Approach to Calculating Uncertainty of Instrument Channels in Nuclear Facilities: Case Study Presentation

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ABSTRACT

The measurement uncertainty of instrument channels in nuclear power plants (NPP's) is of paramount importance for ensuring operational safety and regulatory compliance. This article presents an approach to calculating the uncertainties associated with instrument channels in NPPs. Practical case study of calculation within NPP Krško (NEK) is introduced.

Beginning with an overview of instrument channel uncertainties, the article outlines relevant rules, practices and standards guiding such calculations in NPP's. Short overview of applicable documents ANSI/ISA-67.04.01 and ISA-RP67.04.02 is given and methodology of channel uncertainties calculation from inception to completion is introduced. The necessity for determining instrument channels uncertainties in NPP's is emphasized. Various aspects which must be considered within calculation are discussed including the architecture of instrument channels, data concerning I&C equipment, operational parameters, process and environmental conditions, parameter identification and finally the calculation itself.

In order to illustrate subject on practical example, a case study of calculating Environmental Qualification (EQ) instrument channel uncertainties in NEK is presented.

Keywords: *instrument channel uncertainty, nuclear power plant, calculation, case study*

1 INTRODUCTION

The reliable and safe operation of nuclear power plants very much depends on the operation of control and measuring equipment. This equipment constantly monitors and controls system process parameters, either automatically or by providing information for manual actions by operators. The key feature of such equipment is the performance of its safety function, namely the ability to measure or response in the prescribed accuracy range of the I&C component or system to which each component belongs.

The set of I&C components and modules constitutes an instrument channel when a single path for signal transmission from the instrument to the final system, such as a control system, indicator, data acquisition system, alarm system, or similar, is established. The type and arrangement of components and modules comprising the instrument channel varies depending on the measured quantity and the purpose of the signal. A typical instrument channel may consist of the following major sections: process, process interface, process measurement, signal interface, signal conditioning and actuation. In each of this section, some amount of uncertainty may arise due to various factors, such as environmental conditions, process dynamics, sensor accuracy, calibration accuracy, electronic noise, signal drift, etc. Understanding and quantifying these uncertainties is crucial for determining appropriate setpoints for automatic or manual actions required by the plant. Setpoints are the predefined values at which safety systems or control systems trigger specific actions. If the uncertainties in instrument channels, are not rigorously assessed and accounted for, they can lead to negative consequences. These consequences can range from missed alarms for critical events to unnecessary shutdowns due to overly conservative setpoints. To effectively quantify instrument channel uncertainties, it's essential to conduct thorough calibration procedures, monitor instrument performance over time, account for environmental factors, and use appropriate statistical methods to estimate uncertainties. This ensures that measurements are as accurate and reliable as possible given the instrument's capabilities and limitations.

The following Figure 1 provides graphical presentation of relative positions of system limits, trip setpoints and uncertainties and is based on standard ANSI/ISA-67.04.01 [1].

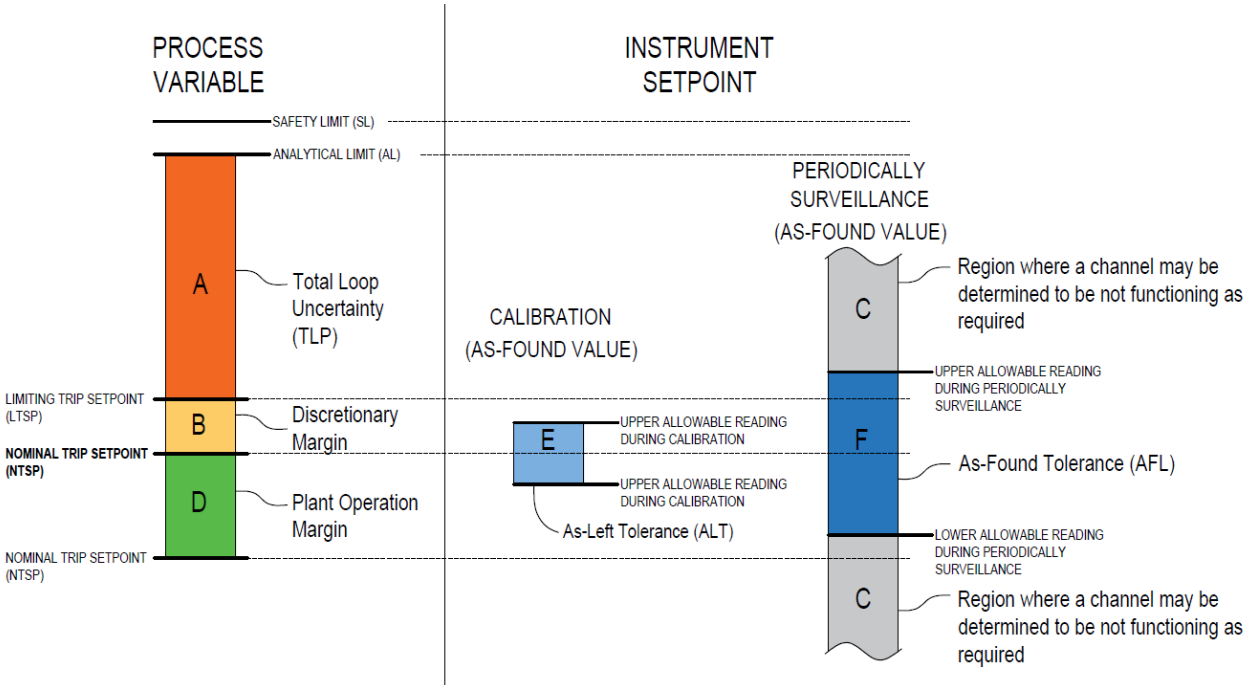


Figure 1: Relative positions of setpoints and limits

Standard defines that trip setpoints in NPP’s and other nuclear reactor facilities must be selected to ensure that a trip or safety actuation occurs at or before the process reaches the so-called analytical limit (AL), which is the value of process variable(s) at which the safety analysis models the initiation of the protection function. Importantly, the AL are selected below the associated safety limits (SL) which are chosen to maintain the integrity of physical barriers that are designed to prevent the uncontrolled release of radioactivity. Trip setpoints are also chosen to assure that the plant can operate and experience expected operation transients without unnecessary trips or safeguard actuations. Instrument uncertainties, which represent the limitations of measurement accuracy, directly affect trip setpoints. These uncertainties shall be carefully considered to ensure the safety systems activate at the appropriate time.

2 INSTRUMENT CHANNEL UNCERTAINTIES

The standards [1] and [2] define uncertainty from the prospective of instrument channels as the amount to which an instrument channel’s output is in doubt (or the allowance made for such doubt) due to possible errors, either random or systematic. The uncertainty is generally identified within a probability and a confidence level. Due to the uncertainties, the exact value of a measured quantity can never be known with absolute certainty. We can, however, calculate the range of possible values within a certain level of confidence.

Both references [1] and [2] provide similar comprehensive list of uncertainties to consider when calculating total instrument channel uncertainties. However, they suggest that list is not exhaustive, but rather provide minimum requirements of consideration. Therefore, any additional recognized uncertainty must also be included in calculation. These standards cover a similar range of potential uncertainties, some of which have already been recognized above. Below is an overview of the uncertainties and their sources recognized by [1] [2].

- **Instrument calibration uncertainties:** These are caused by calibration standards, equipment, methods and setting tolerances.
- **Instrument uncertainties during normal operation:** These are caused by reference accuracy, power supply voltage changes, power supply frequency changes, temperature changes, humidity changes, pressure changes, vibration, radiation exposure, process effects, instrumentation transfer functions, A-D and D-A conversion, electromagnetic interfaces, ageing effects, etc.
- **Instrument drift:** The drift based on instrument specific calibration interval.
- **Instrument uncertainties caused by design-basis events:** For instance, temperature effects, radiation effects and seismic/vibratory effects may introduce additional uncertainties to the instrument channel during and after the design basis event. Only the uncertainties specific to the event and required period of service should be used.
- **Process-dependent effects:** These are uncertainties associated with the process variable.
- **Calculation effects**: These uncertainties resulting from the use of mathematical models to calculate a variable from measured variables.
- **Dynamic effects:** Dynamic effects are defined as behavior of channel’s output as function of the channel input with respect to time. Normally, these effects are accounted for the safety analyses.
- **Calibration and installation bias accounting:** Bias of fixed magnitude and known direction due to equipment installation or the calibration method. If this bias is not eliminated during calibration, it must be accounted for in the uncertainty analysis.

Magnitude of estimated uncertainty terms shall be defined using rigorous means. The uncertainty tolerance interval for random, independent uncertainty terms shall be estimated using statistical and bounding methods such that the tolerance interval estimate bounds the uncertainty of interest with a 95% probability, at a 95% confidence level.

3 APPLICABLE STANDARDS AND DOCUMENTS

Different countries, rely on a variety of standards that provide the framework and specific methods for calculating instrument channel uncertainties. These standards are linked to the regulatory codes each country uses for NPP licensing. Specifically, the requirements of determination of setpoints and associated uncertainties important to safety may be found in standards and documents such as ANSI/ISA 67.04.01-2018 [1], IEC 61888:2002 [2] and IAEA SSG-39-2016 [3].

For example, reference [4] states that NPP’s licensed under the NRC rules meet the regulator’s requirements in this regard if they follow standard ANSI/ISA 67.04.01-2018. While other international standards also offer guidance and methods, each country's national regulatory authority ultimately recognizes specific acceptable standards and methods. Since the authors of this article have extensive experience in applying NRC regulations for instrument uncertainty calculations at NPP Krško, the following sections will focus on the requirements and methodologies recognized by the ANSI/ISA-67.04.01 standard and associated recommended practice document ISA-RP67.04.02[5].

3.1 Standard ANSI/ISA-67.04.01 and Recommended Practice ISA-RP67.04.02

The ANSI/ISA-67.04.01 is standard, which purpose is to define the bases for establishing safety-related and other important instrument setpoints associated with nuclear facilities, while the purpose of document ISA-RP67.04.02 is to present recommended practice including guidelines and examples of methods for the implementation of standard ANSI/ISA-67.04.01 in order to facilitate the performance of instrument uncertainty calculations and setpoint determination for safety-related instrument setpoints in nuclear power plants.

3.1.1 ANSI/ISA-67.04.01-2018: “Setpoints for Nuclear Safety-Related Instrumentation”.

The standard ANSI/ISA-67.04.01 in its first three sections explains its purpose, scope and provides definitions of the expressions used within. The central section of the standard is Section 4 which addresses establishment of instrument setpoints. Regarding the importance of each setpoint, setpoint determination requirements of different levels of rigor may be applied. However, within standard most rigorous setpoint methodology is presented. This should be used for setpoints that have significant importance to safety, as per instance those required by the plant safety analyses and related to reactor protection system, emergency core-cooling systems, containment isolation, and containment heat removal. The other setpoints that may not be of the same level of importance may be determined by less rigorous methodology. Another important section of the standard is Section 5 which outlines the documentation requirements for instrument channel uncertainty calculation, ensuring transparency and traceability. Key aspects to be documented include all instrument uncertainties (calibration, operation, drift, design-basis events), process effects influencing instrument measurement, calculations methods used to determine total instrument channel uncertainty, data sources and justified assumptions made during the uncertainty analysis. The documentation should also provide a comprehensive description of the instrument channel including instrument details, description of identified uncertainties and explanation of the relationship between the instrument's measurement and the process variables. When selecting trip setpoints based on the uncertainty calculation the document must provide the basis for selecting both limiting and nominal trip setpoints together with analytical limits and correction factors used to determine these setpoints.

3.1.2 ISA-67.04.02-2010: “Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation”.

The recommended practice document ISA-67.04.02 in its first three sections explain its purpose, scope and provide definitions of the expressions used within. The Section 4 explains the areas of its use. The recommended practice begins in Section 5, discussing preparation activities and content, such as an instrument channel layout diagram, identification of design parameters and sources of uncertainty. Within Section 5 a flow chart of the setpoint determination process is provided. The main section of the standard which deals with calculation of instrument channel uncertainties is Section 6. This section discusses the amount of an error in terms of probabilities. While a number of methods combining instrument uncertainties may exists, the document discusses the combination of statistical and arithmetic methods that uses statistical square root sum of squares (SRSS) method to combine random uncertainties and then arithmetically combine the nonrandom terms with the result. Further equations and discussion on sources of uncertainty and interpretation of uncertainty data are presented within 6.1 and 6.2 while the equations for calculating total instrument channel uncertainty are presented in 6.3. The Section 7 is focused on establishing the instrument setpoints. It discusses the requirements for the setpoints determination and provide the methods used to determine the setpoints in order to comply with the standard requirements. Further, the document in sections 8, 9 and 10 addresses as-found and as-left uncertainty test criterion, interface between various groups in nuclear facility regarding setpoints and documentation requirements.

The document also includes annexes that provide a glossary of terms and discuss various effects impacting total channel uncertainties in detail. Annex L provides practical examples of how to conduct uncertainty/setpoint calculations, covering scenarios related to pressure, flow, level, and radiation trip.

4 APPROACH TO CALCULATION OF INSTURMENT CHANNEL UNCERTAINTY

In order to be able to calculate instrument channel uncertainties it is essential for analysis engineer to be familiar with the requirements and methods outlined in the standard [1] and recommended practice document [5] discussed in Section 3 of this article. The engineer must understand the nature and sources of each uncertainty. Additionally, the engineer needs to have access to a database of equipment, calibration and process parameters, as well as the knowledge of the process requirements and environmental conditions for each device in the instrument loop. Based on the experience and document [5] following main steps presented with flowchart on Figure 2 have been recognized.

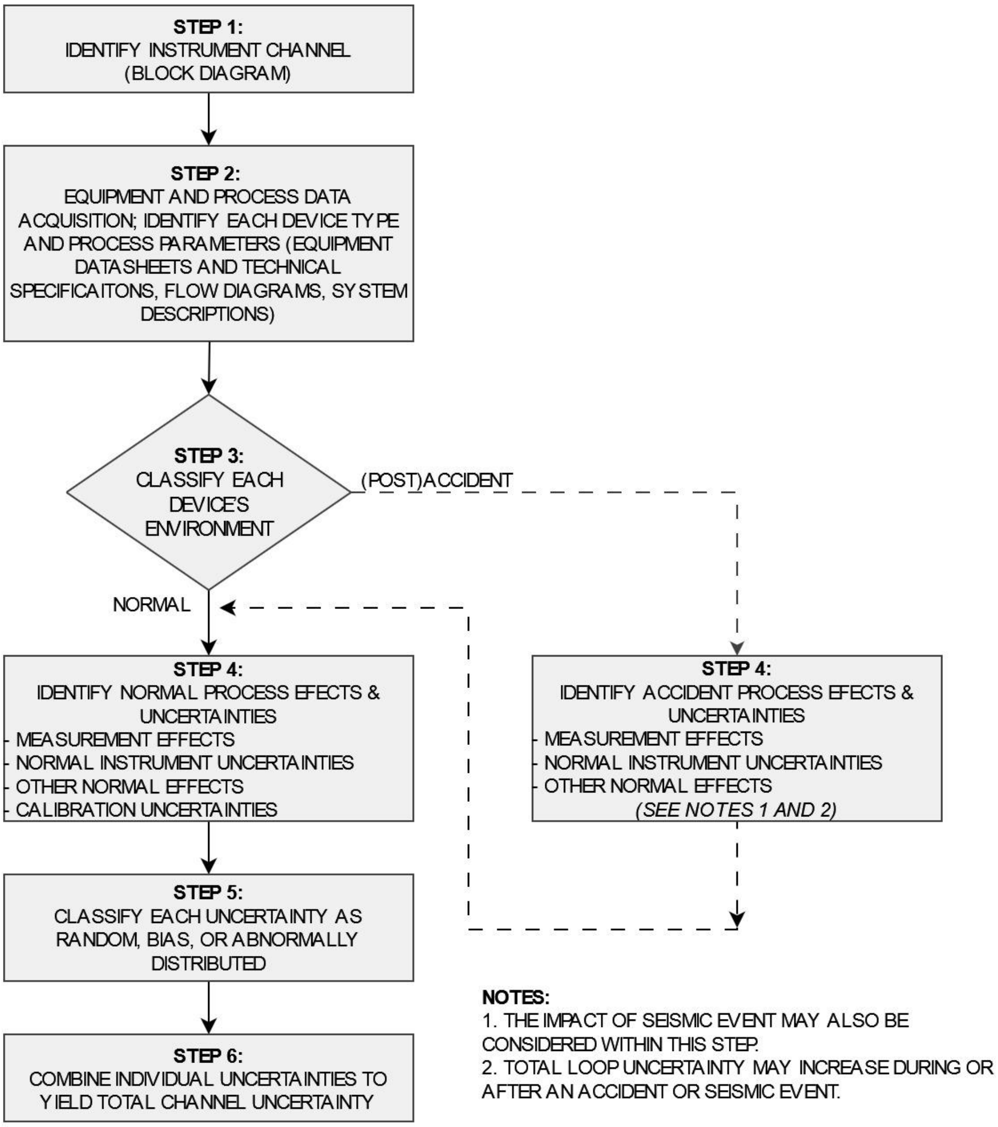
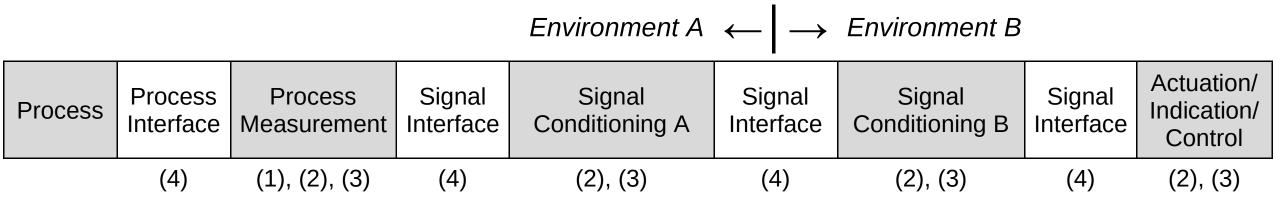


Figure 2: Instrument Channel Uncertainty Calculation Flowchart

STEP 1: Instrument Channel Identification

The first step involves clearly defining the instrument channel under consideration. This includes specifying all components involved, from the sensor and transmitter to any signal conditioning elements and the final display or control device. A detailed instrument loop diagram is a useful input for this purpose.

As a result, the instrument channel layout, as illustrated in Figure 3 below, should be constructed. This layout helps visualize and document the complete path a signal takes, addressing the associated uncertainties and incorporating them into the calculations.



Uncertainty Allowances to Address:

(1) Process Measurement Effects
(2) Equipment Uncertainties
(3) Calibration Uncertainties
(4) Other Uncertainties

Figure 3: Typical Instrument Channel Layout

STEP 2: Data Acquisition

For each identified device within an instrument loop, performance data must be collected. Additionally, data on the measured process, environmental conditions, calibration equipment and acceptable calibration tolerances must be obtained. It is crucial to know sensor measuring range, its accuracy and resolution as well as the operating and accuracy data of other equipment. Furthermore, the impact of environmental conditions during both normal and abnormal operating conditions must be considered.

Accessible databases associated with equipment and facility information can be of great help. These databases may include details such as equipment type, model, settings, measuring ranges, calibration ranges, calibration equipment, and installation location. Access to equipment datasheets, manuals, calibration plans, facility layouts, system descriptions, and other related documentation is also highly beneficial.

STEP 3: Device Environment Classification

The installation location of instruments and devices is crucial because environmental conditions significantly impact their performance. In addition to normal environmental condition at each location also abnormal environmental conditions must be considered. During and after accident events, instruments may be exposed to extreme temperatures, pressure spikes or radiation bursts. Therefore, the impact of changing environmental conditions on each device during and after abnormal events must be carefully evaluated.

In this step, seismic scenarios and their effects on the uncertainty increase for each device may also be considered.

STEP 4: Effects and Uncertainties Identification

The data gathered in Steps 1-3 (instrument loop structure, equipment details and location, environmental conditions, process conditions, calibration equipment, etc.) facilitates the identification of various effects and uncertainties contributing to the total instrument loop uncertainty. Types of effects and uncertainties that correspond to each component or/and interface are identified on Figure 3. These include:

- **process measurement effects** such as head effects, primary element effects, etc.;
- **instrument uncertainties** such as drift, temperature effects, pressure effects etc.;
- **other effects** such as power supply variations, mechanical vibrations, etc.;
- **calibration uncertainties.**

STEP 5: Uncertainty Classification

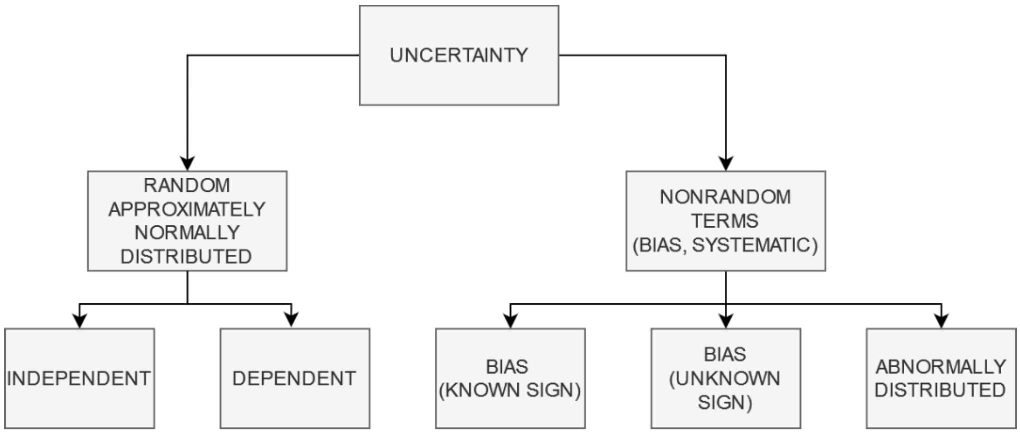
Following the identification of uncertainties in the previous step, this step involves categorizing them according to their characteristics to ensure they will be accurately considered within the calculation. Referring to uncertainty model, presented on Figure 4 uncertainties participating in the total instrument loop uncertainty shall be classified as:

- **Random uncertainties**

Random uncertainties refer to the inherent variability associated with a single measurement or a parameter derived from multiple measurements. They essentially quantify the statistical uncertainty or precision of a measurement. This reflects how closely repeated measurements of the same quantity tend to agree with each other. They are equally likely to be positive or negative with respect to some value. Manufacturer usually specifies them as having ± magnitude. Random uncertainties can be further classified as:

  - ***Independent:*** These uncertainties arise from individual instrument characteristics and are not related to each other. They typically follow predictable statistical patterns. It is generally accepted that most instrument channel uncertainties are independent of each other [5].
  - ***Dependent:*** These uncertainties share a common root cause that influence two or more of the uncertainties with a known relationship. By methodology presented in reference [5], this uncertainty should be added arithmetically to create a new, larger independent uncertainty if a user knows or suspects a common root cause.

- **Non-Random uncertainties:**
  - ***Bias with Known Sign:*** These uncertainties refer to systematic errors that consistently shift the measured value in a known direction and it may be associated with magnitude. Such uncertainty is for example change in flow element differential pressure because of process temperature change.
  - ***Bias with Unknown Sign:*** This bias can't be definitively determined to be positive or negative. The recommended approach is to conservatively consider it by adding it arithmetically in the worst possible direction (positive or negative).
  - ***Abnormal Distributions:*** These uncertainties deviate from expected patterns. They may be random but extremely not normal. The methodology given by reference [5] suggest to treat them as bias against both positive and negative components of module’s uncertainty.



ATTRIBUTES:	Variable Magnitude, Random sign		Variable or Fixed Magnitude and Known Sign	Variable or Fixed Magnitude and Unknown Sign	Variable Magnitude, Random Sign
OTHER NAMES	Statistical, Accidental, Precision	Corrected	Systematic	None	None
COMBINATIONAL RESTRICTIONS:	Square Root Sum of Squares (SRSS)	SRSS after Linear Partial Summing	Combine Like Signs Linearly	Absolute Value to Produce a Conservative Result	
QUANTIFICATION:	Two Sigma (95%) Probability Level		Estimated Limits of Error for Two Sigma (95%) Probability Level		
EQUATION TERMS: (See Equation 1)	±A, ±B, ±C	±D, ±E	+L, -M	±F	

Figure 4: Uncertainty Model

STEP 6: Calculating Total Instrument Loop Uncertainty

Total instrument loop uncertainty refers to the cumulative measurement uncertainty within a complete instrumentation loop. It includes all elements involved in the measurement process, from the primary sensor to the final display or control element. This uncertainty essentially quantifies the potential errors and inaccuracies that can arise from various components within the loop, ultimately affecting the reported value of the measured process variable.

Following the recommendations outlined in reference [5], the total instrument loop uncertainty (TLU) shall be determined by statistically combining random uncertainties using the Square Root Sum of Squares (SRSS) method. Subsequently, the non-random uncertainties are arithmetically combined with the result obtained from the SRSS calculation. The recommended practice document gives the following basic equation for uncertainty calculation:

$$TLU = \pm\sqrt{(A^2 + B^2 + C^2 + (D + E)^2)} \pm |F| + L - M \tag{1}$$

where:

TLU	Resultant uncertainty. The resultant uncertainty combines the random uncertainty with the positive and negative components of the nonrandom terms separately to give a final uncertainty. The positive and negative nonrandom terms are not arithmetically combined before combination with the random component.

A, B, C	Random and independent terms. The terms are zero-centered, approximately normally distributed, and indicated by a ± sign.
D, E	Random dependent uncertainty terms that are independent of terms A, B and C.
F	Abnormally distributed uncertainties and/or biases (unknown sign). The term is used to represent limits of error associated with uncertainties that are not normally distributed and do not have known direction. The magnitude of this term (absolute value) is assumed to contribute to the total uncertainty in a worst-case direction and is also indicated by a ± sign.
L, M	Biases with known sign. The terms can impact an uncertainty in a specific direction and, therefore, have a specific + or - contribution to the total uncertainty.

The total loop uncertainties should first be calculated for normal operating conditions. Afterward, the impacts on total loop uncertainty due to abnormal operating conditions, caused by accident and seismic events, should also be considered.

4.1 Documenting the Calculation

As required by standard [1], the instrument channel uncertainty calculation shall be well documented to ensure transparency and traceability. The document should therefore include all input data or clearly reference the sources of these data. It should provide an instrument channel block diagram, describe the identified uncertainties and calculation methods used, justify any assumptions made, explain the relationship between the instrument and process variables, and provide a clear step-by-step calculation of the total loop uncertainty. The results should be clearly highlighted and, if needed, graphically presented.

5 CASE STUDY: CALCULATING EQ INSTRUMENT CHANNEL UNCERTAINTY IN NEK

The authors of this article participated in a project to calculate all environmentally qualified (EQ) instrument channel uncertainties at NPP Krško (NEK), which had not been previously calculated. A total of 71 EQ instrument loops were evaluated. The project aimed to determine these uncertainties, mainly for the main control room (MCR) indicator readings and to identify increases in uncertainty stemming from the effects of accidents and seismic events.

During normal operation, EQ instrument channel naturally behaves differently than in emergency conditions. In normal operation, the environmental conditions at the locations where the subject equipment is located are Mild. Therefore, in these normal environmental conditions, the accuracy of the equipment is within normal specifications. However, since EQ equipment is the one that must function even in and after the occurrence of DBA conditions, the impact of demanding Harsh environmental conditions on the operation of the subject equipment can be significant.

The 71 instrument loops considered in this project measured a variety of process variables, including: hydrogen concentration, differential pressure, flow, level, pressure, radiation, speed, temperature and position.

The ultimate goal is to incorporate calculated values into training of the operational staff, including the increased loop uncertainties in simulations of accident events. In this way, the staff will be made aware of the possibility of increased uncertainties of specific I&C equipment and channels in accidental events. Currently, in the algorithms of the simulator plant, an equipment normal operating conditions uncertainty are used also for simulation of accident scenarios for some specific instrument channels.

5.1 General Approach to the Project

Since NEK is licensed according to NRC regulations, as mentioned in Section 3 of this article, standards [1] and document [5] were followed. Approach outlined in upper Section 4 was employed in order to calculate each instrument loop uncertainty. However, given the involvement of 71 instrument loops, with some known to be similar, our initial consideration was how to comprehensively address all necessary aspects while avoiding redundant calculations. As a result, two assumptions were introduced.

- **Assumption 1:** Independent instrumentation loops measuring the same quantity of the same or equivalent process may be considered as equivalent if the instrument loop consists of exactly the same or considered as such instrumentation and calibration equipment and the equipment is exposed to the same or equivalent environmental conditions.

- **Assumption 2:** If the two independent instrumentation loops which are measuring the same quantity of the same process in general consist of the same equipment, but with deviation in some parts, they then may be considered as equivalent only in parts where the same instrumentation and calibration equipment is used. Uncertainties of the unique parts of these two independent instrument loops must be calculated separately and then used in the total loop uncertainty respectively, unless unique equipment of these loops are proven to have the same uncertainty.

By applying steps 1 and 2 of the proposed approach to all 71 instrument loops before initiating uncertainty calculations, we were able to leverage the identified similarities and gathered data. These assumptions effectively reduced the number of unique calculation cases to 24 representative cases.

5.2 Steps 1 and 2: Instrument Channel Identification and Data Acquisition

While identifying all components of instrument channels under consideration was relatively straightforward by reviewing the detailed instrument channel loop diagrams available for the plant, acquiring all necessary data proved to be a challenging and time-consuming process. The data had to be gathered from various available sources including NEK-specific databases, process flow diagrams, system specification description, equipment manuals and datasheets, etc. Some of the data was particularly challenging to locate, but ultimately, it was necessary to gather all instrument, process, and environmental data, or estimate them conservatively based on realistic assumptions in case the data were unavailable.

An example of an assumption made is the primary element accuracy in all flow measurement loops. This accuracy was conservatively evaluated to be ±1.25% of span, based mainly on our previous experience with flow measurements and the experience of others. The main reason for this assumption was the lack of data for most installed orifices. The final value includes estimated orifice uncertainty as well as the effects of piping configuration and flow element degradation.

5.3 Step 3: Device Environment Classification

NEK documents detailing environmental conditions for each room provide the following parameters for both normal operating and accident conditions:

- Peak temperature
- Peak pressure
- Maximum humidity
- Chemical spray
- Flood level
- 40(60) year dose gamma

- Accident dose gamma - 1-year post-accident operability time (PAOT)
- Accident dose beta - 1-year PAOT

For each identified device's site location, these parameters were obtained for further consideration within the calculations. Environmental conditions for both design basis accidents (DBA) and design extension conditions (DEC) were considered based on the loop function. The function determines to which accident condition the loop is qualified. Most of the considered instrument loops have a DBA function, while only a few have a DEC function.

5.4 Steps 4 and 5: Effects and Uncertainties Identification and Uncertainties Classification

Considering instrument loop layouts, measured quantities, measurement principles, and locations, we identified the effects and uncertainties within each channel. While all components within an instrument loop contribute to the overall measurement error, transmitters are generally the most exposed and sensitive to different factors affecting their performance. They directly convert the process quantity (e.g., pressure) into an electrical signal, and their performance can be significantly impacted by limitations of the transmitter's internal components, as well as external factors like temperature, pressure, power supply variation, and other.

The information how different factors affect the performance of the equipment in terms of uncertainty is usually provided by the manufacturer within device datasheet. However, in addition to uncertainties provided by manufacturers, other uncertainties such as process element accuracy, uncertainty due to insulation resistance reduction, and calibration uncertainty must also be acknowledged and taken into account.

To illustrate, Figure 5 below shows the instrument loop layout for one of the cases in the project, specifically the Train A supplied air handling units common inlet flow measurement.

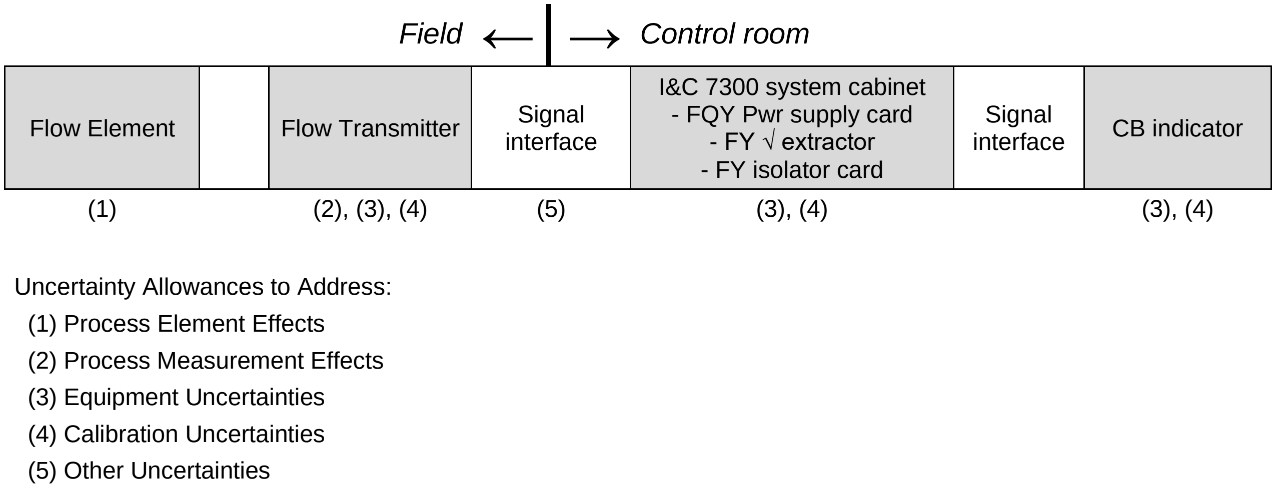


Figure 5: Flow Measurement Instrument Loop Layout

Following this, Table 5-1 provides an overview of the identified effects and uncertainties with assigned type of allowance from Figure 5, uncertainty classification and description for each element within the instrument loop.

Table 5-1: Overview of Identified Effects and Uncertainties with Assigned Type of Allowance and Uncertainty Classification

Effect/Uncertainty	Allowance Type	Uncertainty Classification	Description
Flow Element:			
Primary element accuracy (uncertainty of discharge coefficient of orifice plate and related pipe configuration and other installation effects)	1	Random dependent	Uncertainty of discharge coefficient of orifice plate, related pipe configuration, and other installation effects.
Transmitter:			
Sensor reference accuracy	3	Random independent	Accuracy under reference conditions.
Sensor calibration accuracy	4	Random dependent	Accuracy during calibration.
Sensor measurement and test equipment accuracy (pressure module and multimeter accuracy)	4	Random dependent	Accuracy of measurement and test equipment.
Sensor temperature effect	2	Random independent	Impact of temperature variations on accuracy.
Sensor drift	3	Random independent	Gradual change in sensor output over time.
Sensor pressure effect (sensor pressure zero effect, sensor pressure span effect)	2	Random independent	Impact of pressure variations on sensor zero point and span.
Sensor power supply effect	3	Random independent	Impact of power supply variations on accuracy.
Seismic effect	3	Random independent	Accuracy under seismic condition.
Radiation effect	3	Random dependent	Accuracy under radiation condition.
Steam pressure/temperature exposure	3	Random dependent	Accuracy during steam pressure and temperature exposure.
Signal interface between transmitter and I&C rack:			
Insulation resistance effects	5	Random independent	Impact of insulation resistance on signal integrity.
Westinghouse 7300 system I&C rack:			
Series power supply card reference uncertainty	3	Random independent	Reference uncertainty of the power supply card.
Series square root extractor card reference uncertainty	3	Random independent	Reference uncertainty of the square root extractor card.
Series isolator card reference uncertainty	3	Random independent	Reference uncertainty of the isolator card.
Series power supply card calibration accuracy	4	Random dependent	Calibration accuracy of the power supply card

Effect/Uncertainty	Allowance Type	Uncertainty Classification	Description
Series square root extractor card calibration accuracy	4	Random dependent	Calibration accuracy of the square root extractor card.
Series isolator card calibration accuracy	4	Random dependent	Calibration accuracy of the isolator card.
Rack measurement and test equipment accuracy	4	Random dependent	Accuracy of rack measurement and test equipment.
Rack drift	3	Random independent	Gradual change in rack output over time.
Rack temperature effect	3	Random independent	Impact of temperature variations on rack performance.
Main control board indicator			
Indicator calibration accuracy	4	Random dependent	Calibration accuracy of the indicator.
Indicator measurement and test equipment accuracy	4	Random dependent	Accuracy of indicator measurement and test equipment.
Indicator temperature effect	3	Random independent	Impact of temperature variations on indicator performance.
Indicator drift	3	Random independent	Gradual change in indicator output over time.
Indicator readout accuracy	3	Random independent	Accuracy of the indicator readout.

During plant normal operation, transmitter is working within prescribed environmental conditions, therefore no seismic, radiation, steam pressure/temperature uncertainty is considered for this case. Furthermore, cable from field to I&C rack is not subject of potential insulation reduction due to radiation exposure.

However, in the event of accident events, environmental conditions in each room are considered, and uncertainties related to radiation, steam pressure/temperature, and insulation resistance are added to the normal operation transmitter. Furthermore, insulation resistance uncertainty for cable from the transmitter to the I&C rack is also included.

In addition to these factors, the uncertainty calculations for accident conditions must also account for any changes in normal operating parameters, such as ambient temperature and pressure, that occur during an accident.

Seismic events are addressed separately due to the assumption that it is improbable for both a seismic event and an accident harsh environment to occur simultaneously. Therefore, the uncertainty calculations for seismic events are handled independently.

5.5 Step 6: Calculating Total Instrument Loop Uncertainty

As mentioned earlier in Section 5.1, efforts were made to identify identical or similar instrument loops to avoid redundant calculations. Consequently, 24 different cases were identified. For each case, a reference loop is introduced and calculated. All other loops within each case generally refer to the reference loop and are calculated only for deviated parts, following assumption 2 (see Section 5.1). Deviations may occur in equipment type, process, equipment calibrated span, environmental conditions, etc.

The calculation is performed using Equation 1. The instrument's total loop uncertainty (TLU) calculation is conducted in a per-partes manner, which means that the total uncertainty for each device is first calculated according to the rules presented by Equation 1, with each uncertainty accounted for by its classification (see Table 5-1). These uncertainties are then added together using the SRSS method.

5.5.1 Relationship between the instrument's measurement and the process variables

In most instrument loops, the transmitter converts the measured variable (e.g., pressure, temperature) into a standard electrical signal, typically current or voltage. This signal may then be further conditioned by upstream I&C equipment before reaching its final destination.

It's important to consider that many random uncertainties associated with instrument loops are often expressed a percentage of the measured span and a fixed value. This means the uncertainty value is dependent on the specific measurement value within the span, but as long as the relationship between all variables within the loop remains linear, the Total Loop Uncertainty (TLU) will be relatively constant across the measured span.

However, linear relationships between variables are not always the case. A prime example of this is presented in Section 5.4, where flow measurement is based on Bernoulli's principle. In this case, flow is indirectly measured by observing the differential pressure (Δp) across the orifice plate. When flow is measured indirectly by observing the Δp across the orifice, the flow value is obtained from the measured Δp value, considering the following relation:

$$F = K \cdot \sqrt{\Delta p} \tag{2}$$

where:

F	Volumetric flow rate.
K	Constant that depends on the specific properties of the fluid and the flow restrictor (orifice).
Δp	Differential pressure.

Examining the instrument loop layout (see Figure 5), it becomes apparent that a square root extractor card is utilized within the Westinghouse 7300 I&C system for the associated instrument channel. This extractor is employed due to the linear scale of the MCB indicator across the entire flow rate measurement span.

When calculating total loop uncertainty, it must be accounted that relationships between variables downstream and upstream the square root extractor is no longer linear. Relative uncertainties are therefore assigned to Δp span and flow span, downstream and upstream square root extractor accordingly. For a graphical representation, refer to Figure 6 below.

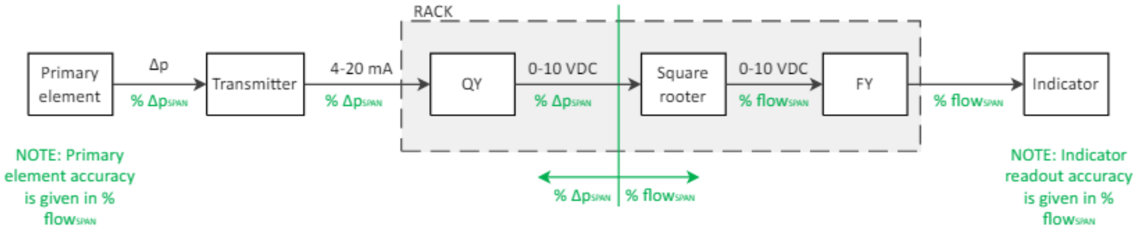


Figure 6: Flow measurement loop with a square root extractor – non-linearly dependent uncertainties

The non-linearity among all variables within the instrument loop results in varying uncertainty at each read-out flow rate across the indicator span. The uncertainty for each flow rate may be calculated by following Equation.

$$TLU_{F\pm} = \pm\sqrt{\left[K \cdot \sqrt{\left(\frac{F}{K}\right)^2 \pm CU_{\Delta p}} - F\right]^2 + CU_F} \tag{3}$$

where:

$TLU_{F\pm}$	Resultant accuracy at each specific flow rate value. It shall be separately calculated for positive and negative value.
F	Volumetric flow rate.
K	Constant that depends on the specific properties of the fluid and the flow restrictor (orifice).
$CU_{\Delta p}$	Channel uncertainty with linear relationship to differential pressure.
CU_F	Channel uncertainty with linear relationship to flow rate.

5.5.2 Normal, Accident and Seismic operation consideration

During plant normal operation, transmitter is working within prescribed environmental conditions, therefore no seismic, radiation, steam pressure/temperature uncertainty is considered for this case. Furthermore, cable from field to I&C rack is not subject of potential insulation reduction due to radiation exposure.

However, in the event of accident events, environmental conditions in each room are considered, and uncertainties related to radiation, steam pressure/temperature, and insulation resistance are added to the normal operation transmitter. Furthermore, insulation resistance uncertainty for cable from the transmitter to the I&C rack is also included.

In addition to these factors, the uncertainty calculations for accident conditions must also account for any changes in normal operating parameters, such as ambient temperature and pressure, that occur during an accident.

Seismic events are addressed separately due to the assumption that it is improbable for both a seismic event and an accident harsh environment to occur simultaneously. Therefore, the uncertainty calculations for seismic events are handled independently.

5.5.3 Results presentation

The results for instrument channels with contact uncertainties may be given by clearly outlining the calculated ± value. For uncertainties that vary across the entire span, it is recommended to present the results in both tabular and graphical formats. Graphical representation can offer extrapolation between calculated values, providing a more comprehensive understanding of the uncertainty distribution across the total indicator range. An example of graphical presentation is provided on Figure 7.

It shall be noted that the absolute value of negative flow rate uncertainty TLU_{F-} may not be greater than reading point value, since the flow rate scale does not show values bellow 0 m^3/h. Therefore CU_{F-} uncertainty for readings below $CU_{\Delta p}$ is determined as negative value of flow reading.

All results and presentations should be provided separately for each operational condition: normal, accident and seismic.

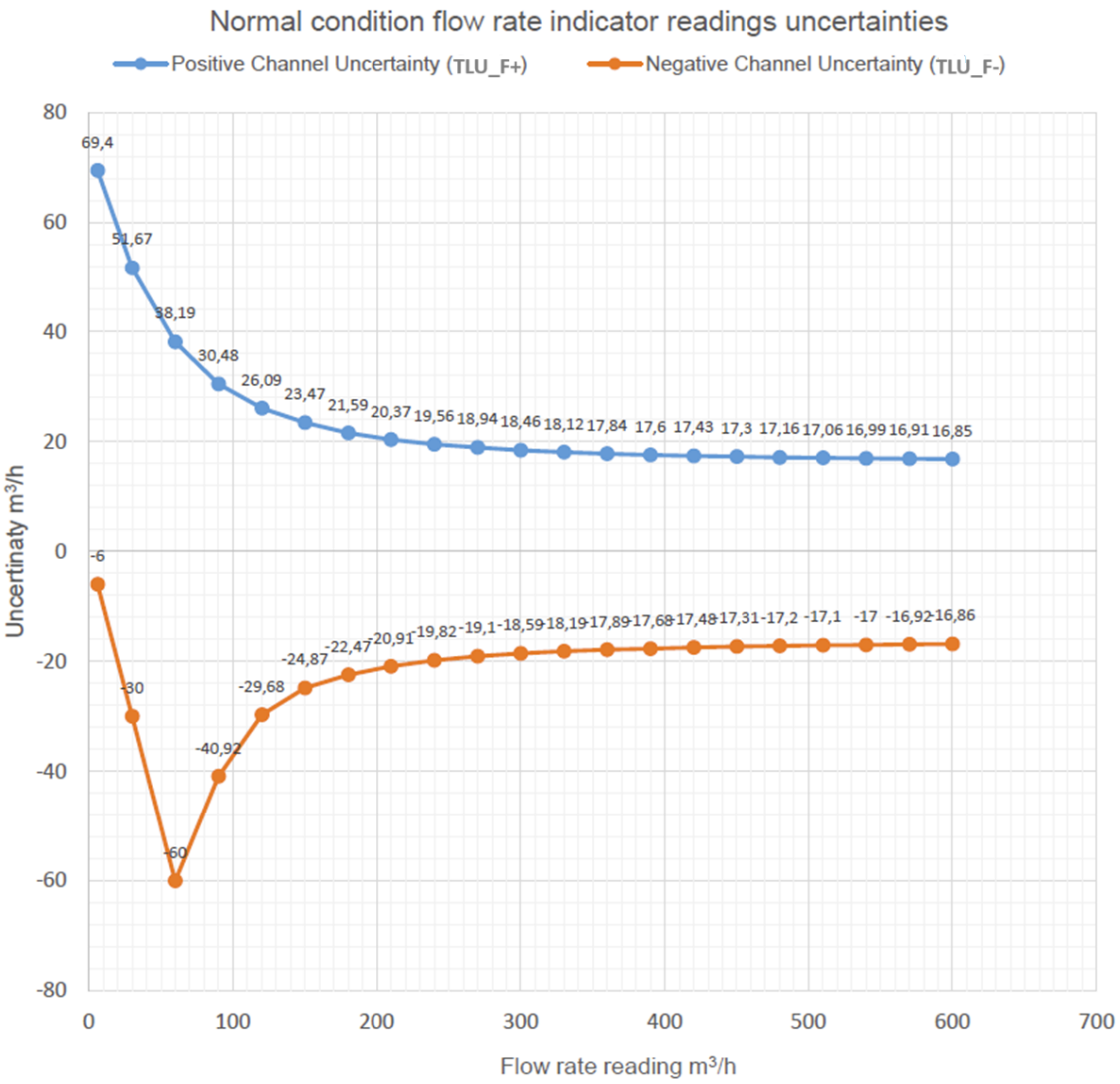


Figure 7: Train A supplied air handling units common inlet flow measurement total loop uncertainty under normal operating conditions.

6 CONCLUSION

The article underscores the significance of understanding instrument channel uncertainties in nuclear power plants (NPP's), particularly in ensuring operational safety and reliability. In the first part, the necessity of conducting uncertainty calculations is thoroughly explored, with an emphasis on the critical role these assessments play during normal operation and in potential accident or seismic scenarios. The regulatory framework, standards, and recommended practices governing such calculations are meticulously outlined, highlighting the importance of adherence to industry best practices.

Moreover, the article suggests a structured approach consisting of six essential steps for calculating total instrument loop uncertainties. This methodical approach serves as a foundation for accurate calculation of the uncertainties.

In the second part of the article, the presented approach is applied to a practical case study involving the calculation of 71 EQ instrument channel uncertainties at the NPP Krško (NEK). Through this case study, the complexities inherent in such calculations are elucidated, offering valuable insights into the challenges and considerations involved. By providing a real-world example, the article enhances understanding and facilitates the application of the outlined approach.

Overall, the article provides a comprehensive overview of the importance of instrument channel uncertainty calculations in NPPs and offers a practical methodology for conducting such assessments.

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