describe this issue.

16) In what manner has the issue of IRI been predicted and solved in your country?

Please describe the issue.

17) Have you diagnosed core barrel oscillations in your country?

If yes, please describe the issue.

18) Do you have any criteria to identify standard (or safe) vibrational behaviour of RPV internals or fuel?

If yes, please briefly describe them.