Main Feedwater Flow Station Measurement Verification by CROSSFLOW

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ABSTRACT

NPP Krsko (NEK) is a two loop PWR plant. Calorimetric power measurement is used to determine reactor power from the plant primary and secondary side parameters: main feedwater flow and temperature, steam generator pressure, blowdown flow, RCS Thot and RCS Tcold temperatures.

Main feedwater flow (MFW) is measured based on the pressure drop principle via two 16” venturi pipes (one per FW line) and associated instrument loops. Existing NEK thermal design uncertainty analysis (SSR-NEK-3.0) is based on MFW uncertainty of 0.81%. Statistical and analytical methods (comparisons of different plant parameters) show that there may be slight deviations in the measured MFW. There are methods and procedures in place to verify and calibrate the measured MFW. Only measurement elements, which cannot be verified with standard calibration procedure (comparison reference versus actual measurement) are MFW venturi pipes. Verification of station MFT measurements was performed in NEK by an ultrasonic method on two occasions, prior High Pressure Turbine replacement and after High Pressure Turbine replacement.

The measurement was performed by AMAG company. Data acquisition was carried out by AMAG’s ultrasonic flow meters (CROSSFLOW) and ultrasonic temperature meters (CORRTEMP), which were installed on the two main feedwater loops and on the common header of the main feedwater piping. CROSSFLOW calibration for the Krsko piping configuration was performed at Alden Research Laboratory, where correction factors were calculated for the acquired data.

This article will present the results of the ultrasonic measurement performed in NEK and its comparison with the current feedwater flow measurement based on venturi pipes.

Keywords: *main feedwater, ultrasonic flow, CROSSFLOW, CORRTEMP*

1 INTRODUCTION

Normal plant operation of nuclear power plants is to operate on full power constantly, where the reactor full power is maintained regarding to the secondary calorimetric calculation. The calculation of secondary calorimetry is based on the Main Feedwater (FW) flow, Blowdown (BD) flows and the enthalpies of the Main Steam (MS), FW and BD systems. The main contribution of all the inputs comes from the FW flow measurement.

Measurable parameters that are used in calorimetry calculation are FW flow, FW temperatures, MS pressure, BD flow, RCS Thot and RCS Tcold temperatures. Instrumentation used to measure those parameters is checked and calibrated periodically to verify that installed equipment is operating properly and within required accuracy. When it comes to flow instrumentation, which most often consists of a flow element and a delta pressure transmitter, it is not possible to calibrate all the components of the system. Flow elements (ex. orifices, venturi nozzles) are installed inside the piping and are defined by their design parameters. Any undetectable changes on the flow elements, like corrosion or fouling, can affect the final measurement and lead to false reading.

NEK is using venturi nozzle as a flow element for the FW flow measurement, pressure difference over venturi (DeltaP) is converted into current signal, which is then used as an input to different applications, one of which is calculation of secondary calorimetric power.

After the Film Forming Amines (FFA) were injected into plant secondary systems to improve chemistry and inhibit corrosion effects, Krsko plant has experienced a minor change in the plant parameters and consequently reduction of the output power MW. To verify accuracy of the FW measurement by venturi, the plant has decided to perform parallel and independent measurement of FW flow by using AMAG’s cross-correlation technique: ultrasonic flow meters (CROSSFLOW) and ultrasonic temperature meters (CORRTEMP). The cross-correlation instrumentation is utilized in a non-safety related application to provide flow measurements that can be used to correct the plant’s feedwater flow instrumentation.

2 MAIN FEEDWATER FLOW MEASUREMENT VERIFICATION

The Main FW system is designed to take suction from the Condensate System increasing fluid pressure, via the FW pumps, to overcome system resistance and steam generator pressure and supply the steam generators with adequate feedwater during all modes of power operation including transient conditions.

Output flow from the two operating FW pumps goes via two pipelines, through the FW heaters, and is recombined into a single pipe (common header) to ensure an even temperature distribution of water being supplied to the steam generators. Common header pipeline then branches into two separate pipelines, where each line contains control system that regulate the flow of feedwater to their respective steam generators. Venturi nozzles are installed on these separated pipelines, as shown on Figure 1. Locations of the CROSSFLOW sensors are also marked on Figure 1.

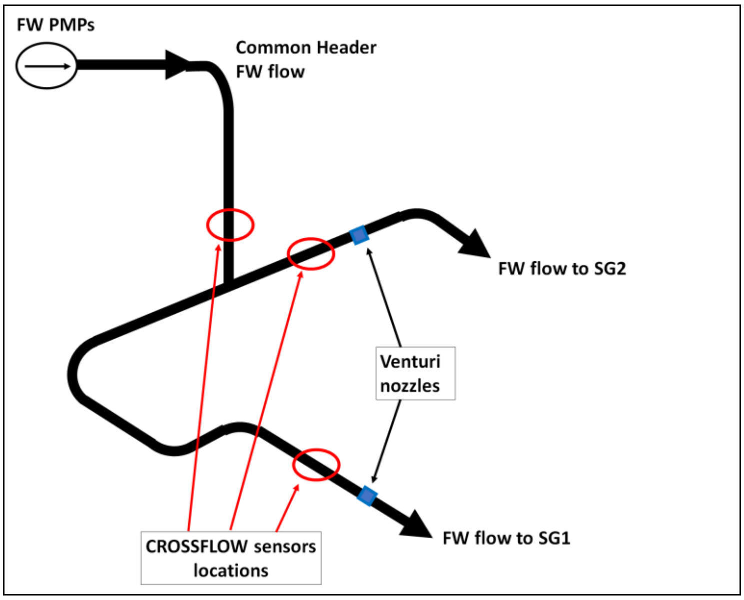

Figure 1: FW pipeline with assigned locations of venturi nozzles and CROSSFLOW sensors

2.1 PRINCIPLE OF FLOW MEASUREMENT WITH VENTURI NOZZLES

Measurement of main FW flow with venturi tube is a standard in nuclear industry. Venturi flow measurement is working on a principle of measuring pressure difference at two different locations on the pipe. This pressure difference is created by reducing a diameter of the pipe at one end, respectively reducing a cross section. Flow measurement is based on Bernoullie equation and the equation of continuity; reducing a cross section will cause an increase in flow velocity and a corresponding pressure drop (DeltaP). DeltaP is measured at the entrance of venturi tube (hi tap) and at the narrowest section of the venturi nozzle (low tap), as it is shown on Figure 2.

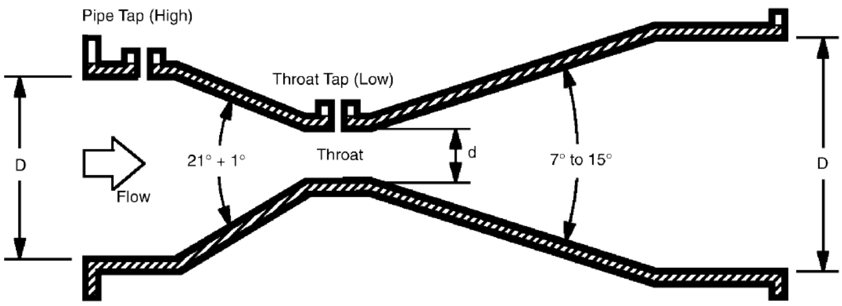

Figure 2: Principle of flow measurement with venturi nozzle

The square root of the measured DeltaP is proportional to the velocity of the fluid:

$$Flow = K \times \sqrt{DeltaP} \tag{1}$$

where K is a function of pipe's normal and reduced cross section, density of the fluid and discharge coefficient.

Venturi flow measurement is very reliable, as long as there is no deviation in physical characteristics of the venturi nozzles, like corrosion effects or fouling of foreign materials on the nozzle. That is why maintaining chemical parameters within acceptable limits is of great importance for long-term operation of nuclear power plants. Uncertainty of the venturi flow measurement in NEK is 0,81%.

2.2 PRINCIPLE OF ULTRASONIC CROSS-FLOW MEASUREMENT

CROSSFLOW system is a non-intrusive measurement which is working on a principle of transmitting a beam of ultrasonic signals at one end of the pipe and receiving the signal on the opposite end of the pipe. The system consists of two sets of ultrasonic transducers (two transmitter-receiver pairs) that are mounted in the same horizontal line and displaced by a known distance, as shown on Figure 3.

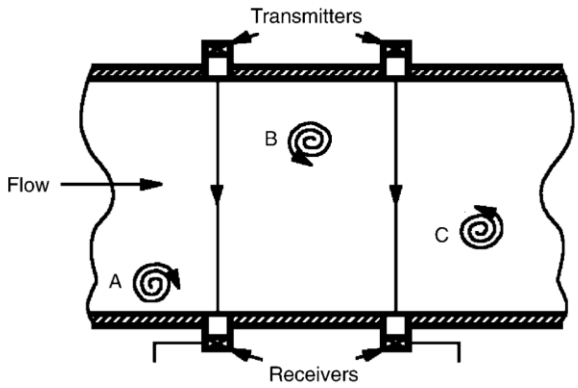

Figure 3: Principle of flow measurement with CROSSFLOW

As the ultrasonic signal passes through the fluid vertically to the direction of flow, turbulences inside the fluid modulate the ultrasound signal in both amplitude and phase. This modulation represents a statistically unique "signature". Detecting the same or similar patterns by both sets of transducers and by determining a time delay between similar patterns on both ends, it is possible to calculate the flow rate with a following equation:

$$Mass\ Flow = K \times \rho \times A \times \frac{L}{\tau_L} \tag{2}$$

where:

K = calibration coefficient (correction factor)

ρ = density of the fluid

A = inner cross-sectional area of pipe

L = distance between upstream and downstream transducers

τ_L = time delay between two similar patterns detected by both sets of sensors

It is important to set a proper distance between two sets of sensors such that detected signal patterns doesn't change too much on both ends, in amplitude and phase. Also, location of the installed equipment should be at a long straight pipe section where no or little upstream disturbance is present. Density of the fluid can be determined from the fluid temperature, while calibration coefficient/correction factor is usually determined by additional laboratory testing. Accuracy of cross-correlation flow measurement is usually within 0,5%.

2.3 ULTRASONIC CROSS-FLOW MEASUREMENT PERFORMED IN NEK

This project was performed in 3 phases [4]:

1) 1st measurement in NEK, prior to the High Pressure Turbine replacement (18 hrs of data acquisition)
2) Hydraulic test at Alden Research Laboratory
3) 2nd measurement in NEK, after the High Pressure Turbine replacement (17.5 hrs of data acquisition)

In the first phase, AMAG's CROSSFLOW ultrasonic flow measurement system was installed on FW flow piping on Loop 1, Loop 2, and Common Header to measure flows at ~100% reactor power. The system used in NEK employs a multi-plane transducer frame assembly which allows performing four flow measurements on the same pipe simultaneously to improve uncertainty of the average flow. Each multi-plane frame uses sixteen ultrasonic transducers that send and receive signals to and from the CROSSFLOW system electronics (4 sets of transmitter-receiver pairs installed on each end of the assembly).

Additionally, AMAG's ultrasonic temperature measurement system CORRTEMP was installed on the FW Loop 1 and 2, aside of CROSSFLOW transducer assembly. This allowed improvement in accuracy of temperature inputs used to calculate mass flow rate of the FW loops and their corresponding uncertainties.

Prior installation of the transducer assemblies, the pipe outside diameter and wall thickness were measured by AMAG personnel for each of the locations. Based on these measurements, the average pipe Internal Diameter (ID) was calculated. The measurements were performed at hot conditions while the plant was approximately at 100% full power. For the purpose of outside diameter and thickness measurements, insulation was removed from the pipe and the pipe surface temperature was about 10°C cooler than the temperature of the water in the pipe. During the actual flow measurement, the pipe was again insulated and pipe wall was assumed to have the same temperature as feedwater water. The measured pipe diameters were corrected for the temperature differences to account for the fact that pipe was insulated during flow measurements. Because the pressure of the water was the same during the pipe measurement and during the flow measurement, no correction was applied for the pipe swelling due to the change in pressure.

Since there is no pressure transmitters installed to measure pressure for FW Loops 1 and 2, pressure readings for Loops 1 and 2 were manually taken from FT510A HI side and FT520A HI side two weeks before CROSSFLOW measurements took place. Acquired data showed that fluctuations of pressure within the FW pipe were less than 0,6 kg/cm^2 peak-to-peak, which is negligible for the CROSSFLOW measurement, so fixed pressure values were used as input data for the CROSSFLOW calculation.

The transducer spacing for all frames was measured for each plane at AMAG at documented room temperature (distance between each two sets of sensors). Since flow measurements were performed on insulated frames, the temperature of the spacer bars is assumed to be of the same as feedwater temperature. The spacing values were re-calculated for thermal expansion using the water temperature as a reference (temperature measured with CORRTEMP system).

As marked on Figure 1, locations of the CROSSFLOW transducer frame assemblies were:

- FW Loop 1 CROSSFLOW transducer frame assembly was installed on horizontal 16" pipe downstream of 90° elbow with 5Ø bend and upstream of the venturi flow element.

- FW loop 2 CROSSFLOW transducer frame assembly was installed on horizontal 16” pipe downstream of 90° out-of-plane elbow with 1.5Ø bend and upstream of the venturi flow element.
- FW Common Header CROSSFLOW transducer frame assembly was installed on a vertical 20” pipe downstream of 90° elbow with 1.5Ø bend.

Configuration of installed CROSSFLOW transducer frame assembly (16 transducers) and CORRTEMP transducer assembly (2 transducers) is shown on Figure 4.

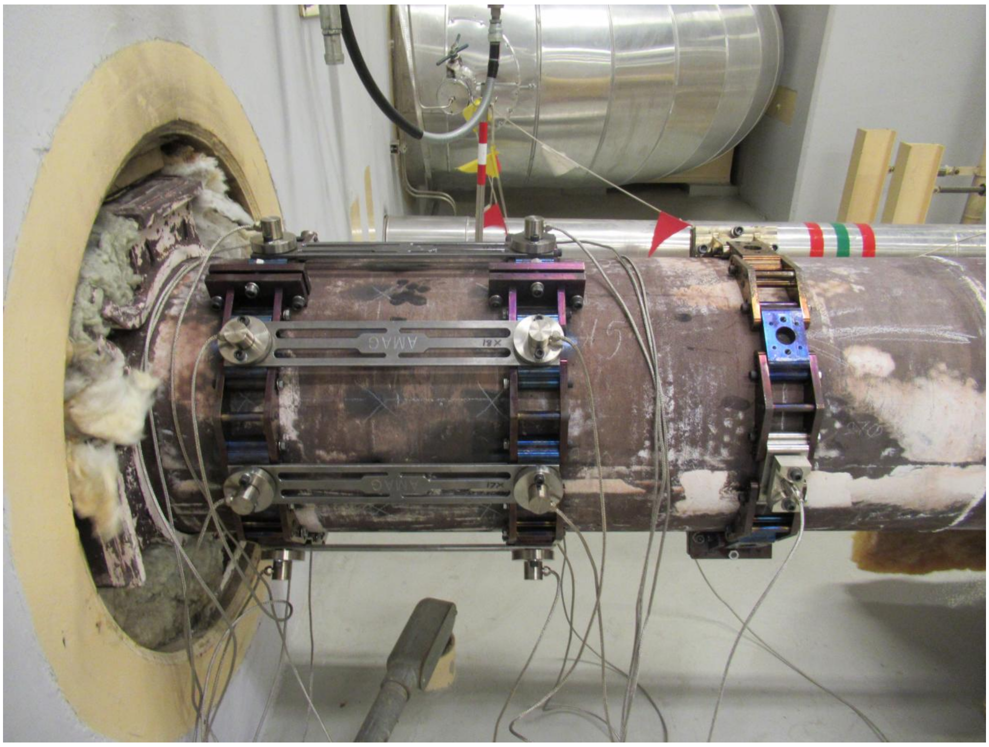

Figure 4: FW Loop #1 CROSSFLOW assembly (left) and CORRTEMP assembly (right)

Both CROSSFLOW and CORRTEMP systems of the associated loop were connected to same data acquisition system. Initial plan was to bring signals from all the transducer assemblies (both FW Loops and Common Header) to data acquisition equipment, which would be located on one spot in the Common Header room. Due to complicated cable routing through penetration between Intermediate Building (Loop 1 and Loop 2 pipelines) and Turbine Budling (Common Header pipeline), that option has been rejected. Instead, electronical equipment for the FW Loop 1 and Loop 2 data acquisition was placed in the Intermediate Building, near the Loop 1 measurement location. This location was chosen based on local area temperature, since the electronical equipment should not be exposed to a room temperature higher than 40 °C. Electronics for Common Header data acquisition was setup besides the Common Header CROSSFLOW sensors in the Turbine Building.

Time interval of data collection was around 18 hrs. In parallel with CROSSFLOW data acquisition, plant data was acquired for different plant parameters. Reason for taking plant data was for comparison with CROSSFLOW results. The following average data from Process Computer System (PIS) was provided to AMAG by NEK:

- FW flow Loop 1 [t/h]
- FW flow Loop 2 [t/h]
- FW temperature Loop 1 [°C]
- FW temperature Loop 2 [°C]
- Common Header pressure [kp/cm2]
- Calorimetric power level [%]
- FW Loop 1 control valve demand voltage [%]
- FW Loop 2 control valve demand voltage [%]
- FW Loop 1 control valve position [%]
- FW Loop 2 control valve position [%]

Acquired CROSSFLOW data gave approximate results for the measured flows. To reach best possible accuracy, additional calibration tests were performed and correction flow factors were calculated in the second phase of testing. A hydraulic test was conducted for each pipe, using 1:1 model of the NEK FW piping upstream of CROSSFLOW installations, to calibrate CROSSFLOW. Testing was performed at Alden Research Laboratories LLC, which is the largest independent supplier of National Institute of Standards and Technology traceable flow meter calibrations in USA. Laboratory test was needed due to a lack of a long straight pipe section, which can be seen on the Figure 1, and to meet the desired flow uncertainty. A built model of NEK FW piping (1:1 model) is showed on Figure 5.

Figure 5: 1:1 model of NEK FW system assembled at Alden Research Laboratory

In the third phase, the CROSSFLOW flow and CORRTEMP measurements were repeated after the HP turbine replacement. Correction factors previously calculated at Alden Research Laboratories were also used for second CROSSFLOW measurement.

AMAG's CROSSFLOW measurements were compared with the independent NEK station flow measurements (data acquired from the Plant Computer), final results are shown in Table 1. It can be seen that station flow indication and CROSSFLOW are in a close agreement which confirms that the venturis are not degraded and within required accuracy.

Table 1: Station FW flow vs CROSSFLOW flow

CROSSFLOW Location	Station Flow (Metric Ton/hr)	CROSSFLOW Flow F_{UT} (Metric Ton/hr)	Uncertainty ε_{FUT} (%)	Difference (%) (relative to station flow)
Measurement #1	**Interval: 31-Aug-2022 13:44 to 01-Sep-2022 08:24**			
Loop 1	1984.04	1993.84	0.44	0.49
Loop 2	1977.94	1969.58	0.44	-0.42
Common Header	3961.99	3975.10	0.41	0.33
Measurement #2	**Interval: 24-Jan-2023 14:31 to 25-Jan-2023 08:00**			
Loop 1	1975.57	1979.92	0.43	0.22
Loop 2	1979.86	1983.78	0.46	0.20
Common Header	3955.43	3966.28	0.41	0.27

On Figure 6 and Figure 7 are presented graphs of unaveraged station FW flows and CROSSFLOW flows for 1st and 2nd measurement, respectively.

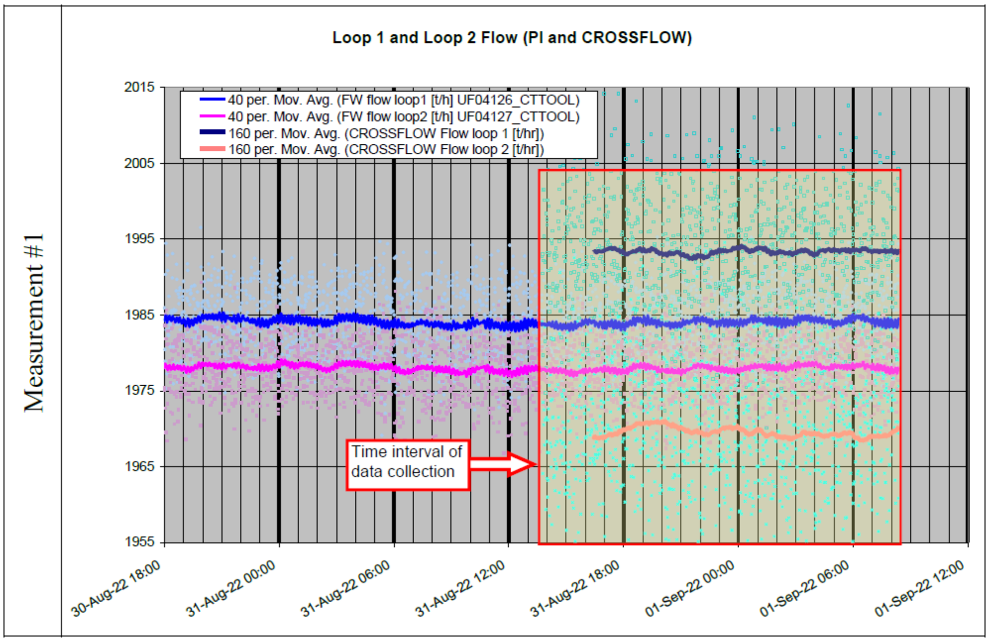

Figure 6: Unaveraged Station FW flow vs CROSSFLOW flow – 1st measurement

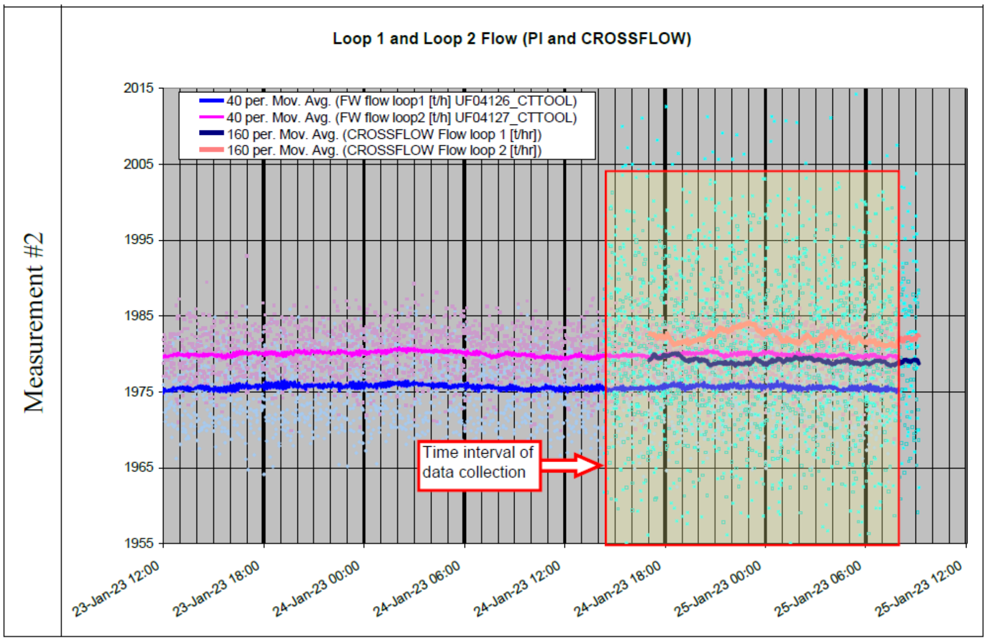

Figure 7: Unaveraged Station FW flow vs CROSSFLOW flow – 2nd measurement

3 CONCLUSION

AMAG's CROSSFLOW ultrasonic flow measurement system was used to collect flow measurement data in the MFW Loop 1, Loop 2 and Common Header. This data was used to calculate mass flow rates and corresponding uncertainties after the completion of the hydraulic test at Alden Laboratories. AMAG's CORRTEMP ultrasonic temperature measurement system was also used on Loop 1 and Loop 2 to measure temperature. These temperature measurements were used as an input to the mass flow calculations.

The final measured mass flow uncertainty is less than 0.5%. The Common Header average flow rate measured by CROSSFLOW agrees with the summation of CROSSFLOW average flow rates of Loop 1 and Loop 2 within their calculated uncertainties. The total station flow measured by venturis is in a close agreement with the station flow measured by CROSSFLOW installed on the loops or at the Common Header.

4 ACKNOWLEDGEMENT

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REFERENCES

[1] EPRI TR-109634, Flow Meter Guideline

[2] EPRI Report 1004582, Measuring Feedwater Flow with Ultrasonic Flow Meters

[3] PWROG document OG-06-216, Bases for Crossflow Technology to Achieve Accurate Flow Measurements in Power Plant Applications

[4] MAG-REP-EN-7744, Main Feedwater Flow Measurement Accuracy Verification by CROSSFLOW