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FFA FW FLOW INFLUENCE AT NPP KRŠKO

VPLIV FFA NA MERITEV FW PRETOKA V NEK

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Abstract

The Krško Nuclear Power Plant (NEK) operates based on a Pressurised Water Reactor (PWR), which utilises three loops for heat transfer: primary, secondary, and tertiary. Heat generation occurs in the primary loop; steam production takes place in the secondary loop; and waste heat is discharged in the tertiary loop. During outages, which occur every 18 months, the secondary systems are exposed to the atmosphere, increasing the risk of corrosion. To prevent this, in 2021, the plant used a chemical solution, Film Forming Amine (FFA), which formed a protective hydrophobic layer on the inner surfaces of the pipelines.

In March 2021, during the first use of FFA, deviations were observed in the main feedwater (FW) flow measurements. This affected the reactor power calculations, leading to a 0.4–0.5 % reduction in plant output (approximately 4 MWe). The main feedwater flow is a critical parameter for secondary calorimetric calculations, and has the largest impact on error in the event of deviations.

The power reduction was confirmed by comparing various process parameters, including changes in the primary loop temperature differences (ΔT), main steam flow (MS), and generator output vs. condenser vacuum. Since the measurement of the main feedwater flow contributes the most to the uncertainty of primary flow and reactor calorimetric calculations, NEK is focused on improving its accuracy.

Developing a numerical model in the computer-based programming environment is proposed

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as part of further research. This model would enable independent calculations of the main feedwater flow, to reduce the impact of the FFA chemicals on the measurement readout and its associated calculations. The model will be based on thermodynamic equations and algorithms for determining the flow with lower uncertainty than the current system. Using this model, correction factors should be obtained to adjust the current venturi meter readings. Ultimately, this approach will ensure better plant management, reduce energy losses, and increase revenues for NEK and its stakeholders.

Povzetek

Nuklearna elektrarna Krško (NEK) deluje na podlagi tlačnovodnega reaktorja (PWR), ki uporablja tri kroge za prenos toplote: primarni, sekundarni in terciarni. V primarnem krogu poteka proizvodnja toplote, v sekundarnem proizvodnja pare in odvajanje odpadne toplote v terciarnem. Med remonti, ki potekajo vsakih 18 mesecev, so sekundarni sistemi izpostavljeni atmosferi, kar povečuje tveganje za korozijo. Da bi to preprečili, je elektrarna leta 2021 uporabila kemično raztopino FFA (Film Forming Amine), ki je na notranjih površinah cevovodov tvorila zaščitni hidrofobni sloj.

Marca 2021, ob prvi uporabi FFA, so se pojavila odstopanja pri meritvah pretoka glavne napajalne vode FW (Feedwater). To je vplivalo na izračun moči reaktorja in povzročilo upad zmogljivosti elektrarne za 0,4–0,5 % (približno 4 MWe). Pretok glavne napajalne vode je ključni parameter za sekundarni kalorimetrični izračun in ima največji vpliv na pogrešek v primeru odstopanja.

Upad moči je bil potrjen s primerjavo različnih procesnih parametrov, kot so spremembe temperaturnih razlik v primarnem krogu (ΔT), s pretokom glavne pare (MS – Main Steam) in meritvijo električne moči na generatorju. Ker meritev pretoka glavne napajalne vode prispeva največ k negotovosti izračuna pretoka primarnega sistema in kalorimetričnega izračuna sredice, smo v NEK osredotočeni na izboljšanje natančnosti te meritve.

V sklopu nadaljnjega raziskovalnega dela se predlaga razvoj numeričnega modela v računalniško podprtem programskem okolju, ki bo omogočil neodvisen izračun pretoka glavne napajalne vode, z namenom zmanjšanja vpliva FFA kemikalije na meritev oziroma s tem povezane izračune moči reaktorja. Model bo temeljil na termodinamičnih enačbah in algoritmih za določanje pretoka z nižjo negotovostjo od sedanje. S pomočjo modela bi morali pridobiti korekcijske faktorje za prilagoditev trenutnih vrednosti venturijevih merilnikov. V končnici bo ta pristop zagotovil boljše upravljanje elektrarne, zmanjšal energetske izgube ter povečal prihodke za NEK in njene lastnike.

1 DESCRIPTION OF THE PROBLEM

Heat transfer in the Krško Nuclear Power Plant (NEK – Nuklearna Elektrarna Krško) occurs in a closed loop, with the primary heat source being a nuclear reactor. The plant features a pressurised water reactor (PWR), the most widely used reactor type worldwide. The facility operates through three largely independent loops [Figure 1].

The primary loop contains the reactor, two steam generators, two reactor pumps, a pressuriser, and primary piping alongside safety system connections. NEK uses two primary loops, circulating coolant water at 155 bar and 323°C. The reactor pumps (22,711 t/h each) circulate the coolant, which transfers the heat to the steam generator without a phase change.

The secondary loop includes steam generators, turbines, reheaters, condensers and a feedwater system. The heat from the primary coolant is transferred to the secondary coolant in the steam generator, where the water is converted to high-pressure steam. The steam drives the turbines, producing mechanical energy to drive the generator. The spent steam then condenses into water in the condenser before returning to the steam generator.

The tertiary loop removes waste heat via the condenser cooling system, which uses Sava River water. The heat is transferred to the river, as the cooling water absorbs energy from the condensing steam, completing the loop.
NEK operates on an 18-month cycle, with maintenance and refuelling occurring every 18 months. The plant runs at full power during operation, following technical specifications limits to ensure safety under normal and accident conditions. The reactor power is a critical parameter that's monitored throughout.

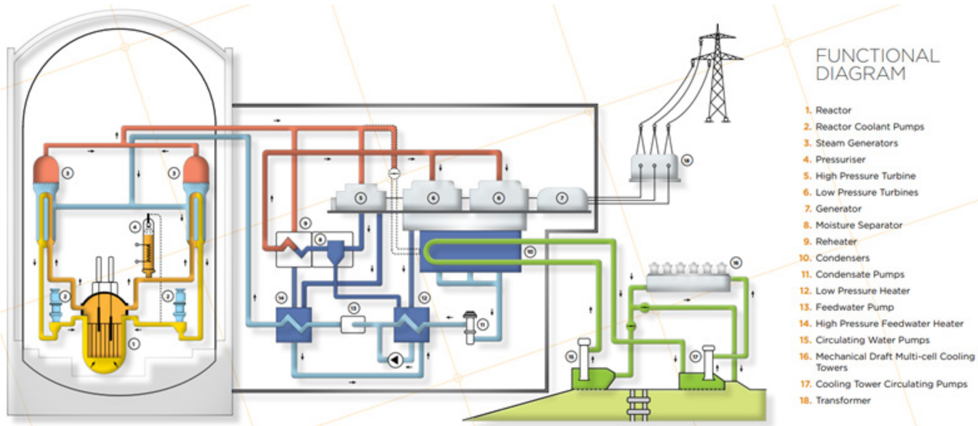

Figure 1: *Functional diagram of NPP Krško; source: www.nek.si*

2 PRIMARY AND SECONDARY SYSTEM INTERACTION

The thermal power of the core can be described by the following equation:

$$\dot{Q}_T = \dot{m}_{prim} \cdot c_p \cdot (T_H - T_C) = \dot{m}_{prim} \cdot c_p \cdot \Delta T \tag{2.1}$$

$\dot{Q}_T$ Reactor thermal power
$\dot{m}_{prim}$ Primary loop mass flow rate
c_p Specific heat capacity of water
T_H Primary loop hot leg temperature
T_C Primary loop cold leg temperature

The temperature difference (ΔT) is a direct indicator of power (assuming that the primary flow rate and specific heat capacity remain unchanged). The losses in the primary loop and additional heat power due to the operation of the primary pumps are not considered in the schematic calculation.

The power on the secondary side is determined through a calorimetric calculation, which is considered the most accurate power measurement, and serves as the basis for safety analyses, as well as monitoring requirements related to reactor power (Rated Thermal Power – RTP = 1994 MW_t).

$$\dot{Q}_{SG} = \dot{Q}_{STM} + \dot{Q}_{BD} \tag{2.2}$$

$\dot{Q}_{SG}$ Steam generator heat flux

$\dot{Q}_{STM}$ Steam heat flux

$\dot{Q}_{BD}$ Blowdown heat flux

According to the NEK procedures, the reactor power is determined based on measurements from ex-core instrumentation, which is calibrated through the determination of secondary calorimetry. The primary parameters used for secondary calorimetry calculations are:

- main feedwater temperature,
- main feedwater flow,
- steam generator pressure,
- blowdown system flow,
- TH average temperature,
- TC average temperature,

The main feedwater flow rate has the greatest impact on the secondary calorimetry measurements, making it a key focus for accuracy. This parameter is associated with the highest uncertainty in reactor power calculations within probabilistic analyses. It is estimated that the deviation of this measurement accounts for 0.66 percentage points of the total 0.81 % calculated uncertainty, within the 2 % limit assumed in the safety analyses.

2.1 Current Secondary Calorimetry Calculation

The calculation of the secondary calorimetry is based on the flow rates of the FW and blowdown (BD) from the steam generators, as well as the enthalpy of the MS at the steam generator outlet, FW and BD system. The thermal power of the steam generators is calculated by subtracting the gains of the reactor coolant pumps (RCP's) and adding the losses of the reactor coolant system (RCS).

The main parameters influencing the calorimetry results include:

- **FW** Flow Rate (Venturi): Measured as Δp and converted to t/h. A 1 % deviation in the Δp measurement (equivalent to 0.72 % in flow) affects power by 0.72 %.
- FW Temperature: A 1 °C deviation impacts the power by 0.249 %.
- MS Pressure: A deviation of 1 bar affects the power by 0.065 %.
- Steam **Moisture Content:** A deviation of 0.1 % impacts the power by 0.084 %.

All the other parameters, and their respective deviations, have a smaller influence on the final result. A complete sensitivity analysis is available in Reference 6.

***Table 1:** Uncertainties in the Calorimetric Reactor Power Calculation Based on Secondary Instrumentation (Source: SSR-NEK-3.0 - REVISED THERMAL DESIGN PROCEDURE [ref. 6])*

COMPONENT	INSTRUMENT UNCERTAINTY		POWER UNCERTAINTY (%POWER)
FEEDWATER FLOW			
VENTURI	0.5 % K		0.500
THERMAL EXPANSION COEFFICIENT			
TEMPERATURE	3.5°F	1.96°C	0.007 *
MATERIAL	5.0%		0.060
DENSITY			
TEMPERATURE	3.5°F	1.96°C	0.148 *
PRESSURE	30.0 psi	2.11 kgf/cm²	0.010**
DELTA P	1.13 %Δp		0.81
FEEDWATER ENTHALPY			
TEMPERATURE	3.5°F	1.96°C	0.487 *
PRESSURE	30.0 psi	2.11 kgf/cm²	0.003 **
STEAM ENTHALPY			
PRESSURE	19.3 psi	1.36 kgf/cm²	0.088
MOISTURE	0.10 %moisture		0.084
NET RCS HEAT ADDITION	20.0 %		0.036

$$U_{RTP} = \sqrt{\frac{0.50^2+(0.148+0.487-0.007)^2+0.06^2+ (0.010-0.003)^2+0.81^2+0.088^2+0.84^2+0.036^2}{2}} = 0.81\ \% \tag{2.3}$$

U_{RTP} Uncertainty in the RTP (Rated Thermal Power) calculation

3 REASONS FOR FFA INJECTION

The NEK shuts down every 18 months for routine maintenance and refuelling. During these outages the secondary systems are drained and exposed to the atmosphere, leading to corrosion of the systems while the plant is offline. Upon restart, a significant portion of the rust formed during the maintenance period is transported to the steam generators, reducing the heat transfer efficiency and contributing to a degradation mechanism known as "denting."

To prevent the formation of corrosive products, NEK decided to inject a protective amine-based film-forming solution (FFA). This chemical creates a protective film that prevents oxygen from reaching the internal surfaces of the secondary systems during outages when internal structures are exposed to the external atmosphere. The FFAs protect the internal surfaces of the carbon steels from corrosion by forming a temperature-resistant hydrophobic film. This film prevents corrosion during periods when the components are open and empty (during maintenance), and enhances the corrosion resistance of the pipelines during operation by reducing the flow-accelerated corrosion.

During operation, when the systems are filled, the reducing conditions are maintained with a high pH, and with hydrazine, which is added to the secondary system as a corrosion inhibitor (oxygen scavenger). However, during maintenance, the surfaces are exposed to oxygen, creating conditions that lead to corrosion. The resulting corrosive products are transported throughout the secondary system during operation and deposited as sediments in the steam generators.

The injection of the FFA solution must occur while the plant operates at full power. The injection point for the FFA solution is located between heaters 4 and 3, where the secondary water pressure remains low enough, and the temperature is sufficient to ensure the proper solubility of the chemical. The first dosing of the FFA chemical was carried out in March 2021.

3.1 Deviation description

An impact on the power plant's efficiency and the generator's output was observed as a result of the initial dosing of the FFA chemical. It was assumed that a change occurred in:

- the measurement of the main FW flow, measured via a Venturi nozzle and Δp meters,
- or the heat transfer in the steam generators.

Since the measurement of the main feedwater flow is linked closely to the reactor power calculation, any deviation in this measurement is associated directly with an impact on the plant's power output and efficiency. At NEK it was presumed at this point that the indicated FW flow value was higher than the actual value, as a loss of MWe at the threshold was noticeable, ranging from -0.4 % to -0.5 %, or approximately 4 Mwe.

ΔT measurements (in °C) were utilised for a representative assessment of the power drop on the primary side. These measurements represent the average values obtained from all the RTD (Resistance Temperature Detector) NR (Narrow Range) measurements of the primary circuit, and are independent of the calorimetric calculations. ΔT is a measurement between T_H and T_C in the primary loop. For better visualisation, a diagram of the average ΔT values over the entire cycle (510 days) is presented in Figure 2. The downward trend is attributed to the phenomenon of "Hot Leg Streaming," with the slope of the curve representing stable full power and the breakpoint indicating the timing of the FFA dosing.

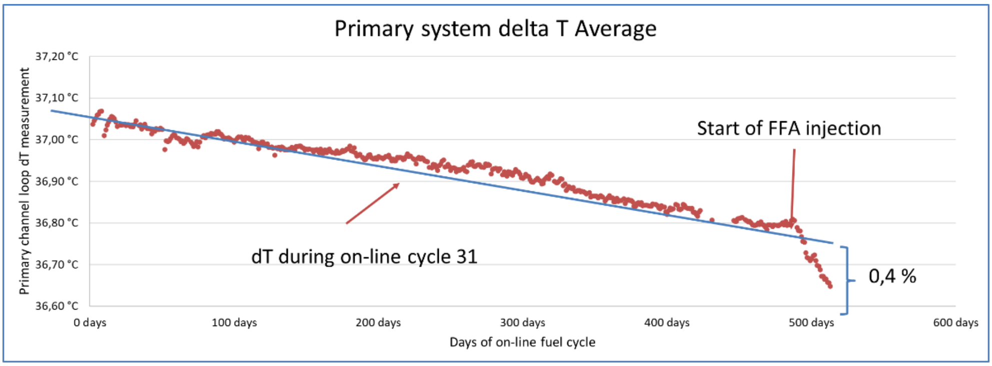

Figure 2: *The drop in calorimetric power based on the ΔT measurement of the primary system*

The next independent assessment was based on the change in MS flow, where the MS calorimetric power is obtained by considering the enthalpies:

$$\dot{Q}_{SG} = \dot{m}_{MS} \cdot \Delta h_{MS} + \dot{m}_{BD} \cdot \Delta h_{BD} \tag{3.1}$$

$\dot{Q}_{SG}$	Steam generator thermal power
$\dot{m}_{MS}$	Main steam mass flow rate
Δh_{MS}	Enthalpy change of water during evaporation
$\dot{m}_{BD}$	Blowdown system mass flow rate
Δh_{BD}	Enthalpy change of water in the blowdown system

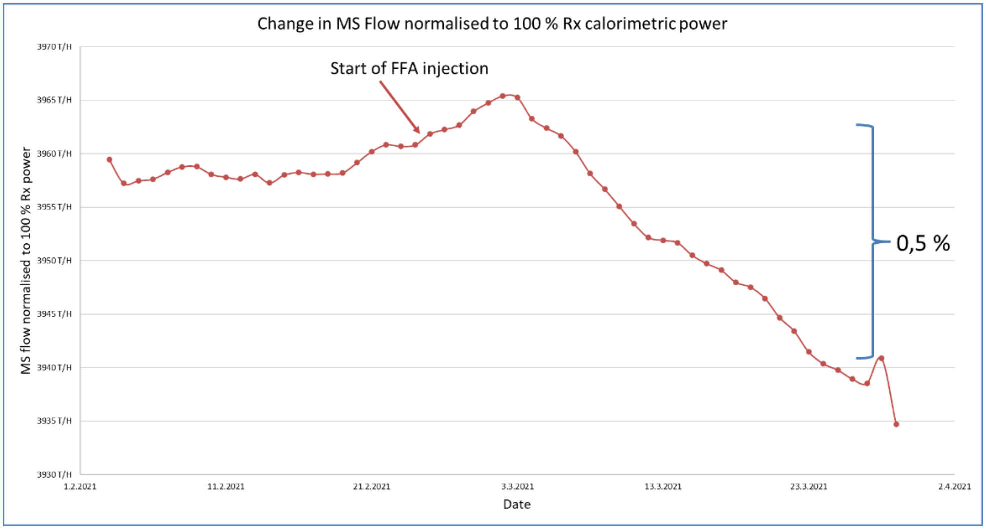

Figure 3: *The reduction in MS flow normalised to 100 % Rx calorimetric power*

The change in power from the MW-power characteristic relative to the vacuum was examined additionally. This characteristic illustrates the gross MWe energy as a function of the vacuum, enabling an assessment of power variation independent of changes in the thermodynamic efficiency (the vacuum in the condenser).

Based on evaluations of the reactor power reduction through independent reviews of the following parameters, it was concluded that:

- The ΔT measurement between the hot and cold legs of the primary circuit indicated a decrease of approximately -0.4 %.
- The change in MS flow indicated a decrease of about -0.5 %, as shown in Figure 3.
- The change in the power characteristic at the generator relative to the vacuum in the condenser suggested a reduction of approximately -4 MWe, or between -0.4 % and -0.5 % of the plant's power, as shown in Figure 4.

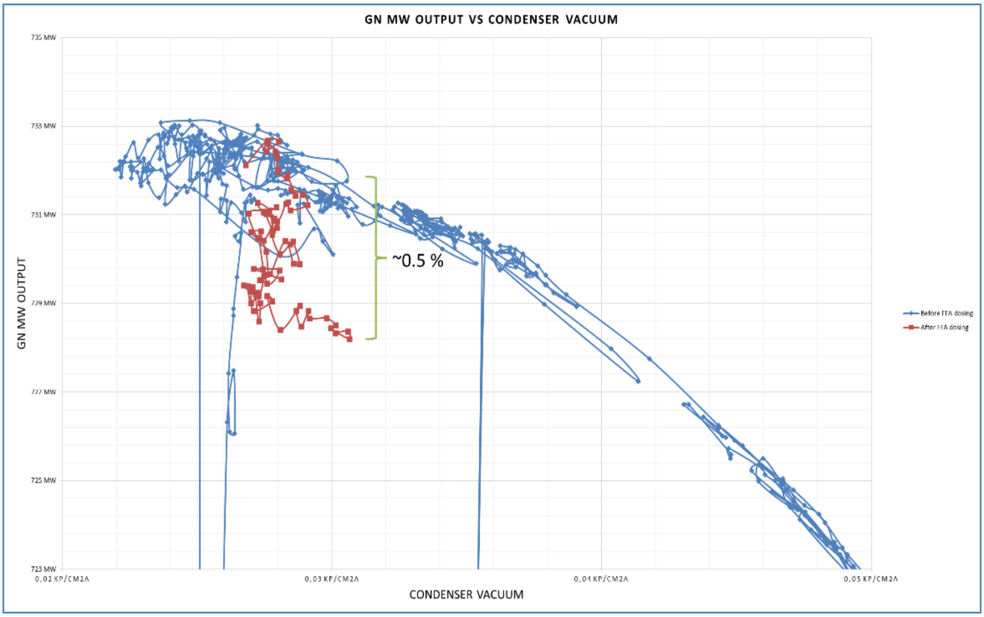

Figure 4: *The MWe characteristic at the generator relative to vacuum during the addition of FFA chemicals*

The operators follow "live" calculations of the plant's calorimetric power, ensuring that the reactor was kept within a two-hour average range of 99.94 % to 99.98 % during March when the FFA chemicals were dosed. However, an issue arose due to suspected inaccuracies in the calorimetric calculation, attributed to the influence of the FFA chemicals on the FW flow measurement, or changes in the heat transfer coefficient in the steam generators.

At NEK, the long-term steam generator maintenance strategy has been set to include FFA chemical dosing before every second outage, starting in September 2025. During this period, accurate FW flow measurements will need to be performed, to correct the current "live" calorimetric calculations and prevent further MWe losses at the generator.

The cost of electricity purchased from NEK by the owners, Gen Energija and HEP, is approximately 40€/MWh. Over an 18-month cycle, this results in a significant loss of revenue for NEK, and, subsequently, for the owners, who market this energy further.

4 PURPOSE AND OBJECTIVES OF FUTURE RESEARCH WORK

The purpose and objective of the future research work is to establish an independent calculation of the calorimetric power of the Krško Nuclear Power Plant. This calculation would enable the determination of "live/real-time" correction factors to be applied in the current calorimetric calculation, ensuring that future injections of FFA chemicals do not result in further power changes caused by their impact on the existing measurements.

To achieve an independent calculation of calorimetric power, a detailed model of the plant is to be developed in a numerically and computationally supported environment. This environment must allow matrix manipulations, function plotting, database/measurement integration, and the implementation of algorithms, to achieve a more precise final calculation of feedwater (FW) flow than the current method, ensuring its suitability for flow correction.

The computationally supported calculation of the main feedwater flow must remain independent of the actual measured FW flow value. Instead, it should rely on the thermodynamic interdependence of other process variables within the system. Additionally, the calculation must meet the accuracy criteria currently set for FW flow measurement. By achieving this, the current measured flow value could be corrected using the mathematically derived value.

If the above equation (2.3) is reformulated to eliminate uncertainties associated with the Venturi flow meter, the theoretical uncertainty of the parameter can be reduced from 0.81 % to 0.69 %.

This reduction highlights the potential of utilising advanced computational modelling to achieve higher accuracy in feedwater flow determination, thereby improving the precision of the overall thermal power calculations.

$$U_{RTPNEW} = \sqrt{\frac{0.487^2+0.010^2+0,003^2+0.088^2+0.84^2+0.036^2}{2}} = 0.69\ \% \tag{4.1}$$

U_{RTPNEW} New computationally derived uncertainty in the RTP calculation

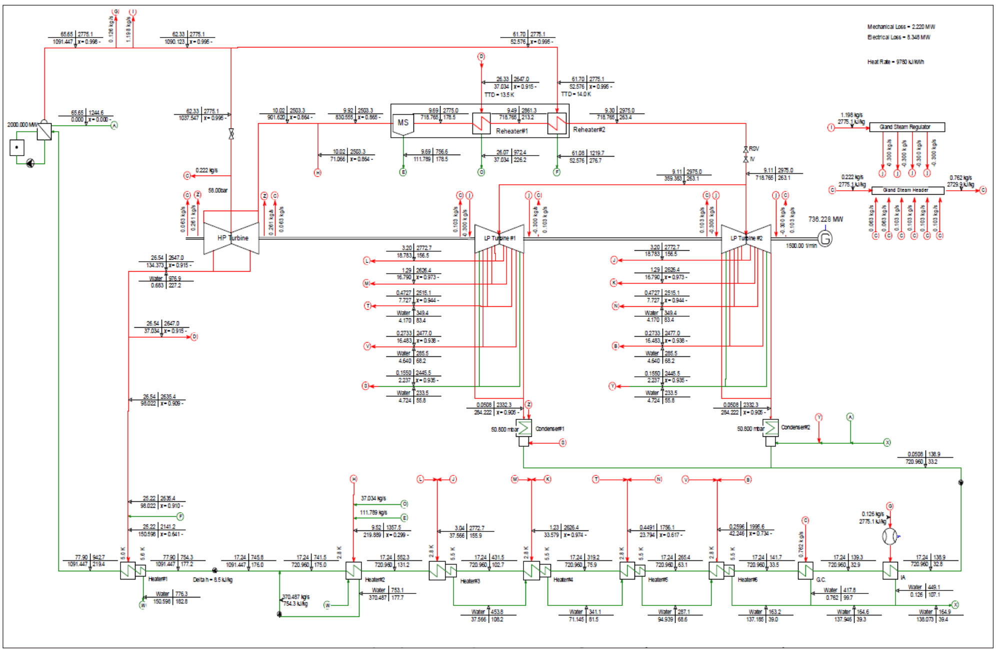

Figure 5: *Heat balance diagram of NEK (Source: NEK*

The required correction factor can be calculated with the newly obtained value of the FW flow. This factor would be applied to the displayed flow value, to calibrate it, and ensure that the actual display reflects the corrected and more accurate flow measurement.

It is assumed that it is possible to model the power plant's secondary system accurately with all the necessary process variables, to the extent that the computer-based model will be capable of performing the FW flow calculation with less uncertainty than is currently included in the NEK safety analyses. The model also assumes that the current measurement of the main feedwater flow will not be required as an input variable in the calculation, but can, instead, be determined/calculated based on other measurable interdependent variables. The NEK model will follow the logic of the current heat balance diagram used at NEK [Figure 5], which will then be supplemented with on-line process data.

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Nomenclature

(Symbols)	(Symbol meaning)
bar	Unit of pressure: 1 bar = 10^5 Pa (Pascal)
BD	Blowdown system
°C	Degrees Celsius
€/MWh	Euro per megawatt hour
°F	Degree Fahrenheit
FFA	Film-Forming Amines
FW	Feedwater system
K	Degree Kelvin
kgf/cm²	Unit of pressure in kilogram-force/square centimetre: 1kgf/cm^2 = 98066,5 Pa
MS	Main Steam system
MWe	Megawatt electric
MWt	Megawatt thermal
NEK	Krško Nuclear Power Plant (Nuklearna Elektrarna Krško)
NPP	Nuclear Power Plant
NR	Narrow Range
Δp	Delta pressure/pressure drop

psi	Unit of pressure in Pounds per Square Inch
PWR	Pressurised Water Reactor
RCP	Reactor Coolant Pumps
RCS	Reactor Coolant System
RTD	Resistance Temperature Detector
RTP	Rated Thermal Power
t/h	Ton per hour
ΔT	The difference in temperature between the hot leg and cold leg of the primary system