SIMULATION OF LEAKING FUEL RODS

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Abstract

The behaviour of failed fuel rods includes several complex phenomena. The cladding failure initiates the release of fission product from the fuel and in case of large defect even urania grains can be released into the coolant. In steady state conditions an equilibrium – diffusion type – release is expected. During transients the release is driven by a convective type leaching mechanism. There are very few experimental data on leaking VVER fuel rods. For this reason the activity measurements at the nuclear power plants provide very important information. The evaluation of measured data can help in the estimation of failed fuel rod characteristics and the prediction of transient release dynamics in power plant transients.

The paper deals with the simulation of leaking fuel rods under steady state and transient conditions and describes the following new results:

- *A new algorithm has been developed for the simulation of leaking fuel rods under steady state conditions and the specific parameters of the model for the Paks NPP has been determined.*
- *The steady state model has been applied to calculation of leaking fuel characteristics using iodine and noble gas activity measurement data.*
- *A new computational method has been developed for the simulation of leaking fuel rods under transient conditions and the specific parameters for the Paks NPP has been determined.*
- *The transient model has been applied to the simulation of shutdown process at the Paks NPP and for the prediction of the time and magnitude of ^{131}I activity peak.*
- *Using Paks NPP data a conservative value has been determined for the upper limit of the ^{131}I release from failed fuel rods during transients.*

Keywords:
leaking fuel rods, coolant activity, spiking

1. INTRODUCTION

The technology of nuclear fuel production and the power plant operational procedures have been significantly improved and optimised during the last decades. As a result of these actions the leaking of only one out of one hundred-thousand fuels rod can be expected today [1]. At the Paks Nuclear Power Plant leaking fuel elements can be found in each fourth cycle on an average.

The presence of leaking fuel rods can be detected on the basis of primary circuit coolant activity measurements. An example is shown in Figure 1 that indicates the loss of cladding integrity in a fuel rod of Paks NPP Unit 3 in January 2000. The activity measurement data taken in the first period of the cycle are typical for operation without defective fuel rods: the ^{131}I activity concentration is ~10^3 Bq/l. After the failure of the fuel rod this parameter increases and the new stable value is the order of ~10^4 Bq/l that is typical for a leaking fuel rod in a VVER-440 reactor.

In order to evaluate the primary coolant activities in each cycle a numerical procedure has been developed at the Institute of Nuclear Technology of the Budapest Technical and Economical University (BME NTI) based on the recommendations of Soviet regulators for VVER-440 reactors and taking into account the EPRI approach [2]. The procedure evaluates meanly the iodine activity measurement data and gives estimation on the number of leaking fuel rods and amount of tramp uranium in the reactor core.

The primary activity measurements include noble gases too. Xenon and krypton isotopes are also indicators of fuel failure. The detection of leaking fuel elements in several power plants is based on noble gas data [3-7}. One of the motivations of the present work was the evaluation of additional information originated from noble gas activity measurements at the Paks NPP.

If the reactor core includes leaking fuel elements the power plant transients can lead to activity increase in the coolant. There are very few models capable to predict the timing and amplitude of this activity peak in power plants [8-11] and earlier there was no such a model available in Hungary. At the Paks NPP there was no tool for the simulation of transient fuel leaking phenomena.

Beside the evaluation of power plant transients the development of a transient model seemed to be necessary for safety analysis purposes as well. Only a few transient leaking models exist [10] and concerning VVER applications very simple approach was used for the prediction of iodine spiking.

The spiking effect shall be considered in the safety analysis [12]. The values used earlier in the Hungarian safety analysis were of Finnish origin and the physical picture behind the used values was not well known. The current evaluation of Paks NPP activity transients however provided a possibility for the estimation of activity release from failed fuel rods in accidental situations.

The main objective of the present work was to develop a numerical procedure for the simulation of leaking fuel rods under steady state and transient conditions at the Paks NPP. Several steps were needed to reach this objective. As a first step the main leaking fuel element related phenomena had to be identified on the basis of literature review, covering the basic mechanisms of fuel failure, release of radioactive isotopes and uranium, the comparison of steady state and transient phenomena, identification of differences between iodine and noble gas behaviour. The next step was the critical review of existing models and their potential applicability to the Paks NPP conditions. Finally the activity measurements of the power plants had to be deeply understood, as their evaluation and analysis was one of the main aims of the work.

During the evaluation of steady state model the main requirements were the consideration of both iodine and noble gas data and the application of VVER-440 specific correlations and data. The calculations should give estimation on the number of leaking fuel rods, the amount of tramp uranium and the size of cladding failure.

The primary objective of transient model development was the simulation of operational transients and design basis accidents without power increase. The results of calculations should describe the iodine activity in the coolant as function of time and determine the total release during the transients.

The last objective was the determination of expected activity release from failed fuel rods during accidents on the basis of the evaluation of shutdown activity data.

2. SIMULATION OF STEADY STATE LEAKING

The steady state model simulates the release path of iodine and noble gas isotopes from the their place of birth in the fuel pellet into the coolant and takes into account the fissions in the tramp uranium on the fuel rod surfaces (Figure 2). The transport of isotopes is driven by diffusion mechanism in the pellet, other release mechanisms (recoil, knockout) are considered negligible. The release from the gap into the coolant is proportional to the inventory of the given isotope in the coolant. The half life period of the considered isotopes is short enough to reach equilibrium concentrations. Isotopes produced as results of fission in the tramp uranium are promptly released into the coolant. The model applies only core average characteristics and for this reason gives no information on the burnup and power of the leaking fuel rod or the position of the failure.

The steady state solution of the differential equations describing the above requirements serves as the basis of the model. Two systems of equations are solved by a numerical simplex method: one for the noble gas and another for the iodine isotopes. The release-to-birth rate is determined from measured data and those values are approached by the model equations (Figure 3), the parameters of which make possible the determination of the number of leaking fuel rods, the size of failure and the amount of tramp uranium. The diffusion coefficients of the fuel rods were determined on the basis of experimental values and the results were compared to calculated results of BME NTI and the experiences of Paks NPP.

A new algorithm has been developed for the simulation of leaking fuel rods under steady state conditions and the specific parameters of the model for the Paks NPP has been determined. On the basis of the new algorithm a new computer code named RING (Release of Iodine and Noble Gases) has been created. Typical distribution of the release-to-birth ratio (R/B) for iodine isotopes as function of decay constant is shown in Figure 4. In case of surface contamination by fission material (tramp uranium) it is supposed that the fission product goes directly into the coolant after the fission took place. For this reason the dependence of R/B shows a horizontal line. In case of leaking fuel rods the R/B value of short lived isotopes is less than that of long lived ones due to the decay process during the release from the pellet into the gap and coolant. The slope of the line for leaking fuel rods characterizes the escape rate from the fuel, thus the size of the defect on the cladding. In a real case both tramp uranium and leaking rods can be present in the core (Figure 4).

The new method has several advantages over the existing procedures for the evaluation of Paks NPP primary coolant activity measurement data. The steady state model is capable to handle both iodine and noble gas data and gives estimation on the size of the failure on the basis of a VVER-440 specific correlation. A special numerical solution method has been developed for the fitting of model equations to the measured data.

The steady state model has been applied to calculation of leaking fuel characteristics using iodine and noble gas activity measurement data at the Paks NPP.

The first series showed very good agreement between the results of the present model and the numerical procedure regularly applied at the BME NTI.

The model proved to be capable to describe the main phenomena taking place during a single cycle and during several years of operation. Figure 5 shows the activity concentrations of iodine isotopes during the first cycles of Unit 4 of Paks NPP. The activities were very low during the first three cycles, but later significant increase can be observed. (The vertical lines in the figure show the spiking phenomena during shutdowns for refuelling.) The calculated results indicated that the high activity concentrations were caused by leaking fuel rods in cycles 4-6 and 8, while in case of cycle 7 the surface contamination was the source of radioactive isotopes measured in the coolant. Figure 6 shows the estimated number of leaking rods. The calculated mass of tramp uranium is presented in Figure 7.

The noble gas calculations showed that the failed fuel rods could be detected on the basis of xenon and krypton activity data as well. The results of steady state calculations determine the main characteristics of failed fuel rods and the steady state gap activity.

3. SIMULATION OF TRANSIENT LEAKING

The transient model describes two basic release mechanisms:

1. at high fuel pellet temperature the gap is filled by steam and the release of radioactive isotopes is driven by a diffusion mechanism,

2. at low fuel pellet temperature the gap is filled by water and a convection type inflow-outflow mechanism drives the release of radioactive isotopes (illustrated in Figure 8).

The transition between the above two cases is expected at low power, in the present model this limit is 100 MW core power. It means that the second *leaching* mechanism takes place only in the decay power range. The model considers no release from tramp uranium at decay heat and no release of uranium from the fuel is taken into account during the transient process. No diffusional release from the pellet is expected at decay heat. The transient gap activity is constant at high power and its radioactive decay driven decrease is considered at decay heat. The coolant activity is determined by release from failed fuel rods and from tramp uranium, the operation of water make-up system and the radioactive decay of isotopes. The release rate is not constant during the transient, but the release accelerates as a function of changes in primary pressure, core power and boric acid concentration. The released activity is mixed in the total volume of the primary coolant.

The model development focused on normal operational transients without increase of fuel pellet temperature. In these cases no noble gas release takes place, for this reason the transient model describes iodine release only. The transient model uses the results of steady state calculations: the release rate, the number of failed fuel rods, and amount of tramp uranium. The calculation consists of a set of consecutive time steps, and determines the time-dependent coolant activity concentration and the total release during the calculated period [13-15]. A new transient module has been added to the RING code.

During the model development it turned out that the total release could be higher than the steady state gap activity. For this reason in the transient calculations the activity originated from the leaching of fuel pellets and cladding is considered beyond the steady state gap activity. The release acceleration parameters were determined on the basis of Paks NPP pressure, power and boric acid histories during shutdown for refuelling period.

The transient model has been applied to the simulation of shutdown process at the Paks NPP and for the prediction of the time and magnitude of ^{131}I activity peak. Transient calculations have been performed for six shutdown transients with leaking fuel rods. In some cases calculations were performed before the transients, the RING code generally gave a good prediction on the value and timing of activity peak. Figure 9 shows the main technological parameters influencing the spiking phenomena during reactor shutdown. The sequence of events starts with reactor scram, then the boric acid concentration is increased and the pressure is decreased in two steps to ~ 20 bars and to atmospheric pressure. The highest activity concentrations are measured at the times of pressure changes (Figure 10). The RING code calculates the activity concentration of ^{131}I isotope during the reactor transient using the histories of technological parameters and taking into account the characteristics of steady state leaking before the transient. The model calculates the value of maximum activity concentration and the time of activity peak in good agreement with the measured data (Figures 10 and 11).

Another example of transient calculation is shown in Figure 12: during the cycle 16 of Paks NPP Unit 3 the water purification system was switched off for several days. The activity concentrations significantly increased. The short lived isotopes reached new equilibrium concentration (e.g. ^{133}I in Figure 12), while the long lived isotopes showed continuous increase even before switching back the system (^{132}I in Figure 12). After coming back to the normal operation of water purification system the concentrations returned to similar to those values that were recorded before this transient,

The RING code has been successfully applied to the simulation of a power decrease and fuel failure calculations as well.

4. MAXIMUM ACTIVITY RELEASE DURING SPIKING

Using Paks NPP data a conservative value has been determined for the upper limit of the release for some iodine and caesium isotopes from failed fuel rods during transients.

The maximum ^{131}I release from a failed fuel rod during a transient can be estimated as $3{,}4 \cdot 10^{11}$ Bq on the basis of six shutdown transients. (The measured activity concentration maximums and calculated integral release are summarised in Table 1). It is more than two times higher than the steady state gap activity. The current safety analyses for Paks NPP are carried on the basis of this conservative estimation. Similar values were determined for ^{134}Cs ($1{,}1 \cdot 10^{11}$ Bq) and ^{137}Cs ($1{,}1 \cdot 10^{11}$ Bq) isotopes as well.

5. CONCLUSIONS

A new algorithm has been developed for the simulation of leaking fuel rods under steady state and transient conditions and the specific parameters of the model for the Paks NPP have been determined.

The RING code has been applied to calculation of leaking fuel characteristics using iodine and noble gas activity measurement data and to the simulation of transient processes at the Paks NPP and for the prediction of the time and magnitude of ^{131}I activity peak during refuelling.

Using Paks NPP data a conservative value has been determined for the upper limit of the ^{131}I release from failed fuel rods during transients.

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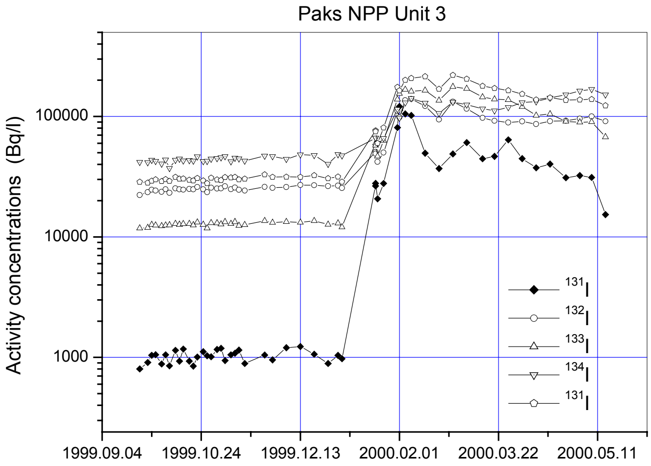

Fig. 1. Measured iodine activity concentrations at Unit 3 of Paks NPP (cycle 14)

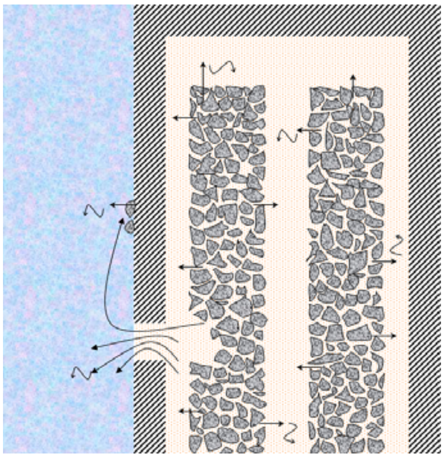

Fig. 2. Scheme of activity release from failed fuel rod during steady state conditions

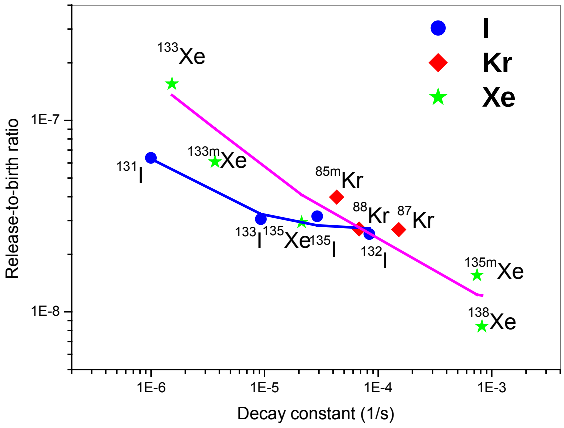

Fig. 3. Approximation of measured data (symbols) by model equations (solid lines)

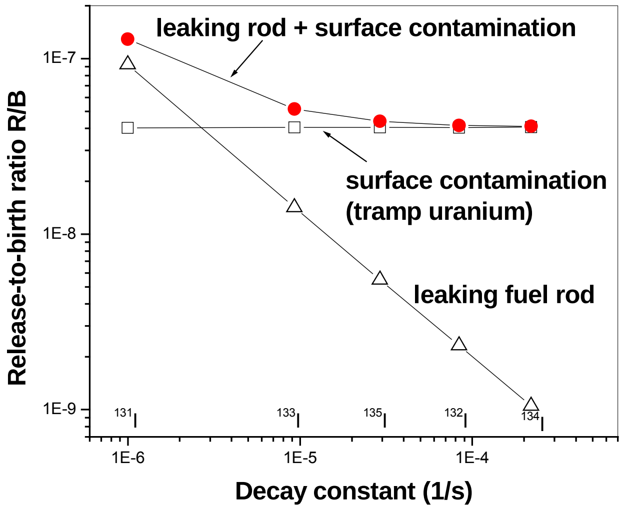

Fig. 4. Typical distribution of R/B for leaking fuel rod and surface contamination

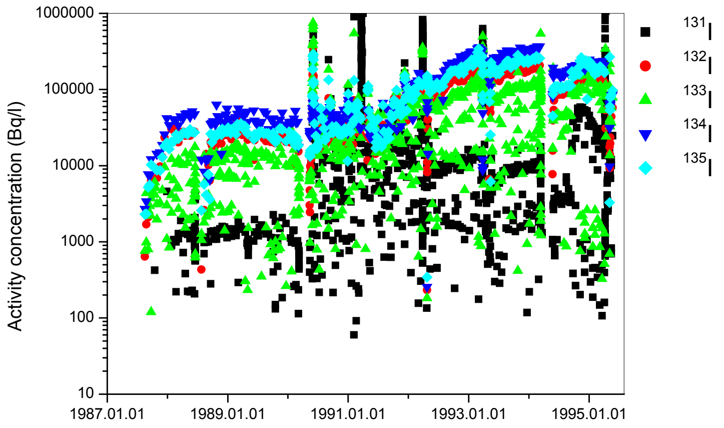

Fig. 5. Measured iodine activity concentrations for Unit 4 of Paks NPP (cycles 1-8)

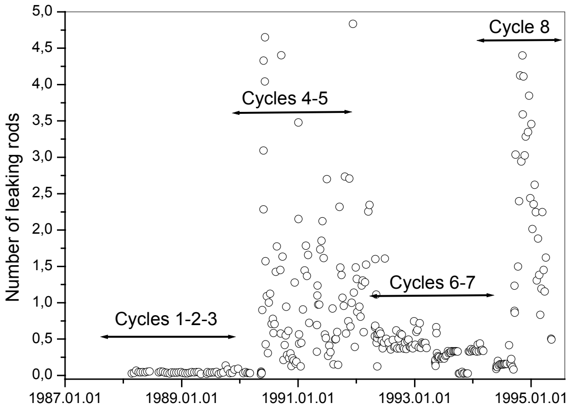

Fig. 6. Calculated number of leaking fuel rods for Unit 4 of Paks NPP (cycles 1-8)

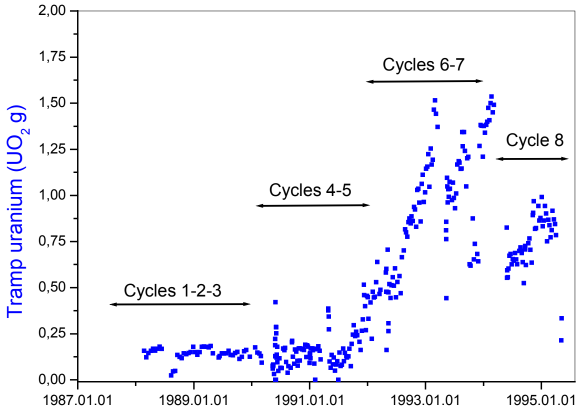

Fig. 7. Calculated amount of tramp uranium for Unit 4 of Paks NPP (cycles 1-8)

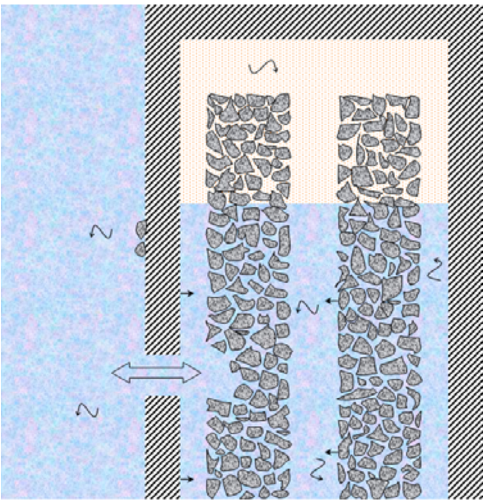

Fig. 8. Scheme of activity release from failed fuel rod during transient conditions

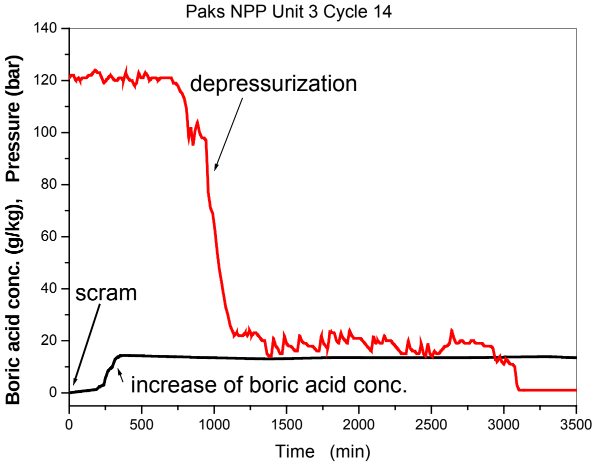

Fig. 9. Main technological parameters during shutdown (Paks NPP Unit 3 Cycle 14)

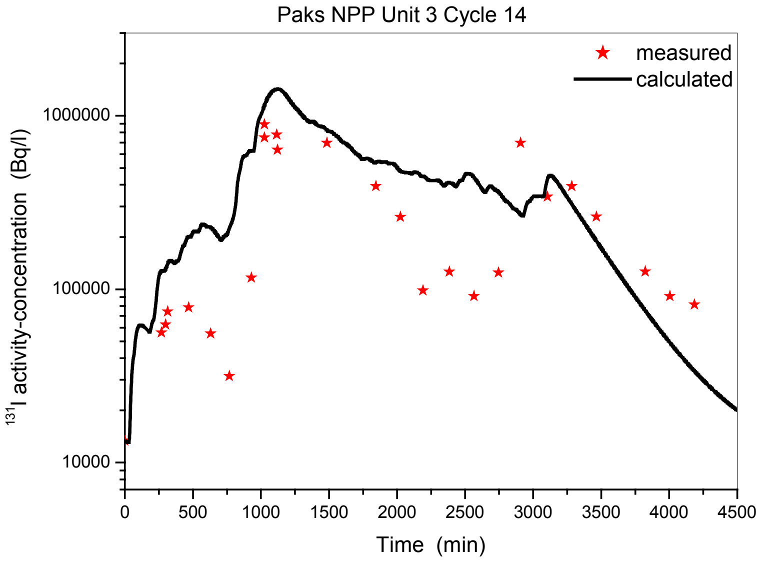

Fig. 10. Measured and calculated ^{131}I activity concentrations during shutdown (Paks NPP Unit 3 Cycle 14)

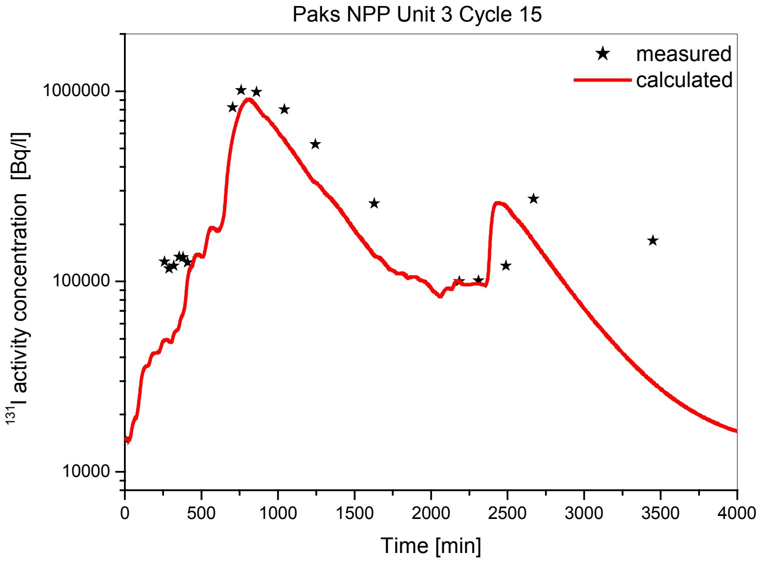

Fig. 11. Measured and calculated ^{131}I activity concentrations during shutdown (Paks NPP Unit 3 Cycle 15)

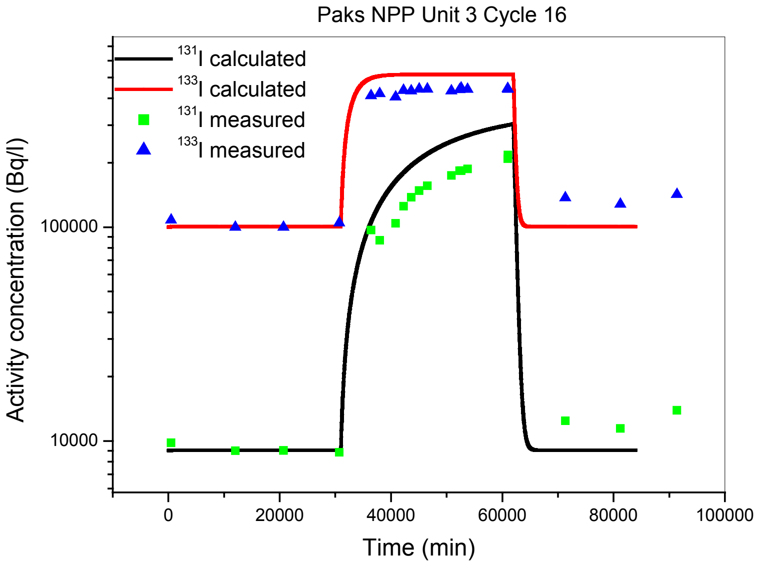

Fig. 12. Measured and calculated iodine activity concentrations with and without water purification system (Paks NPP Unit 3 Cycle 16)

Unit	Cycle	Highest activity ^{131}I concentration [Bq/l]	Total activity release during shutdown [Bq]
2	14	513370	$1{,}0\cdot10^{11}$
3	12	330250	$1{,}4\cdot10^{11}$
3	13	269840	$0{,}5\cdot10^{11}$
3	14	890900	$3{,}3\cdot10^{11}$
3	15	1010000	$2{,}9\cdot10^{11}$
3	16	462000	$1{,}1\cdot10^{11}$

Table 1. ^{131}I release during six shut down transients at the Paks NPP