Tutorial on

Reactor noise analysis applications in NPPs

IMORN-31

Delft, The Netherlands, September 9-12, 2024

Oszvald Glöckler

Senior Consultant

The purpose of this tutorial is to present some of the issues and the process of applying reactor noise analysis (RNA) in NPPs.

The following assumptions were made when this tutorial was designed:

- The meeting has already introduced reactor noise analysis (RNA) basics, in general, by now
- The audience has an interest in how to put RNA in future use in NPPs
- The audience may include:
  - NPP managements, engineers, interested in the potentials of RNA in NPPs
  - Technical support organization seeing opportunities for providing RNA services in NPPs

Self-introduction

Previous full-time work experience:

- I&C QA contractor, Fennovoima-Hanhikivi-1 NPP new build project, Finland, 2020-2021
- Scientific Secretary, IAEA, NKM & HR Development, 2017-2020
- CEO of an international I&C engineering consulting company (SunPort SA), Switzerland, 2012-2017
- Scientific Secretary, European Commission JRC Task Force of the Post-Fukushima Stress Test, 2011-2012
- Scientific Secretary, IAEA, NPP Instrumentation & Control, 2004-2011
- Senior Technical Expert, Reactor diagnostics applications in operating CANDU NPPs, Ontario Power Generation, Canada, 1992-2004
- Teaching and research in Nuclear Engineering, University of New Brunswick, Canada, 1991-1992
- Senior Research Scientist, Atomic Energy Research Institute, Central Research Institute for Physics (AEKI-KFKI), Hungary, 1989-1991
- Teaching and research in Nuclear Engineering, University of Tennessee, USA, 1986-1989
- Research Scientist, Atomic Energy Research Institute, Central Research Institute for Physics (AEKI-KFKI), Hungary, 1981-1986

My involvement in reactor noise analysis

- University Diploma (1981)
  - Eötvös Loránd Tudomány Egyetem (ELTE), Budapest, Hungary
- University Doctorate Degree (1984)
  - Eötvös Loránd Tudomány Egyetem (ELTE), Budapest, Hungary
  - Központi Fizikai Kutatóintézet (KFKI), Budapest, Hungary
- Paks NPP, Hungary (1982-1986)
- University of Tennessee, Knoxville, USA (1986-1989)
  - LOFT Reactor at INEL, Sequoyah NPP of TVA, Alcoa noise data
- Paks NPP, Hungary (1989-1991)

My involvement in reactor noise analysis

- University of New Brunswick, Fredericton, Canada (1991-1992)
  - Point Lepreau NPP in New Brunswick (CANDU 600 MW)
- Ontario Hydro Nuclear / Ontario Power Generation / Bruce Power, Ontario, Canada (1992-2004)
- Then no noise at all for 18 years!
  - IAEA (2004-2011)
  - EC-JRC (2011-2012)
  - SunPort SA (2012-2017)
  - IAEA (2017-2020)
- Resurrection of CANDU noise analysis, working with Canadian Nuclear Laboratories and MDA/Calian (2021 – present)
  - Ontario Power Generation, Bruce Power, Point Lepreau CANDU NPPs

My involvement in reactor noise analysis

- Ringhals-3 PWR (Sweden): cold-leg RTD, Ex-core ion chambers, core exit TC (1996?)
- Reinsberg PWR (DDR): boiling detection (1983-84?)

My involvement in reactor noise analysis

The most successful period:

Ontario Hydro Nuclear / Ontario Power Generation / Bruce Power, Ontario, Canada (1992-2004)

Examples of factors needed for success (technical to management):

- Triplicated instrument channels
- Well documented design information
- Access to analog safety and regulating system signals to record
- Dedicated in-house “reactor noise analysis team”
- Financial and HR resources were provided
- Station management engaged with interest and questioning attitude

Reactor Name	Model	Reactor Type	Net Capacity (MWe)	Construction Start	First Grid Connection
Bruce 1	CANDU 791	PHWR	732	1971-06-01	1977-01-14
Bruce 2	CANDU 791	PHWR	732	1970-12-01	1976-09-04
Bruce 3	CANDU 750A	PHWR	750	1972-07-01	1977-12-12
Bruce 4	CANDU 750A	PHWR	750	1972-09-01	1978-12-21
Bruce 5	CANDU 750B	PHWR	822	1978-05-31	1984-12-02
Bruce 6	CANDU 750B	PHWR	822	1978-01-01	1984-06-26
Bruce 7	CANDU 750B	PHWR	822	1979-05-01	1986-02-22
Bruce 8	CANDU 750B	PHWR	795	1979-07-30	1987-03-09
Darlington 1	CANDU 850	PHWR	881	1982-04-01	1990-12-19
Darlington 2	CANDU 850	PHWR	881	1981-09-01	1990-01-15
Darlington 3	CANDU 850	PHWR	881	1984-09-01	1992-12-07
Darlington 4	CANDU 850	PHWR	881	1985-07-01	1993-04-17
Pickering 1	CANDU 500A	PHWR	508	1966-06-01	1971-04-04
Pickering 4	CANDU 500A	PHWR	508	1968-05-01	1973-05-21
Pickering 5	CANDU 500B	PHWR	516	1974-11-01	1982-12-19
Pickering 6	CANDU 500B	PHWR	516	1975-10-01	1983-11-08
Pickering 7	CANDU 500B	PHWR	516	1976-03-01	1984-11-17
Pickering 8	CANDU 500B	PHWR	516	1976-09-01	1986-01-21
Point Lepreau	CANDU 6	PHWR	660	1975-05-01	1982-09-11

Reactor Noise Analysis Basics in NPPs

Reactor noise analysis (RNA) is based on signals recorded from standard, built-in NPP detectors used in the following regular NPP systems/functions designed for:

- passive monitoring/surveillance systems
- normal operation (reactor control/regulating systems)
- accidents prevention and mitigation (safety or reactor protection systems)

Operating conditions during data acquisition:

- Steady-state, full-power operation (90% of the time)
    - Optimal for NPP operation
    - Essential for recording noise signals for analysis

Boundry of RNA applications

Historically, traditional noise analysis is not going beyond the reactor area

- Steam generators/boilers?
- Main coolant pumps?
- Spent fuel pools?
- Too simple without neutrons?
- Not “academic” enough?
- Not instrumented enough?

Station signals for noise analysis

Typical signals that might be available for noise analysis in an NPP:

- In-core neutron flux detectors (SPNDs)
- Ex-core ion chambers
- Coolant/moderator reactor core inlet and outlet temperature (RTDs, TCs)
- Coolant/moderator reactor core inlet and outlet flow (orifice or Venturi-tube based)
- Coolant/moderator pressure, differential pressure (e.g. Rosemount)
- Water level (differential pressure)

No add-ons

Not considered as “classic” noise analysis – out of scope of this presentation:

- Accelerations/displacement vibration sensors
- Acoustic “microphones”
- Ultrasonic flow probes

The heydays of reactor noise analysis

At the beginning:

- RNA in academia and NPP industry
- publications in scientific journals, reports
- large conferences, intensive international communication

Participants from at least 20 countries:

- research institutes
- universities
- NPPs
- engineering service companies
- commercial tech companies

RNA advantages for NPP operation

- Passive, non-intrusive ("listening only")
- Analyzing signals from the standard instrumentations of the NPP
- No need "to stick in noise analysis sensors"
- Signal recording can be (must be) done at steady-state operation
- No need to maneuver the NPP for transient response analysis
- Information on the dynamics of I&C and reactor systems can be gained from "steady-state" measurements

Challenges for the current application of RNA in NPPs

- RNA is not part of the NPP vendor-supplied package
- NPP vendors do not build in noise analysis capabilities, not even connection points (“patch panels”)
- RNA is sometimes an afterthought triggered by NPP needs
- RNA is not a straightforward engineering tool that NPP system responsible engineers (SREs) would operate
- RNA concepts are far away from the deterministic SRE mentality
- Signals are straight line at steady-state operation (MCR) vs. fluctuating components around them (R&D)

Challenges for the current application of RNA in NPPs

Cautious management approach

- “Nothing is stochastic in my reactor”
- Misunderstanding of “noise”
- RNA concepts are new to management, engineers, project leaders, etc.
- At meetings, we often have to explain RNA from the very basic concepts, as opposed to talking about the latest results

Legacy:

- Received bad reputation occasionally, over-selling, not producing a reliable, documented in-house tool for the NPP (internal or external service-based)
- Still research oriented, not ready for near-term deployment

Example 1994

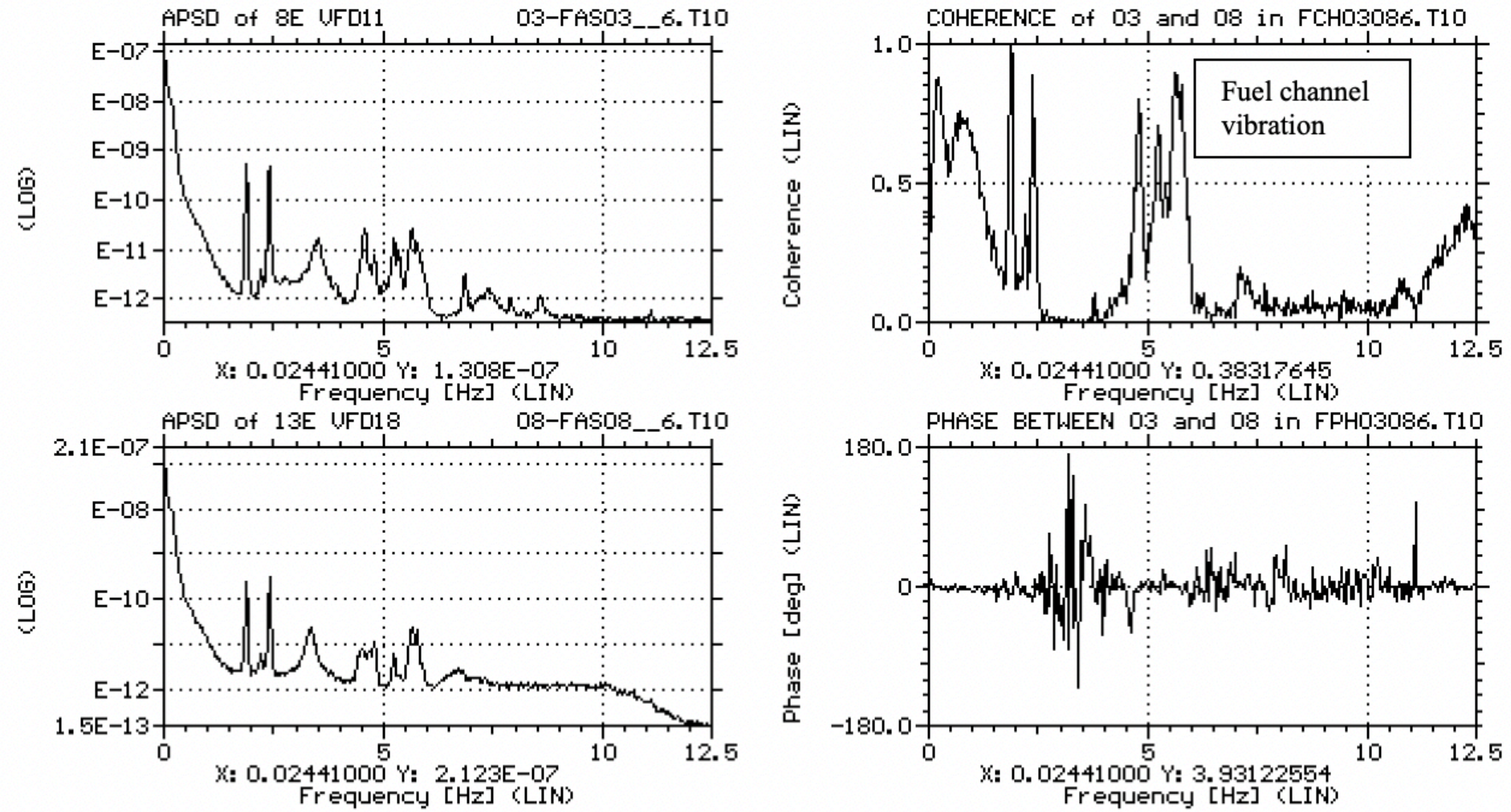

Figure 4. APSD, Coherence and Phase functions of noise signals of two vertical in-core flux detectors lined up along the same set of horizontal fuel channels in DNGS Unit 4

Example 2021

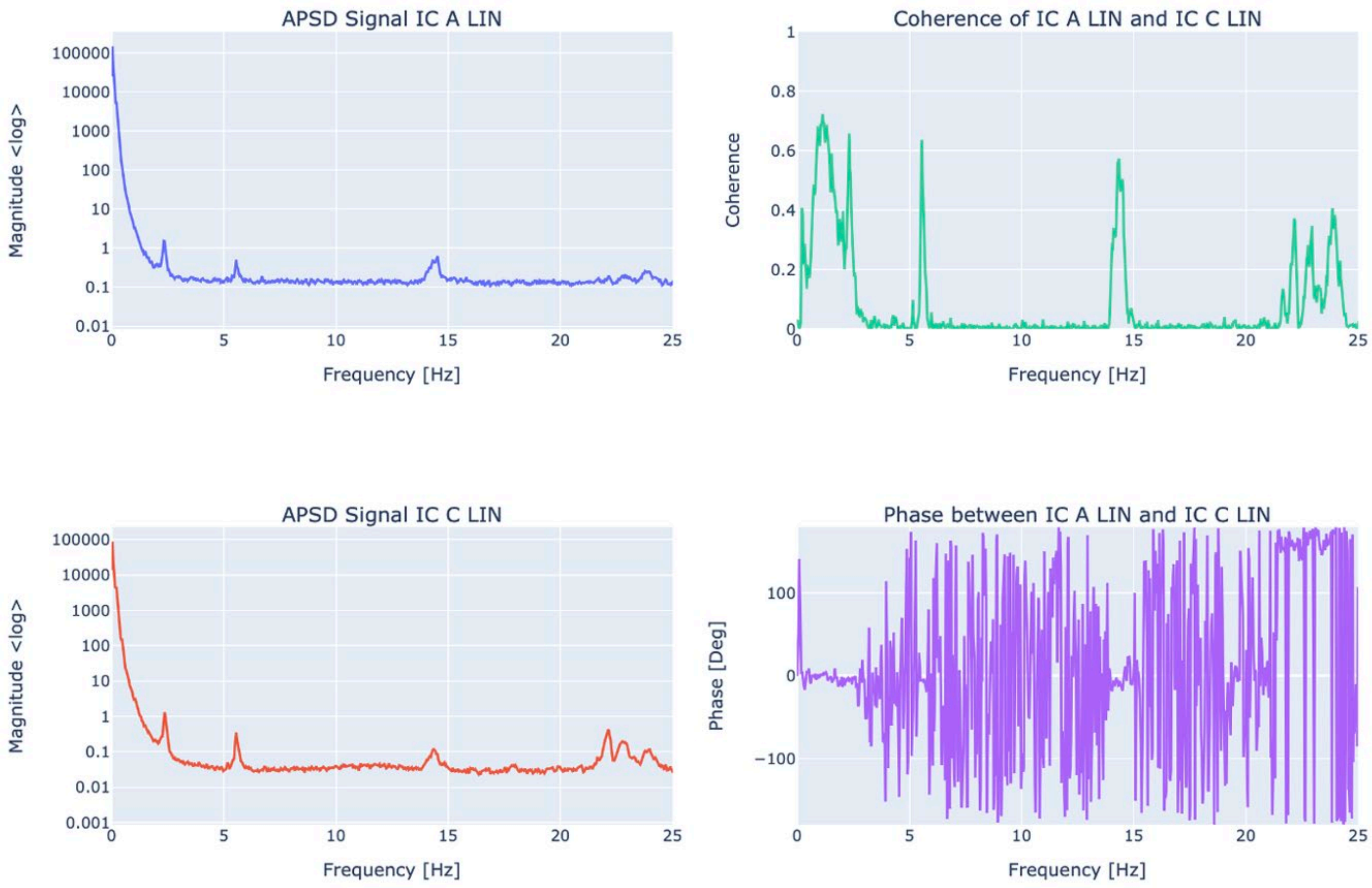

Figure 7. APSD, Coherence and Phase functions of LIN output signals of two ex-core ion chambers in DNGS Unit 4 (2021)

The “lake effect” analogy

The “lake effect” analogy – a make-belief story

- Crews at the Pickering and Darlington stations were measuring the depth of Lake Ontario very accurately.
- Because of the surface waves, the measured depth fluctuated around a constant value (100 m), that is, the depth was a function of time.
- This was recorded at both stations in sync, continuously for one day, then they passed the recorded time series data to noise experts to analyze.
- They found that the surface had large and long waves with a maximum amplitude of 1 m with all kinds of random-looking shorter and smaller ripples riding on them.
- They were as small as 1 mm in amplitude, peak-to-peak, that is, 0.001% of the average depth.

The “lake effect” analogy – a make-belief story

- We analyzed how the surface fluctuations were coupled or correlated between the two stations.
- This included not only the slow and relatively large surface waves, but all the small ripples as well.
- Surface fluctuations of certain wavelength showed correlations with a well-defined phase difference, while other wavelengths turned out to be independent.
- When Bruce Power joined in measuring their lake, correlations with them were also found but weaker and with some phase shift.
- By adding lake temperature, flow and wind measurements at more locations, we were able to learn a lot about lake surface dynamics.

The complete end-to-end noise analysis process

Why would an NPP go for noise analysis?

Lessons learned

The complete end-to-end noise analysis process

Front end: starting from scratch

- NPP’s motivation (“we have a problem” vs. “we have a tool”)
- starting with a small application
- starting with non-safety systems
- proving immediate or short-term usefulness for O&M
- not making troubles for operation
- making a business case for management (cost & benefit)
- no regulatory involvement yet

The complete end-to-end noise analysis process

Back end: noise analysis becomes a routine

NPP considers noise analysis as an established diagnostics / on-line monitoring service

- Documented (procedures, reports, trending, etc.)
- QA-controlled
- reliable and sustainable service with NPP involvement (CM, SRE)
- sense of ownership by station (in-house expertise vs. external service)
- regulatory involvement and requirements

Examples of technical issues between front and back ends: The whole process

1. Developing data acquisition (DAQ) systems to record noise signals
2. Deploying and operating DAQ systems in NPPs to record noise signals
3. Statistical analysis of recorded noise signals, processing large volume of measurement data
4. Interpretation of noise analysis results in terms of NPP processes
5. Reporting to station management, supporting O&M, inspection outage planning, etc.
6. Trend monitoring and long-term sustainability of reactor noise analysis

Examples of supporting activities

- Development of SW tools
  - In-house R&D
  - Production tools

- Analytical and computer models (e.g. Ansys)
  - Interpretation of / understanding noise results
  - Predictions for applicability, sensitivity analysis

- Laboratory models
  - Mock-up systems, test loops
  - Research reactors

1. Data acquisition (DAQ) systems designed to record noise signals

Function: converting analog station signals into digital time series files

Condition for use: Meeting operation and safety requirements

Portable vs. permanently installed DAQs (pros and cons)

- General purpose vs. dedicated
- Trouble-shooting tool vs. problem-specific, long-term monitoring

1. Data acquisition (DAQ) systems designed to record noise signals

Permanent DAQs:

- Large initial investment and commitment by the NPP
- Designed in by NPP vendor vs. an after-thought by NPP
- If intended for fault detection, but faults do not happen frequently enough – no need to monitor
- Inflexible, but good for trend monitoring
- No time-consuming procedures are needed for connecting / disconnecting signals
- Customized signal processing and analysis can be built in
- Report-ready results

1. Data acquisition (DAQ) systems designed to record noise signals

Portable DAQs:

- Time-consuming procedures are needed for connecting / disconnecting signals (CM, WO, scheduling, O&M personnel)
- Custom-made DAQ to meet specific functional requirements – commercial recorders may not meet all requirements
- Can be used on an as-needed-basis for infrequent applications
- Flexible, DAQs can be configured for various signal sets
- Methodology development is needed for analyzing customized noise applications
- Only experienced analysts can produce results

1. Data acquisition (DAQ) systems designed to record noise signals

Functionalities of portable DAQs:

- In-coming signals are digitized, displayed and stored locally
- In-depth analysis is done off-line
- DAQ user-interface is only to set recording parameters and display – no signal processing functionalities
- 24-channel DAQ systems with a capability of multiple DAQ units being synchronized
- Conditioning of analog signals: I/V conversion, isolation amp, DC offset or HP-filtering, amplification/gain, LP-filtering, ADC conversion
- ADC resolution (fixed for all channels): 16-bit (24-bit would cover all)
- Sampling frequency (adjustable): max. 1 kHz

2. Deploying and operating DAQ systems in NPPs to record noise signals (continued)

Hardware side:

- Control Maintenance Procedures to connect and disconnect DAQ systems in the NPP at full-power steady-state operation
- Channels of NPP safety and control systems are taken out of service while connecting/disconnecting signals (2oo3 logic)
- 24-channel DAQ systems – multiple unit deployed at various NPP locations are synchronized
- Requirement of optically isolated inputs in DAQ systems

2. Deploying and operating DAQ systems in NPPs to record noise signals (continued)

Procedural side:

- Involvement of System Responsible Engineers in planning and execution of data recording
- Coordination with Control Room personnel
- Minimizing impact on operation and maintenance
- Fitting in the overall work planning flow of O&M

2. Deploying and operating DAQ systems in NPPs to record noise signals (continued)

Future options:

- Permanently installed patch-panels for connecting station signals to DAQ systems
- Permanently installed complete noise analysis systems for a limited set of signals of safety and control systems

Both needs serious station commitment and investment, plus regulatory approval

Classic noise analysis systems are not part of the NPP design by the vendor companies

3. Statistical analysis of recorded noise signals

- Off-line signal processing according to application-specific protocols (research vs. production)
- Processing large volume of data from several DAQ systems (e.g. 10 times 24 channels)
- Minimum: FFT-based APSD, CPSD, coherence and phase functions ("quad plots")
- Large number of "quad plots" to analyze and compare (by experts or AI)
- Additional options when real cause-and-effect relations are present in the monitored systems:
    - Transfer functions, impulse and step response functions
    - MAR-based spectral functions, signal-transmission-path analysis

4. Interpretation of noise analysis results in terms of NPP processes

- “Interpretation”: turning noise signatures (spectra) into technical parameters that are relevant to operation, maintenance, inspection, and licensing (e.g. MTC, coolant flow, response time, flux detector prompt fraction, vibration of core internals)
- Needs simple physical models and conceptual understanding of NPP systems
- Importance of availability of accurate design drawings, flow charts, core maps, etc.
- Ability to explain changes found in trend-monitoring of noise signatures
- Sensitivity analysis: how sensitive the noise signatures are to changes in the NPP systems

4. Interpretation of noise analysis results in terms of NPP processes (continued)

Noise-based applications:

- Monitoring detector tube vibration in the reactor core
- Monitoring fuel channel vibration
- Estimation of the prompt fraction of in-core flux detectors in safety systems
- Response time estimation of signals of temperature detectors, flow and pressure transmitters
- Diagnostics of sensing lines of flow and pressure measurement loops (e.g. leak detection, excessive vibration, blockage)
- Monitoring moderator circulation
- Diagnostics of Liquid Zone Control system (local power control in CANDU)
- Fault detection and signal validation

5. Reporting to station management, supporting O&M, inspection, outage planning

Deliverables:

- Technical reports for record keeping – detailed at noise analyst level
- Executive summaries to Directors of Engineering, Inspection, Maintenance, Licensing and Research Departments
- Other Technical Support Organization (TSOs)? – could be potential competitors
- Presentations at industry organizations and user groups
- Linkage to international applications and success stories

5. Reporting to station management, supporting O&M, inspection, outage planning (continued)

Matching your available noise analysis toolbox with solving a task in NPP:

- Respond to calls from NPPs for solving their problems
- Search NPPs' O&M problems (OPEX database), decide if your noise analysis tools can help to resolve them
- If specific problems occur in the NPP, offer noise analysis capabilities, unknown to management, that you think noise analysis can resolve

5. Reporting to station management, supporting O&M, inspection, outage planning (continued)

Developing new noise analysis tools and applications addressing new problems in NPPs:

- Feasibility of new noise analysis tools for NPPs' needs?
- Is it technically sound?
- Is it financially viable?

6. Trend monitoring and long-term sustainability of noise analysis

Typical examples of elements of long-term noise analysis at NPPs

- Baseline noise measurements
- Periodic follow-up noise measurements, plus ad-hoc ones, as needed
- Pre-outage noise measurements at full-power steady-state operation
- Consistent, systematic and repeatable noise measurements over years
- Everything needs to be documented and “proceduralized”

6. Trend monitoring and long-term sustainability of noise analysis (continued)

Typical examples of elements of long-term noise analysis at NPPs

- Training of noise recording personnel – station staff vs specialists?
- Training of noise analysts
- Maintaining station’s interest by delivering services valuable to them
- Relevance to the NPP for meeting O&M and regulatory requirements
- Innovate, upgrade, communicate, publish, present, sell noise analysis

The purpose of this tutorial was to present (discuss?) the issues and the process of applying reactor noise analysis (RNA) in NPPs.

Thank you!

Questions?