Influence of Decontamination of the WWER-440 Primary Circuit Equipment on Pressure Drop in the Reactor

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The activity of deposits is known to be proportional to the amount of corrosion products circulating in the circuit, therefore all models of mass transfer in the circuit include the change of corrosion products concentration and the corrosion rate in time, removing these products by filters and deposition. During decontamination of the circuit segments and equipment replacement local change of corrosion rate occurs which results in the increase of corrosion products concentration in the circuit and the increase of deposits on surfaces. If due to incorrect water chemistry conditions for corrosion products deposition in the core are created not only the activity of the coolant increases but the hydraulic resistance of the reactor also grows which results in the increase of the pressure drop at the reactor. When the pressure drop at the reactor exceeds 3.75 bar emergency shutdown is envisaged. [1].

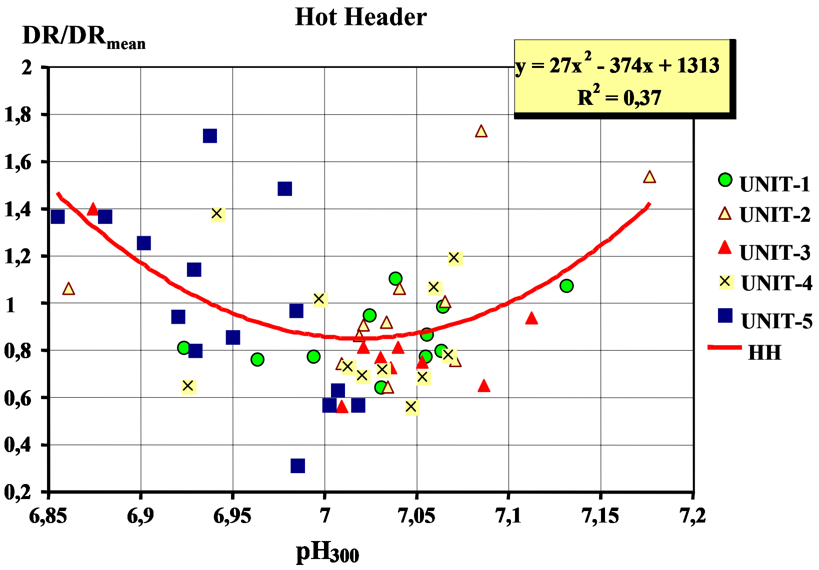

Figure 1. The dose rate of the hot header (HH) of the steam generator at 1-5 power units with WWER-440 plotted against mean pH$_{300}$ during a lifetime

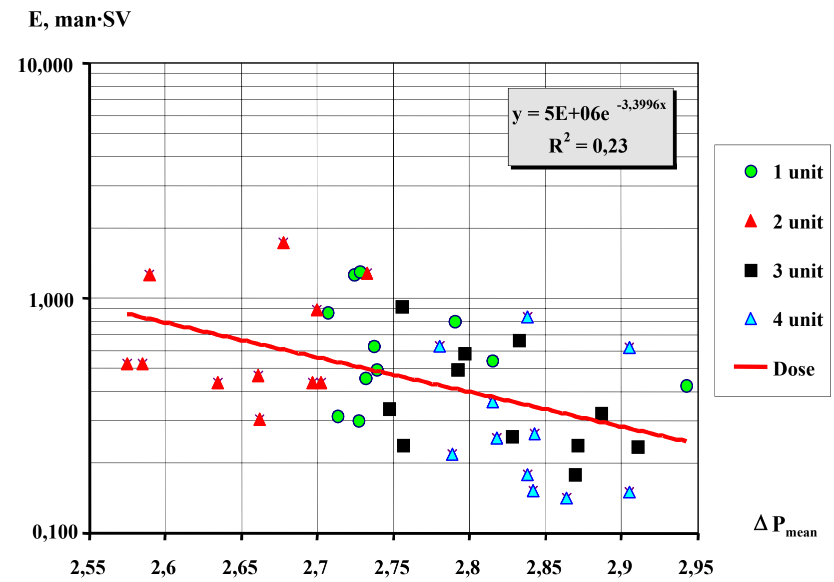

Figure 2. Correlation of collective dose expenditures and the mean pressure drop during a lifetime at the reactor of WWER-440 nuclear power plant

We have analyzed over 40 reactor cycles at four power units of the WWER-440 nuclear power plant. The pH values, ammonia and hydrogen concentration were considered as main parameters of water chemistry. It was stated that the dose rate (DR) is determined definitely by ammonia concentration and pH$_{300}$. The dose rate from the hot collector of the steam generator nuclear power plants plotted against mean pH$_{300}$ during a lifetime is presented in Figure 1. (The calculation of pH$_{300}$ was made with the aid of the program developed by the VNIPIET Federal State Unitary Enterprise). To exclude the influence of special features of the power unit, the period of its operation etc the mean value of the dose rate over the whole power unit was specified as standard DR.

The minimum of the dose rate is in the interval pH=7.0-7.05. Basing on the data obtained at the WWER-440 nuclear power plant we tried to explain the rise of pressure drop at WWER-440 reactors under a certain combination of conditions. The preliminary analysis showed that the values of exposures (E) and the dose rate (DR) from the equipment of the primary circuit are correlated inversely with the pressure drop. The correlation of staff radiation exposure (E) after the *i*-th lifetime and the mean pressure drop during the *i*-th lifetime at 4 nuclear power plant over the period 15 years is shown in Figure 2.

The value of the square of the correlation factor exceeds critical value (0.08 [3]) and the correlation is significant.

Similar trustworthy correlation is observed between the values of pressure drop and the values of dose rate from pipelines, the main circulation pump, and the reactor cover prior to its opening during the appropriate lifetime. The same relationship is characteristic for steam generators too but same years both increase of pressure drop and the dose rate from the steam generator were observed in some power units due to some reasons that will be considered below, therefore the correlation factors obtained were considerably below the critical values.

The phenomenon of correlation can be explained by deposition of corrosion products in the circuit mostly on hotter surfaces (the reactor itself) or on cooler surfaces as compared to the coolant (the rest part of the circuit).

Each lifetime can be characterized by the pressure drop during a lifetime, the pressure drop between the lifetimes and the mean value of the pressure drop during the lifetime. The rise of pressure drop between lifetimes is caused by the fact that non-fixed part of corrosion products tends to move during commissioning and sticks in the grids. Besides the solubility of magnetite decreases sharply with the rise of temperature and the magnetite is deposed in the circuit and under specific pH conditions – first of all on hot surfaces.

However besides operational characteristics these values depend on structural features of the power unit and the period of its operation. The parameters that characterize the changes of pres-

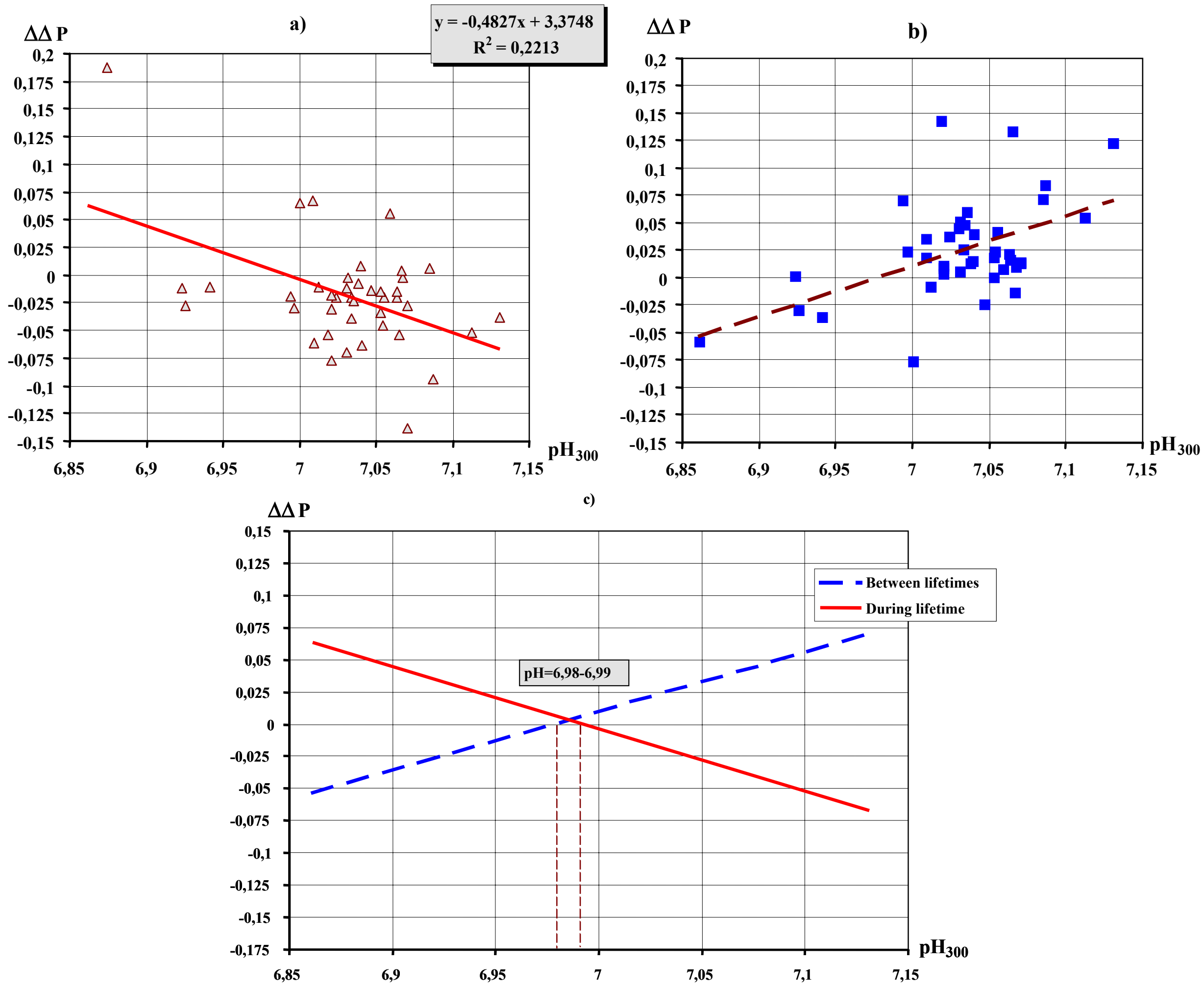

Figure 3. Change of pressure drop during a lifetime (a) and between lifetimes (b) depending on mean value of pH_{300} during a lifetime; (c) overlapping of trends from (a) and (b)

sure drop during the lifetime and between lifetimes are more reliable in this respect. These values are calculated in the following way:

$$\Delta^2 P_{\,during\ a\ lifetime}{}^{(i)} = \Delta P_e^{(i)} - \Delta P_b^{(i)} \qquad (1)$$

$$\Delta^2 P_{\,between\ lifetimes}{}^{(i)} = \Delta P_b^{(i)} - \Delta P_e^{(i-1)} \qquad (2)$$

where index "*b*" refers to the beginning of the lifetime and index "*e*" – to the end of the lifetime.

The change of these values depending on mean value of pH_{300} during a lifetime is shown in Figure 3. The values of pH for calculation of pressure drop changes between lifetimes were taken from the preceding lifetime.

The regression equations obtained are significant. On the one hand higher values of pH conduce to decrease of pressure drop during a lifetime but on the other hand it causes the rise of pressure drop after shutdown. The intersection point of two curves corresponds to the zero pressure drop during and between lifetimes and is characterized by a value of pH_{300} close to 7.

The rise of the pressure drop at the beginning of the lifetime is connected with the low value of pH by the moment of start-up. The change of pressure drop and pH at power unit 1 of the "PAKS" at the beginning of lifetimes 19 and 20 is shown in Figure 4. As it can be seen in the figures the rise of pressure drop occurs at pH under 6.8. When pH exceeds 6.8 the pressure drop in the reactor is stabilized. The boundary values of pH are shown in the figures. These values are calculated for the case when the total content of alkali metals in accordance with the standard and real concentrations of boric acid, ammonia and hydrogen and therefore the lines are uneven.

These data show that during the first three months of the lifetime the process is conducted at pH below the value specified by the standard. Another important moment is the necessity to maintain constant pH during the whole lifetime as the less is the change of pH during the lifetime the less is mass transfer in the circuit as the constancy of solubility and constancy of temperature gradient of solubility is ensured in this case.

According to the standard in force the upper and the lower limits of the total content of al-

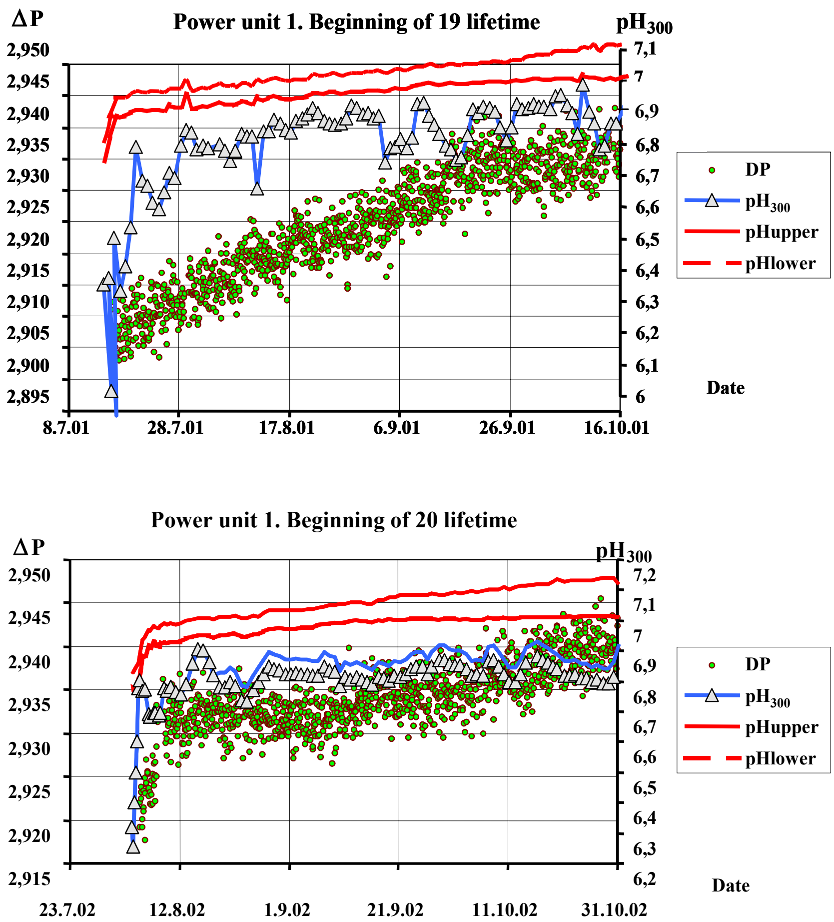

Figure 4. Change of pressure drop and pH_{300} at power unit 1 of NPP PAKS during start-up in 2001 and 2002

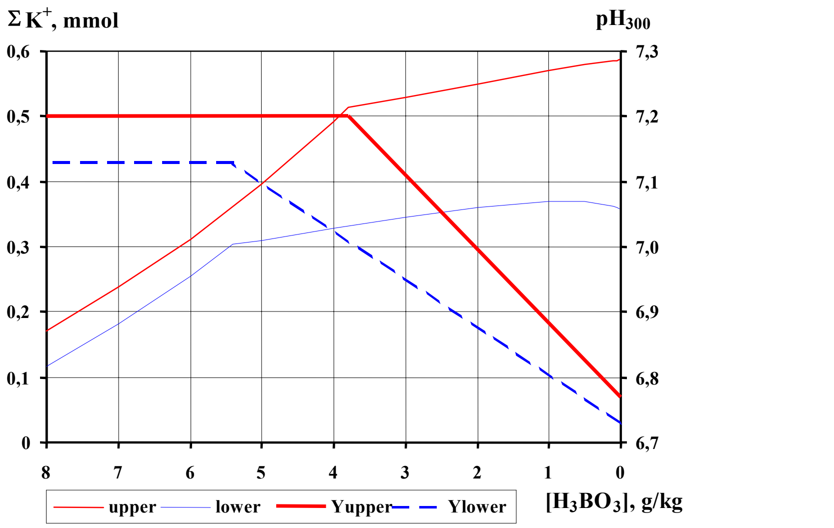

Figure 5. Total concentration of alkali metals and pH_{300} depending on concentration of boric acid in accordance with the standard for NPP WWER-440

kali metals are specified for the NPP WWER-440 as shown in Figure 5. We calculated values of pH_{300}, that correspond to the concentration of boric acid and the total content of alkali. The lower limit of pH value is within the range 6.8-7.1, in this case at a concentration of boric acid below 6.73 the permissible value of pH will exceed 6.9. In our opinion strict observance of this standard will conduce to reduction of pressure drop in the reactor. Still it would be reasonable to narrow the permissible range especially in the area of low concentrations of boric acid taking into consideration the fact that the concentration of ammonia influences considerably on pH value at the end of the lifetime.

Another factor that influences directly on the character of deposits in the circuit is decontamination of steam generators. The $^{58}Co/^{60}Co$ activity ratio can be considered to be the measure of the age of deposits. During the first start-up of the reactor the ratio is much in excess of 1 and only after 5-7 years of operation it is stabilized at a level under 1. During decontamination these deposits are removed. After the next lifetime the deposits are formed at the same level. Significant differences in activity of deposits on decontaminated and not decontaminated steam generators were not detected. However relationship between the number of decontaminated steam generators in the *i*-th lifetime and the $^{58}Co/^{60}Co$ activity ratio after the (*i*+1)-st lifetime was established (Figure 6).

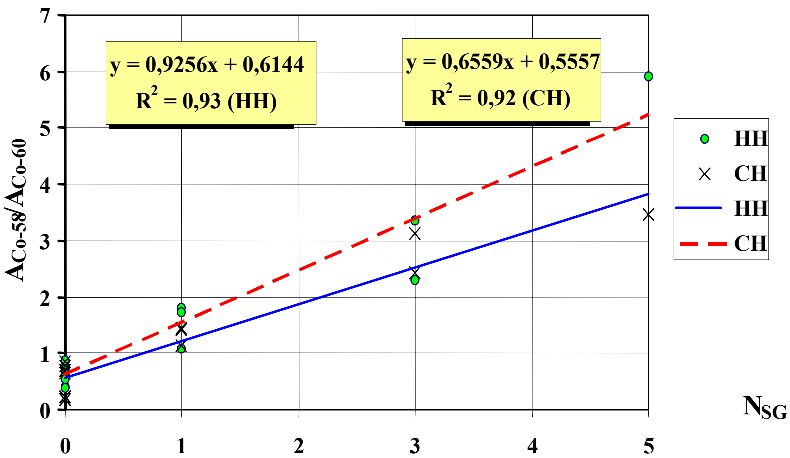

Figure 6. **$^{58}Co/^{60}Co$ ratio in the *i*-th lifetime depending on the number of steam generators (SG) decontaminated during one preventive maintenance in the (*i*-1)-st lifetime; HH – hot header, CH – cold header**

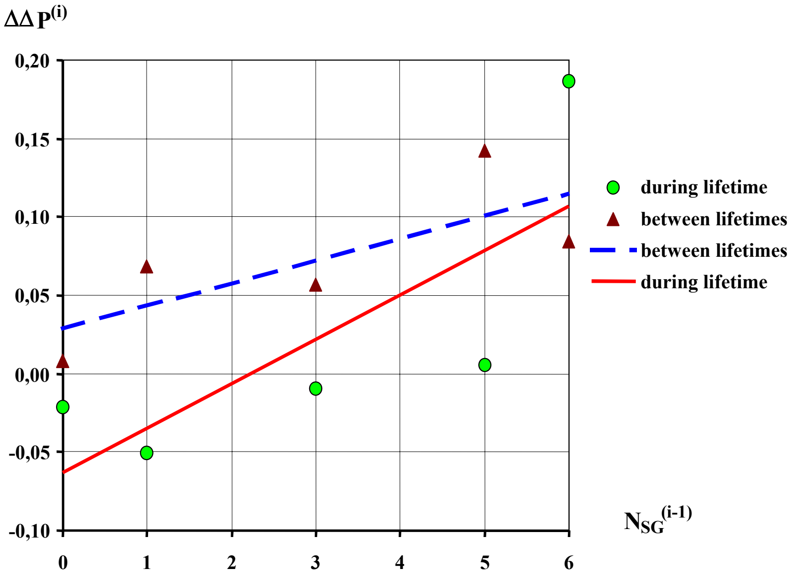

Figure 7. **Pressure drop values between *i*-th and (*i*-1)-st lifetimes and during the *i*-th lifetime depending on the number of steam generators decontaminated after shutdown of steam generators after the (*i*-1)-st lifetime**

The correlation coefficients obtained turned to be very high - 0.96, which shows practically functional relationship. It can be explained by the fact that after decontamination in the *i*-th lifetime due to increase of corrosion because of insufficient passivation and secondary deposition of dissolved corrosion products in the circuit at the beginning of the (*i*+1)-st lifetime additional amount of corrosion products is generated and these products are deposited in the core and after activation they are re-distributed in the circuit.

The proof of remarkable secondary deposition of corrosion products in steam generators during decontamination is the relationship between the effectiveness of decontamination and the rate of the decontamination solution pumping. P. Tilky and J. Shunk [4] stated that with the increase of pumping rate by 2.1 times the surface decontamination factor increases by seven times.

The increase of deposits in the core after decontamination is clearly illustrated by Figure 7. The rise of pressure drop between the *i*-th and the (*i*+1)-st lifetimes and during the (*i*+1)-st lifetime at power units of the NPP WWER-440 is connected with the increase of the number of steam generators decontaminated in the *i*-th lifetime, i.e. it is proportional to the area of the decontaminated surface. It is the additional amount of cor-

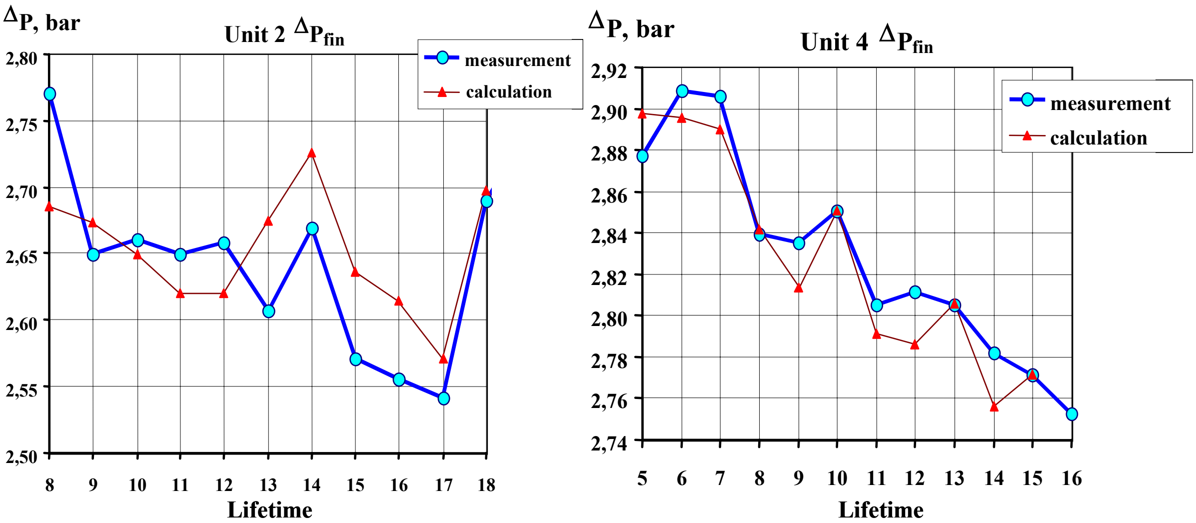

Figure 8. Pressure drop values (measured and calculated) at power of PAKS NPP, Units 2 and 4

rosion products after decontamination of steam generators that explains simultaneous increase of the pressure drop at power units 1-3 of the PAKS NPP in 2001-2002.

The lowest rise of pressure drop between lifetimes and during the lifetime was observed at power unit 4 of the PAKS nuclear station where decontamination of steam generators was not carried out.

We have developed a model of pressure drop changes during a lifetime and between lifetimes which takes into consideration the parameters:

N_{SG} - number of steam generators decontaminated in the (i-1)-th cycle;

τ_{pb} - time of operation of the power unit at pH<6.9 at the lifetime, days.

Cobalt isotopes activity (ratio $A_{Co\text{-}58}/A_{Co\text{-}60}$) on the surface of the steam generator.

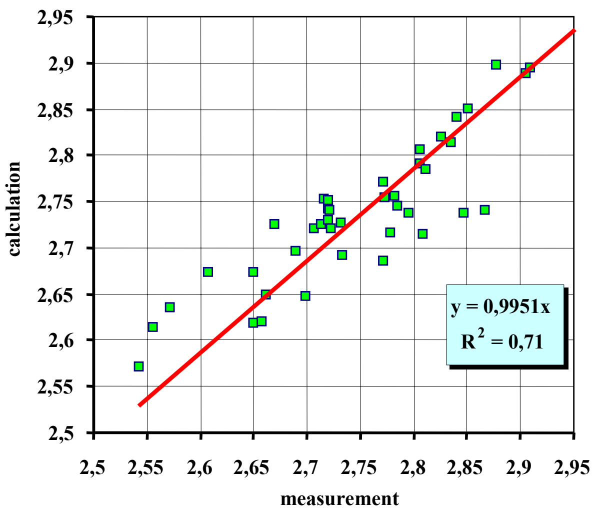

Figure 9. Correlation between of the calculated and measured pressure drop values in the final company at power of PAKS NPP, Units 1-4

Thermodynamic data of solubility of magnetite in-core.

Results of calculation you can see at Figures 8 and 9. The pressure drop after decontamination of the assembled circuit without changing the technique of passivation can exceed more then 0.2 bar.

This phenomenon was observed at the Lovvisa-2 NPP after the lifetime of 1994.

At the Lovvisa-2 NPP an abnormal rise of temperature at the reactor outlet was observed during the first 2-3 months of lifetime 15 (October 1994). The reason of this phenomenon was the reduction of coolant flow through a part of fuel assemblies due to the increase of hydraulic resistance in the core which caused emergency shutdown of the reactor. After removal of assemblies with highest hydraulic resistance they were inspected. The highest reduction of flow rate was registered in six fuel assemblies installed in the reactor before the beginning of the lifetime [2]. The reduction of the coolant flow was caused by deposits on the stringers especially in the bottom part of the assembly. It should be pointed out that during the refuelling of 1994 (the 14-th cycle) the whole first circuit was decontaminated as it was found that otherwise individual and staff collective dose will be too high. After the start-up of the reactor increased concentration of crud in the coolant was observed.

Besides deposits on stringers one were detected on the whole surface of shroud tubes (inside and outside). The thickness of deposits was to 120-140 µm. Dense fine layer of deposits was 5-7 µm thick. Crystals to 50 µm long were found in this layer. The growth of crystals was orientated in the direction of the flow. No deposits were found on the surfaces of fuel elements.

It is most probable that this phenomenon can be explained by the fact that the temperature of shroud tubes was lower than that of fuel elements i.e. deposition takes place on a cooler surface. The thermodynamical calculation of the temperature gradient of magnetite solubility shows that at certain values of pH_T (pH_{300}<6.6) it has a negative value in the lower part of the reactor i.e. deposition of magnetite occurs mostly on “cool” surfaces in the bottom part of fuel assemblies.

Conclusions

1. It is shown that staff radiation exposure and the dose rate at segments of the first circuit are inversely correlated with the value of pressure drop at the reactor which is connected with the mechanism of redistribution of deposits and radioactive nuclides between the reactor and the rest part of the circuit.
2. The influence of pH_T on formation of the dose rate from equipment and the change of pressure drop in the reactor WWER-440 is studies. The optimal range of pH_T values for these parameters is determined which is 6.95-7.05 and these values are within the range of water chemistry standards.
3. The correlation between the changes of pressure drop and the number of decontaminated steam generators is established. This correlation shows that the pressure drop at the reactor grows with the increase of steam generators decontaminated during one preventive maintenance.

Acknowledgements

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