NENE
International Conference
Nuclear Energy for New Europe

VIBRATION IMPACT IN NUCLEAR POWER GENERATION: GO-VIKING ADVANCEMENTS

Kateryna PILIUHINA, Roberta CIRILLO, Gabriel Lazaro PAVEL
ENEN – EUROPEAN NUCLEAR EDUCATION NETWORK
Rue d'Egmont
1000, Brussels, Belgium
kateryna.piliuhina@enen.eu, roberta.cirillo@enen.eu, gabriel.pavel@enen.eu

Angel PAPUKCHIEV,
GRS gGmbH - GESELLSCHAFT FUR ANLAGEN UND REAKTORSICHERHEIT GGMBH,
Schwertnergasse 1, Koln 50667, Germany
Angel.Papukchiev@grs.de

Kevin ZWIJSEN,
NRG - NUCLEAR RESEARCH AND CONSULTANCY GROUP
Westerduinweg 3, Petten 1755 LE, Netherlands,
zwijsen@nrg.eu

Philippe PLANQUART,
VKI - VON KARMAN INSTITUTE FOR FLUID DYNAMICS,
Chaussee de Waterloo 72, Rhode Saint Genese 1640, Belgium
philippe.planquart@vki.ac.be

ABSTRACT

The integrity of the nuclear steam supply system (NSSS) of a nuclear power plant (NPP) is essential for its safety and operability. Key NSSS components such as fuel assemblies (FA) or steam generator (SG) tubes are subject to several ageing challenges like high multiple corrosion mechanisms, neutron flux (embrittlement), and also long-term vibratory loads. Vibrations induced by coolant flow are particularly important challenges, as they lead to increased wear and tear and/or material fatigue, so that they have been and remain important contributors to key components' failures. Such failures can degrade NPP safety features and fail confinement barriers.

Being a part of the Euroatom Research and Training Programme The **G**athering expertise **O**n **V**ibration **I**mpa**K**t **I**n **N**uclear power **G**eneration (GO-VIKING) project addresses the key issue of material degradation in a structured manner. The GO-VIKING project aims at improving the safety of contemporary reactors and the design evaluation of new concepts by making available new experimental results and improved numerical approaches for the evaluation of flow-induced vibrations (FIV).

Driven by a team of experts from all over the world in fluid dynamics, FIV phenomena and structural integrity of key NPP components the project will collect and synthesize best international practices in this area and propose improved state-of-the-art methods and numerical tools to evaluate FIV and manage their impact into NSSS components. This can lead to a substantial decrease of NPP fuel failures and standstill costs of the outages.

In order to disseminate and ensure a widespread application of the project results, educational material and trainings for young scientists, master and PhD students on Fluid-Structure Interaction related to nuclear applications will be delivered based on the contents provided by GO-VIKING experts.

The expected results of the project will be presented and briefly described.

1 INTRODUCTION

The NSSS is one of the key systems of an NPP when it comes to safety. Ageing of the elements of this system is accelerated by the physical processes taking place in the course of NPP operation such as corrosion, neutron flux and vibrations of different types. In particular, FIV phenomena may cause failure in main NSSS components such as fuel assemblies and steam generators. An in-depth understanding and prediction of FIV phenomena will ensure the safe operation of the existing plants, especially those involved in long-term operation programmes.

Preventive measures against FIV should be taken in the component design and during the operation of the NSSS to avoid structural wear, damage or even incidental or accidental scenarios with potential radioactivity release to the environment.

Therefore, it is important to properly consider FIV loads in the component design and the operational surveillance and maintenance program. This also holds for increasing the uprate power levels at which NPP could operate and plant long-term operation (LTO) programs. Considering that tests and measurements under operational conditions are often costly or not feasible, prediction of FIV loads by simulation would be a practical solution.

2 GO-VIKING PROJECT

The GO-VIKING project takes over from the VIKING (Vibration ImpaKt In Nuclear power Generation) initiative that started in 2020 as an in-kind collaboration of European vendors, technical support organizations, universities, and research organizations to improve the understanding and the prediction of FIV phenomena relevant to NPPs.

The VIKING collaboration considered FIV issues in nuclear power plants. It was implemented in a partnership between Framatome (France), Framatome (Germany), GRS (Germany), IRSN (France), NRG (Netherlands), EDF (France), Vattenfall (Sweden), EDF-Energy (UK) and University of Manchester (UK). The objective was to utilize experimental data available from the partners together with reference numerical data to further develop and validate numerical engineering methods [1].

The GO-VIKING project goes further with the overall objective to enhance FIV knowledge, support development of modern FIV methods and tools for operating and designing new NPPs and strengthen the EU network of FIV researchers and practitioners and their international collaborations. This will contribute considerably to safety and reliability increase of NPPs, including SMRs and innovative nuclear reactors utilizing other than water substances as coolants.

To realise this objective, the GO-VIKING collaboration includes joint expertise of 18 partners: Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH, Germany (GRS); Nuclear Research and consultancy Group, The Netherlands (NRG); Universiteit Gent, Belgium (UGENT); LGI Sustainable Innovation, France (LGI); Electricité De France, France (EDF); Technische Universiteit Delft, The Netherlands (TUD); Teknologian tutkimuskeskus VTT Oy, Finland (VTT); Framatome GmbH, Germany (FRA-G); Institut de Radioprotection et de Sûreté

Nucléaire, France (IRSN); Institut von Karman de dynamique des fluides, Belgium (VKI); IPP Centre LLC, Ukraine (IPP); EDF Energy, United Kingdom (EDF-E); European Nuclear Education Network, Belgium (ENEN); University of Manchester, United Kingdom (UoM); Forsmarks Kraftgrupp AB, Sweden (FK); Commissariat à l'énergie atomique et aux energies alternatives, France (CEA); Pennsylvania State University, USA (PSU); Virginia Commonwealth University, USA (VCU).

The GO-VIKING project combines the expertise of these partners to realize the advantages of fluid-structure interaction (FSI) methods by:

- Providing developed and validated methods and tools for FSI applications in nuclear safety
- Giving guidance to stakeholders on how to efficiently apply FSI methods
- Reaching out to stakeholders, including regulators, and deriving acceptance criteria for FSI methods
- Training stakeholders in FSI methods and good practice

The GO-VIKING partners have identified two investigation fields where benefits of FSI tools and techniques can be realized in the short term:

- FIV in fuel assemblies (FAs), with focus on the design and safe operation of nuclear fuel;
- FIV in steam generators (SGs), with focus on the design and safe operation of SGs.

This includes the challenging evaluation of FIV in two-phase flow environment, which is nearly unexplored, and where the formation mechanisms are not understood, although two-phase conditions are relevant for BWR cores and for PWR SG tubes under normal operation.

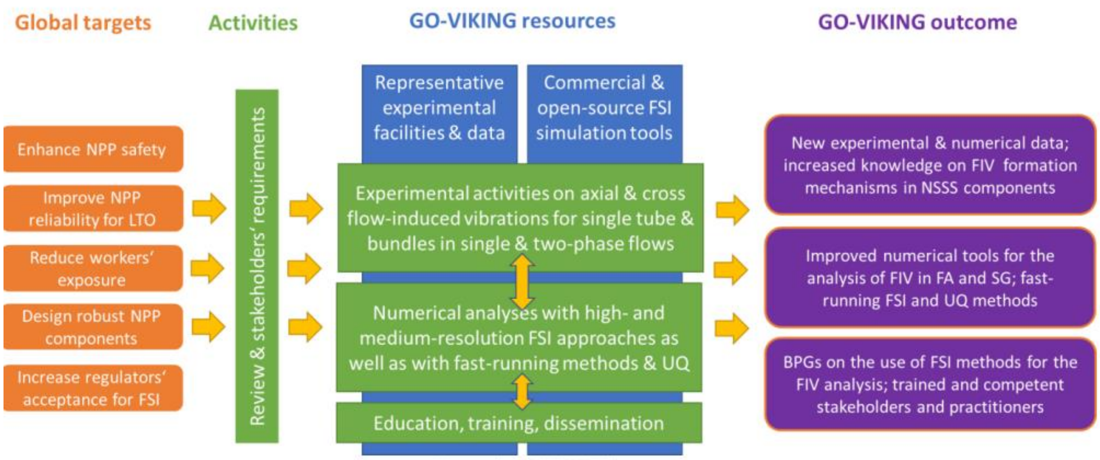

Figure 1: GO-VIKING project concept

The gained experience and know-how throughout the whole project will be synthesized in a single document that will provide the stakeholders with best practices on the use of FSI methods for the analysis of FIV (Figure 1).

GO-VIKING will provide a sound foundation to answer the abovementioned questions. The project partners review the current-state-of the-art practices and gather information on the needs of the stakeholders for numerical FSI analysis. They couple commercial and open-source computational programs for Fluid Dynamics (CFD) and Structural Mechanics (CSM) to develop sophisticated 3D FSI tools for FIV evaluation. Innovative, fast-running models are developed to reduce the prohibitive CPU time of FSI simulations being one of the main bottlenecks today. With the help of the fast-running models efficient Uncertainty Quantification (UQ) methods will be developed to supplement best-estimate FSI analyses. The entire numerical effort is supported by a variety of high-resolution experiments to be performed within the GO-VIKING project with the aim to provide the partners with validation data for the developed models and methods on a variety of industrial configurations, ranging from single rods/tubes in water up to fuel rod/tube bundles in two-phase flows.

3 PROJECT STRUCTURE

The project consists of eight Work Packages (WP) and their outputs are intended to contribute to five pillars, which are building the main course of the project [2]:

- Generation of new experimental and high-resolution numerical data, relevant for nuclear fuel assemblies and steam generators.
- Expanded knowledge on efficiency, accuracy and reliability of fluid-structure interaction methods.
- Provision of validated fast-running FSI tools with uncertainty quantification methods.
- Highly increased expertise of and awareness on FIV phenomena in NPPs.
- Synthesis of best practices and training of stakeholders and graduates in numerical FIV analysis.

The pillars will be supported by three cross-cutting activities: Dissemination and Training, Project Management, and Ethics.

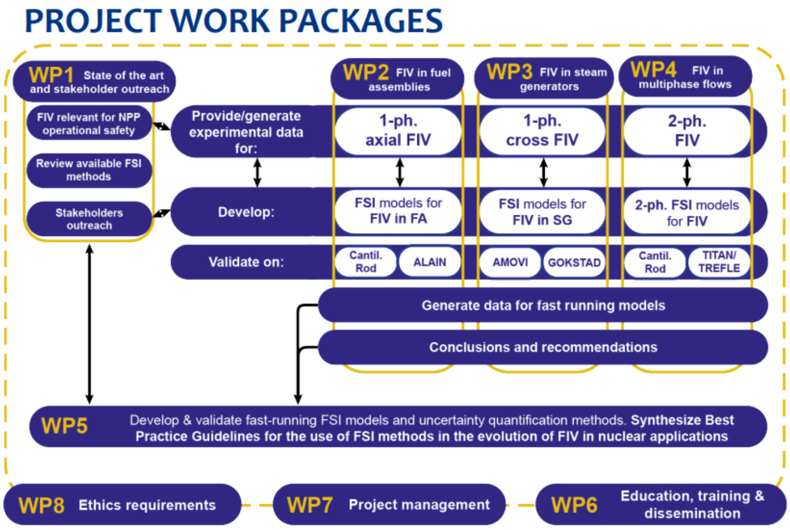

Figure 2: GO-VIKING project structure, articulated in Work Packages

The spread of actions within the project Work Packages is presented in Figure 2 above, which describes how five pillars are addressed by the activities and the outputs of the project.

3.1 WP1 – State of the art and stakeholder outreach

In WP1 the relevant FIV phenomena in NPP will be reviewed and input (relevant geometry and boundary conditions) will be provided and taken into account as far as possible in all new experimental activities in order to close as much as possible existing gaps. After reviewing the available FSI methods and taking into consideration the needs of the stakeholders, important findings and conclusions will be provided to WP2-WP5, where FSI methods and models are developed and validated. The feedback from the stakeholders outreach will be also addressed as much as possible in the foreseen experiments.

The principal objectives of the WP1 are:

- to document any existing data on the FIV phenomena relevant for the operational safety of the NPPs
- to review currently available experimental data and numerical methods related to FIV phenomena
- to identify industry needs and regulatory expectations
- to specify requirements for advanced numerical methods and tools for the analysis of FIV phenomena.

3.2 WP2 – Flow-induced vibrations in fuel assemblies

WP2 aims at developing advanced simulation methods and tools to facilitate the understanding of FIV in fuel assemblies. The involved partners apply different simulation techniques for FIV in single-phase axial-flow and validate the generated results against two experiments: The Cantilever Rod experiment (UoM) and the ALAIN 5x5 PWR rod bundle experiment (FRA-G).

3.3 WP3 – Flow-induced vibrations in steam generators

WP3 focusses on the development of methods to provide reliable assessment of structural vibrations occurring in heat exchangers and steam generators under cross-flow conditions. Data for the numerical analysis of FIV in tube bundles in cross-flow, are provided by the new GOKSTAD experiment (VKI), as well as by the existing AMOVI tube bundle experiment (CEA).

3.4 WP4 – Flow-induced vibrations in multiphase flows

The objective of WP4 is the development of advanced simulation tools to provide deeper understanding of vibrations induced by a two-phase flow in nuclear reactor components and their validation against available experimental data. For this purpose, the Cantilever Rod experiment is extended for two-phase axial flows, while the vibration behaviour of tube bundles in two-phase cross-flow conditions is evaluated in the TREFLE (IRSN) and TITAN (CEA) experimental facilities.

3.5 WP5 – Fast-running methods, uncertainty quantification and best practice guidelines

Data from WP2, WP3 and WP4 will be used as an input for the development of fast-running methods in WP5. UQ methods for FSI simulations, based on fast-running methods, will be developed, and the experience gained in all other technical WPs will be synthesized in Best Practice Guidelines on the Use of FSI Methods for the Evaluation of FIV in Nuclear Applications. This WP will summarize the results of the scientific studies and recommendations based on the different approaches and experimental facilities involved in the project. The principal objectives of WP5 are:

- Development and implementation of fast-running Fluid-Structure Interaction methods for efficient analysis of FIV phenomena
- Validation of fast-running methods and identify their limitations
- Development, implementation and application of approaches to quantify the uncertainty in the FIV evaluation in reactor components

- Elaboration of guidance to vendors, operators and regulators on robust and efficient FIV assessments.

3.6 WP6 - Education, training and dissemination

WP6 is dealing with the dissemination of the project results and delivers educational materials and trainings based on the results obtained by the WP2-5. Aside of the regular dissemination and communication actions which includes provision of the project information through the project web-tools [3], WP6 also plans:

- yearly open lecture on FIV for educational institutions (TUD, ENEN)
- Lecture Series given by GO-VIKING experts to share the knowledge obtained during the project and to train the new generation of engineers in the field of FIV with the latest developments (VKI)
- training sessions in OpenFOAM and TrioCFD to train the stakeholders and the new generation of users (CEA, GRS)
- Final International Workshop which is a stand-alone event or embedded within a relevant conference to maximize its impact to the scientific community and associated stakeholders (ENEN, VKI).

3.7 WP7 - Project Management

WP7 is the second transversal activity of the project. Its objective is to provide an efficient management of the GO-VIKING activities including overall project steering.

3.8 WP8 - Ethics requirements

This work package sets out the 'ethics requirements' that the project must comply with.

4 EXPERIMENTAL FACILITIES

The numerical activities within GO-VIKING will be supported by high-resolution experimental data [4, 5]. The experiments are dedicated to FA and SGs in single and multiphase flows with geometrical and flow parameters matching closer than before those of NPP FA and SG configurations. The experiments are split in WPs dealing with FA and SG as described in Section 2, being the important NPP components with pronounced FIV susceptibility to be investigated in the project.

Experiments with axial flow are mainly relevant for FA, and the ones with cross-flow - for SG. Cross-flow vibration phenomenon called baffle jetting (impinging jet from the core bypass on the FA in the core periphery) that may occur in reactor cores will be indirectly addressed by the experiments in single-phase cross-flow to be performed in WP3. Further, the ascending and descending part of the U-tubes in the SG vibrate in axial flow (WP2), while the top, arc formed part of the tubes is exposed to a cross-flow.

Short descriptions of the GO-VIKING experiments are provided below.

4.1 AMOVI and TITAN

CEA has an experimental facility equipped with three test-sections (AMOVI, DIVA, TITAN), aimed at studying FIV phenomena in tube bundles exposed to cross-flows, mainly relevant to SG applications. In GO-VIKING, existing and new data from the single-phase experiment AMOVI, as well as from the two-phase experiment TITAN will be used for code validation. TITAN has a tube array with a triangular lattice that is particularly relevant for some French SG designs.

4.2 GOKSTAD and TREFLE

Two completely new experiments dealing with tube bundles in a cross-flow, related to SGs, will be built within GO-VIKING project.

GOKSTAD (GO-VIKING experimental SeTup to Assess FIV by cross-flow in tube bundles, Figure 3) is a completely new single-phase experiment with a bundle of 7x5 plus 2 columns with 5 semi-tubes that will be built at VKI in Brussels.

The targeted Reynolds number will be higher than that currently available in the literature and in the AMOVI experiment. Time-Resolved Particle Image Velocimetry (TR-PIV) is used to measure the flow field (mean, fluctuating components, Reynolds stresses), essential for proper validation of the flow solver used in the FSI models. Data will be generated for a range of flow velocities, as well as for cases involving all rigid tubes, one centrally flexible tube, as well as two flexible tubes, both in-line as side-to-side.

TREFLE consists of 5x5 tubes with 30 mm diameter, positioned in a square lattice and exposed to a two-phase cross-flow. The two-phase environment will be achieved by water and air flow, whereas the air fraction will vary between 0% and 100%. TREFLE has an extensive measurement system that includes Wire Mesh Sensors (WMS) to capture the void distribution, as well as high-speed camera and optical probes for the flow pattern. Measurements will be also performed for the inlet section in order to provide the numerical activities with accurate boundary conditions.

The design of GOKSTAD and TREFLE will be adjustable, allowing to vary the number and the positions of the flexible tubes, and sustainable, allowing them to be used in future relevant experimental campaigns.

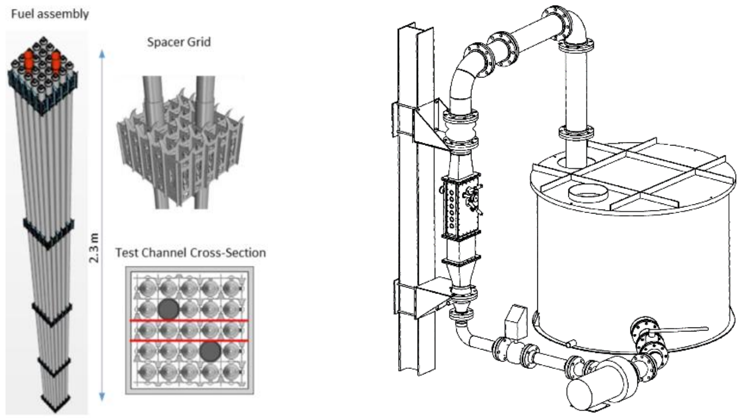

Figure 3: ALAIN 5x5 Rod Bundle (left) and sketch of the GOKSTAD water loop (right) [4]

4.3 Cantilever Rod and ALAIN 5x5 PWR Bundle

These two experiments are mainly related to FIV in FA. The main objective in designing the Cantilever Rod experiment is to generate experimental data in controlled conditions with non-invasive simultaneous resolution of structural vibration. The length of the cantilever rod is 1 m and its diameter is 10 mm. The water is directed from the free end of the rod to the fixed end. Single phase experimental data is available and will be provided to the GO-VIKING partners, while new, two-phase experiments will be carried out in Manchester in the frame of the project. The experimental configuration is simplified, but relevant for PWR and BWR FA.

The ALAIN experiment had been performed by Framatome GmbH in Erlangen. It represents a reduced 5x5 PWR FA test bundle, placed in a channel with a square cross-section with a nominal lateral gap between the bundle and test channel of 1.5 mm. The assembly is 2.3 m long and built of 23 rods in a square lattice, two guide tubes and five spacer grids. The vibration response of the fuel bundle and fuel rods was measured using laser for a wide range of the flow rates corresponding to average axial velocity between 3 to 7 m/s (Figure 3).

5 CURRENT PROJECT STATUS AND VISION

The project is currently in its second year of implementation. During the first year of the project, the stakeholders' outreach and literature review has provided important and relevant input for all partners to better understand the current gaps and needs in regard to FIV in NPPs. This input has been used by the experimentalists, ensuring the data they deliver allow the project to address these needs. So far, five out of the seven experiments have already generated all or a part of the promised data. The other two experimental facilities, being brand new, have gone through the design phase and are currently in the procurement (GOKSTAD) and initial testing (TREFLE) stage.

With the available experimental data, the numerical partners have also recently begun with the modelling work. The first models have already been created. The GO-VIKING project is scheduled to end in May 2026 after 48 months of implementation.

ACKNOWLEDGMENTS

This project has received funding from the EURATOM Research and Innovation Actions under grant agreement No 101060826.

REFERENCES

[1] Zwijsen, K., et al, 2022, VIKING: A joint industry project on Flow-Induced Vibrations, NURETH-19, Brussels, Belgium

[2] GO-VIKING Description of Action, Grant Agreement number 101060826

[3] Main project website https://go-viking.eu/

[4] K. Zwijsen , A. Papukchiev , D. Vivaldi , H. Hadžić , S. Benhamadouche , W. Benguigui, P. Planquart, “GO-VIKING: A HORIZON EUROPE Project On Flow-Induced Vibrations”, Proc. 12th International Conference on Flow-Induced Vibration'2022, Paris-Saclay, France, July 5-8, Laboratoire EM2C, CNRS, CentraleSupélec, Université Paris-Saclay, 2022, pp. 507-514

[5] A. Papukchiev, K. Zwijsen, D. Vivaldi, H. Hadžić, S. Benhamadouche, W. Benguigui, P. Planquart, “The European GO-VIKING Project on Flow-Induced Vibrations”, Proc. of the NURETH-23 conference, August 20-25, 2023.