A STUDY ON LOVIISA NUCLEAR POWER PLANT (VVER-440) DOSE RATE MEASUREMENT'S ABILITY TO DETECT SMALL PRIMARY TO SECONDARY COOLANT LEAKS

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Introduction:

The secondary circuit of the pressurized water reactor (PWR)-plant at the normal power operation-state, can be assumed as activity-free, especially when comparing to the primary coolant. In the case of the primary-to-secondary leaks, active primary coolant will have nearly free access to environment. Therefore primary-to-secondary coolant leaks are typical design base transients in PWR-plants as well as Loviisa's VVER-type nuclear power plants.

Coolant leaks will be detected on the basis of different parameters. Loviisa NPP has specified operating procedures for different kinds of the coolant leak incidents and accidents which will be executed when operating limits for certain parameters will be exceeded. The low liquid level of the pressurizer or high liquid level of the steam generator can indicate the primary-to-secondary coolant leaks. Because of the large difference between activity concentrations of the primary and secondary coolants, leak will raise the activity of the secondary circuit from background level. In the case of the small leak, primary-to-secondary coolant leaks can be distinguished from the other losts of coolant accident -transients by the information of the dose rate measurements. The object of the study was to identify small primary-to-secondary coolant leaks by dose rate measurements during transients. The research was made with SEKUN computer code.

The SEKUN computer code

The SEKUN computer code is 1989 documented FORTRAN code which originally was developed to calculate activity releases and radiation doses to power plant's environment in primary-to-secondary coolant leaks [1]. The node model of SEKUN consists of two steam generators: the one for damaged steam generator and another for other, undamaged, steam generators. The both steam generators are divided to the steam and liquid sides. One calculation node is used for feed water in the tanks and condensers.

Thermohydraulic values, mainly mass flows, and nuclide specific activity concentration of the primary and the secondary coolants are the input values that SEKUN needs to operate. The variables are fed to the SEKUN as a function of time. The SEKUN calculates activity concentrations as a function of time for every node, e.g. nuclide-specific activity concentration in the liquid node of the damaged steam generator:

$$\frac{d}{dt} A_{prim,n} = -\left(\frac{q_{m,prim,d} + q_{m,prim,ud} + \zeta \cdot q_{m,primbd,s} + q_{m,primbd,w}}{m_{prim}} + \mu_{clean,n} \right) \cdot A_{prim,n} + R_{spi,n} + \lambda_n \cdot \left(A_{prim,n-1} - A_{prim,n} \right) + R_{0,n} \tag{1}$$

where

m_{prim}	is mass of the primary coolant [kg],
$q_{m,prim,d}$	is mass flow from primary circuit to the damaged steam generator [kg/s],
$q_{m,prim,ud}$	is mass flow from primary circuit to the undamaged steam generators [kg/s],
ζ	is fraction of the steam exiting via primary circuit's blowdown system [-],

$q_{m,primbd,s}$	is steam Mass flow from the primary circuit's blowdown [kg/s] ,	$R_{spi,n}$	is nuclide specific activity releasing from fuel rod during the spiking phenomenon [Bq/s] ,
$q_{m,primbd,w}$	is liquid mass flow from the primary circuit's blowdown [kg/s] ,	λ_n	is nuclide specific decay constant [1/s] and
$\mu_{clean,n}$	is nuclide specific cleaning factor [1/s],	$R_{0,n}$	is nuclide specific activity source term [Bq/s].

Monitored dose rates in the primary and the secondary circuits are estimated on the bases of the calculated activities. The dose rate measurements were programmed to the code during the study.

Dose rate measurements

Loviisa NPP has a real time radiation dose measurement (RYxxR001) of the liquid phase water in blowdown systems of all six steam generators. RYxxR001 (RY in the following text) -monitors are 1,25"x1" sodium iodide scintillation detectors for gamma radiation. Energy window for gamma radiation is 0,15 - 2,1 MeV. Measuring range for monitor is 10 - $1*10^6$ kBq/m^3, presented as activity concentration of Co-60-equivalent. RY-dose rate measurements were modeled to the SEKUN code through activity concentrations:

$$a_{RY,n}(t) = \frac{A_{w,d,n}}{m_{w,d}}(t) \cdot e^{-\lambda_n \cdot t_{delay,RY}} \cdot \rho_w, \tag{2}$$

where $a_{RY,n}(t)$ is specific activity of nuclide n detected by RY measurement $\left[\frac{Bq}{m^3}\right]$,

$A_{w,d,n}$ is nuclide specific activity of the water in the damaged steam generator $[Bq]$,

$m_{w,d}$ is mass of the liquid in the damaged steam generator $[kg]$ and

$t_{delay,RY}$ is RY's measuring delay $[s]$ which approximately is 10 - 13 min.

Count rate detected by RY measurement:

$$C_{RY}(t) = \sum_{n=1} \left(a_{RY,n}(t) \cdot \gamma_{RY,n}\right), \tag{3}$$

where $C_{RY}(t)$ is counts per second $[cps]$ and

$\gamma_{RY,n}$ is nuclide specific calibration factor for RY $\left[\frac{cps}{Bq/m^3}\right]$.

Radiation dose of the secondary circuit´s steam side is measured by RA -monitors. These monitors are sodium iodide scintillation detectors placed in all six main steam pipes. RA -meters have two energy windows: the lower one, RA-921 (0,2 - 2,2 MeV), mainly for noble gases and the higher one, RA-911 (4,5 - 7,0 MeV), for N-16. The half life of N-16 is very short, only 7.13 s, therefore results of the N-16 -measurement are affected by the reactor power, Table 1 and Figure 1.

Table 1. Min. & max leak sizes detected by RA-921 N-16 monitor

Power	Delay time, from sg to measuring point $[s]$	Minimum primary-to-secondary coolant leak size $\left[\frac{kg}{s}\right]$	Maximum primary-to-secondary coolant leak size $\left[\frac{kg}{s}\right]$
3 %	110,0	27,7	138610
4 %	82,5	1,48	7398
5 %	66,0	0,245	1226
6 %	55,0	0,072	361
8 %	41,3	0,015	75
10 %	33,0	$5{,}68\cdot10^{-3}$	28
20 %	16,5	$7{,}17\cdot10^{-4}$	3,6
30 %	11,0	$3{,}37\cdot10^{-4}$	1,7
40 %	8,3	$2{,}26\cdot10^{-4}$	1,1
50 %	6,6	$1{,}76\cdot10^{-4}$	0,88
60 %	5,5	$1{,}49\cdot10^{-4}$	0,74
70 %	4,7	$1{,}31\cdot10^{-4}$	0,66
80 %	4,1	$1{,}20\cdot10^{-4}$	0,60
90 %	3,7	$1{,}11\cdot10^{-4}$	0,55
100 %	3,3	$1{,}04\cdot10^{-4}$	0,52

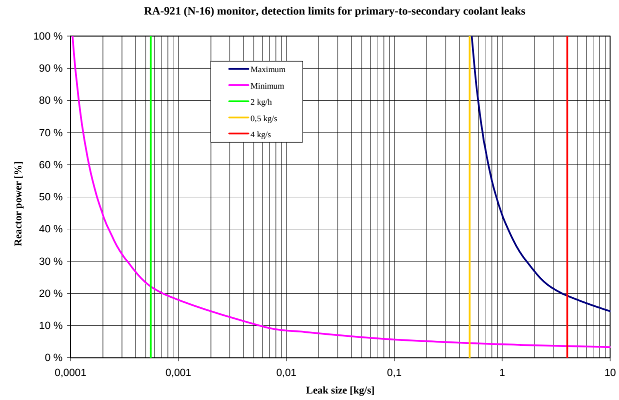

Figure 1. N-16 monitor´s detection limits for the primary-to-secondary leaks

The other dose rate monitors of RA -steam lines, RA-911, measure absorbed dose rates occurred by noble gas and Iodine activity concentrations of the steam. The measuring range is approximately 150 - 10 000 counts per second. RA-911 -monitors were modeled to the SEKUN similarly as the RY-measurements:

$$a_{RA-911,n}(t) = \frac{A_{s,d,n}}{m_{s,d}}(t) \cdot \rho_s \tag{4}$$

where $a_{RA-911,n}(t)$ is specific activity of nuclide n detected by RA-911 measurement $\left[\frac{Bq}{m^3}\right]$

$A_{s,d,n}$ is nuclide specific activity of the steam in the damaged steam generator $[Bq]$ and

$m_{s,d}$ is mass of the steam in the damaged steam generator $[kg]$.

Count rate detected by RA-911 measurement:

$$C_{RA-911}(t) = \sum_{n=1} \left(a_{RA-911,n}(t) \cdot \gamma_{RA-911,n} \right), \tag{5}$$

where $C_{RA-911}(t)$ is counts per second $[cps]$ and

$\gamma_{RA-911,n}$ is nuclide specific calibration factor for RA-911 $\left[\frac{cps}{Bq/m^3}\right]$.

Interpretation of the dose rates measured for the secondary coolant requires information about nuclide specific activities in the primary circuit. TV04R001 -dose rate monitor is a 1"x0,5" sodium iodide scintillation detector with 0,15 - 2,2 MeV energy window for the measurements of the activity concentration of the primary coolant. The measurement range of the monitor is ~$1*10^5$-$1*10^{10}$ kBq/m^3, and delay time is approximately 10 minutes, what is about the same for RY-meters' delay. TV04R001 has been modeled to the SEKUN code as well:

$$a_{TV04,n}(t) = \frac{A_{prim,n}}{m_{prim}}(t) \cdot e^{-\lambda_n \cdot t_{delay,TV04}} \cdot \rho_w, \tag{6}$$

where $a_{TV04,n}(t)$ is specific activity of nuclide n detected by TV04 measurement $\left[\frac{Bq}{m^3}\right]$,

$A_{w,d,n}$ is nuclide specific activity of the water in the damaged steam generator $[Bq]$,

$m_{w,d}$ is mass of the $[kg]$ and

$t_{delay,TV04}$ is TV04's measuring delay $[s]$.

And count rate detected by TV04 measurement:

$$C_{TV04}(t) = \sum_{n=1} \left(a_{TV04,n}(t) \cdot \gamma_{TV04,n} \right), \tag{7}$$

where $C_{TV04}(t)$ is counts per second $[cps]$

$\gamma_{TV04,n}$ is nuclide specific calibration factor for TV04 $\left[\frac{cps}{Bq/m^3} \right]$.

The spiking phenomenon

If there are untight fuel rods in the core, changes in the primary circuit thermal conditions can increase the leakage rate of the fission products from the gas gaps of the defected rods. This phenomenon is called spiking and it is usually a consequence of pressure, temperature or power fluctuation. The concentration of noble gas, Cs and, especially, I in the primary coolant is affected by the spiking phenomenon. The spiking process is shown schematically in Figure 2.

The spiking has a significant impact of the activity concentration on the primary coolant therefore it has to be taken account in primary-to-secondary leakage cases. Several models of spiking have been described in the literature. In the SEKUN code, two different spiking models can be utilized. In the simpler model the gas gap activity of the spiking fuel rods is released to the primary coolant at a constant rate. Another model allows to define the spiking release rate to proportional to the remaining activity in the gas gap.

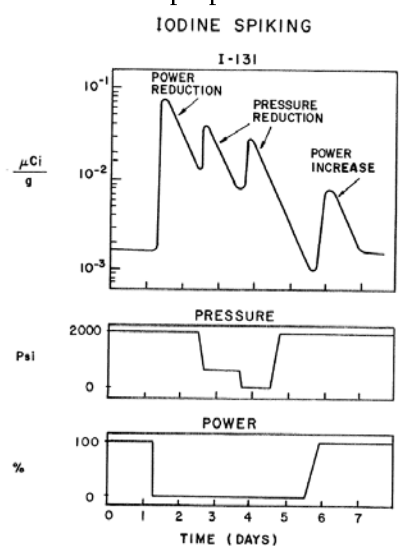

Figure 2. Schematic representation of iodine spiking [2].

Hypothesis and initial data of the study

Measuring results of TV04-, RY- and RA-911 -monitors were modeled in various primary-to-secondary coolant leak cases. Leak size and specific activity of the primary coolant were variable input. The calculations were made in two operational states: power operation and hot standby. In hot standby analysis the reactor was first driven down from the power operation -states and the beginning of the leak was assumed to take place 10 hours after the reactor trip.

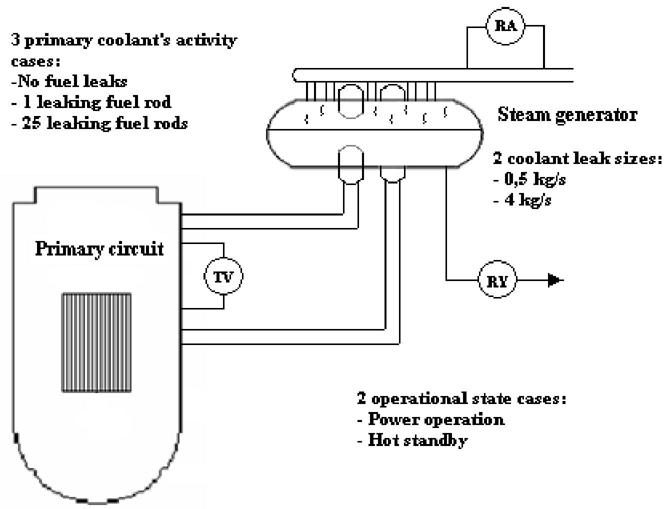

Figure 3. The basic idea of the study

The leak of 2 kg/h is defined as a maximum allowed according to the power plant's specifications. So this small-sized leak at the top tube row of the steam generator before the actual leak was used as a starting hypothesis. The leak sizes were chosen to be similar to those defined in the Loviisa NPP's incident and accident specifications. Thermohydraulic parameters during the leakage transients were simulated with Loviisa NPP model for the APROS simulation software [3]. The migration of activity was modeled with the SEKUN code.

Results

The activity detected by RY- and TV04 -measurements, in accordance with output data of the SEKUN computing, can be represented graphically, e.g. Figures 4-5 for 0,5 kg/s leakages. The effect of the spiking phenomenon that raises the activity level on the primary and the secondary circuits can clearly be seen on Figure 5.

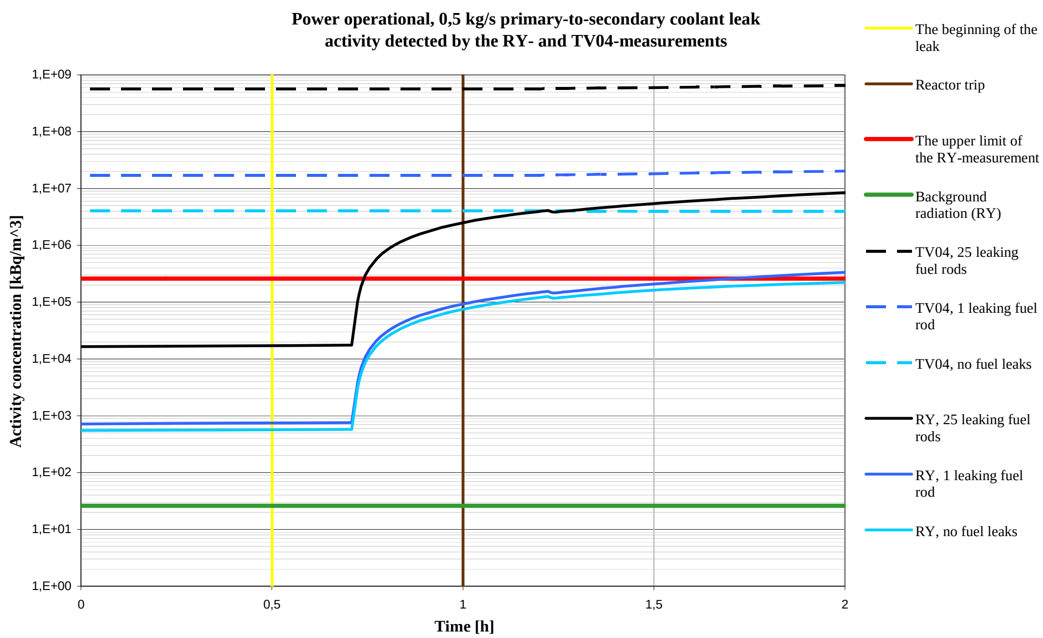

Figure 4. 0,5 kg/s p-to-s leakage in power operation, RY- and TV04-monitors

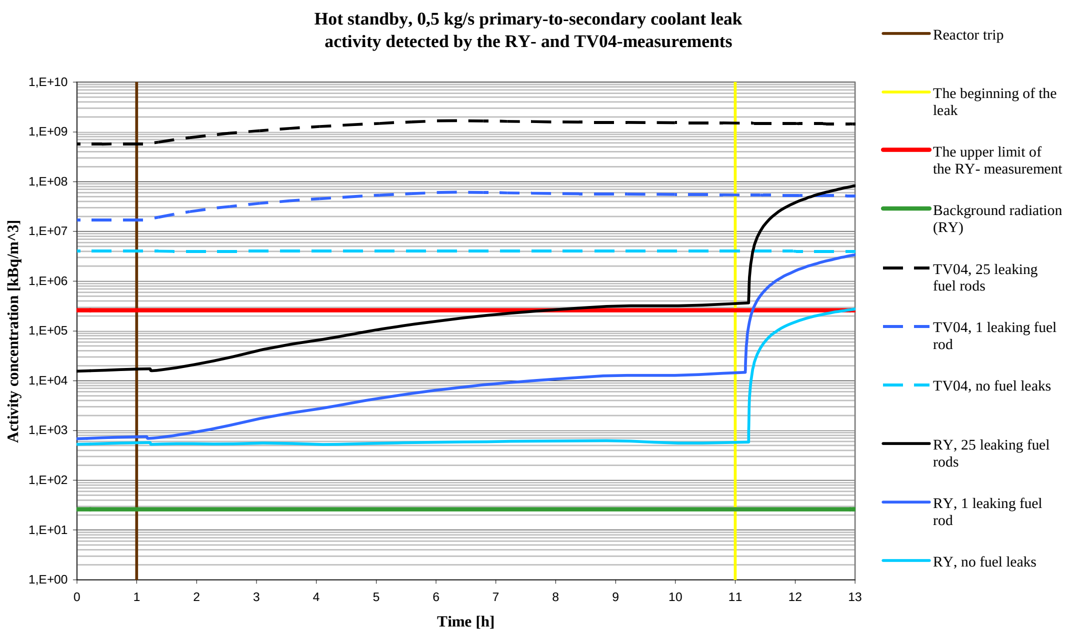

Figure 5. 0,5 kg/s p-to-s leakage in hot standby, RY- and TV04-monitors

The results for RA-911-monitors in 0,5 kg/s primary-to-secondary leakage -cases are shown in Figures 6 and 7. RY-monitor results can be compared straightforward to the activities of the primary coolant. Because the RA-911 measurements describe the situation of the steam lines, pulse rates would be the best way to present these data.

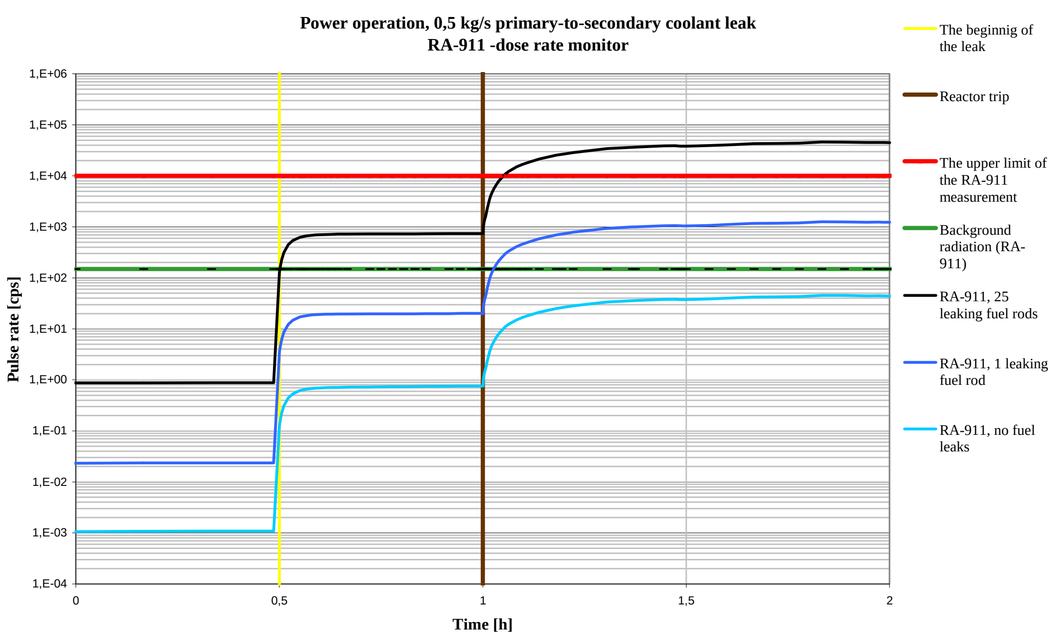

Figure 6. 0,5 kg/s p-to-s leakage in power operation, RA-911-monitors

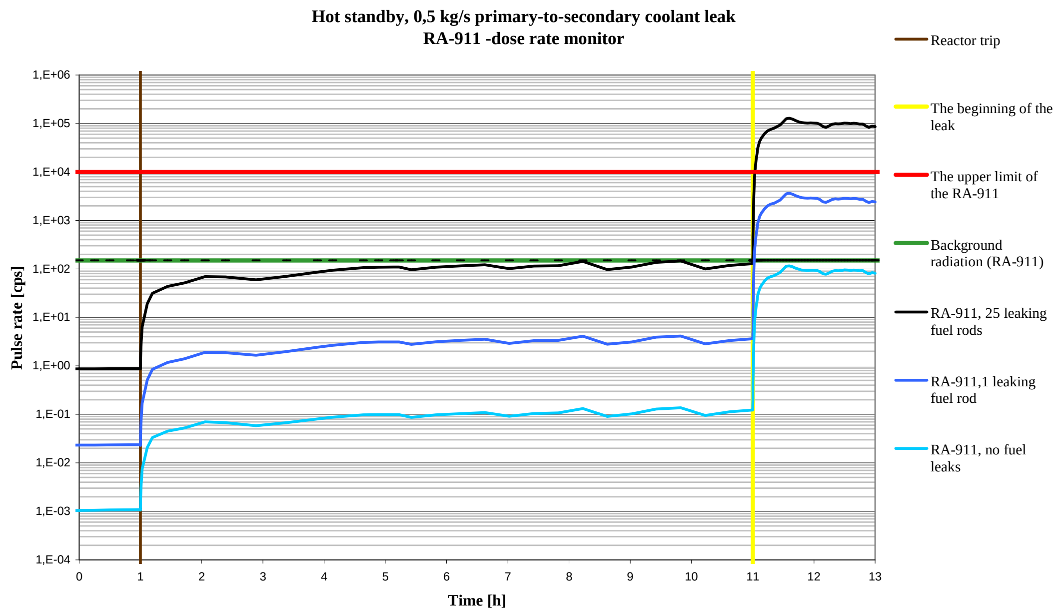

Figure 7. 0,5 kg/s p-to-s leakage in hot standby, RA-911-monitors

Conclusions

As can be seen from the Figures 4-7, activity concentration level of the secondary circuit raises broadly in consequence of small primary-to-secondary coolant leak. Figures 8-9 show simplified graphs that reflect relationship between leak size and the measuring results in power operation:

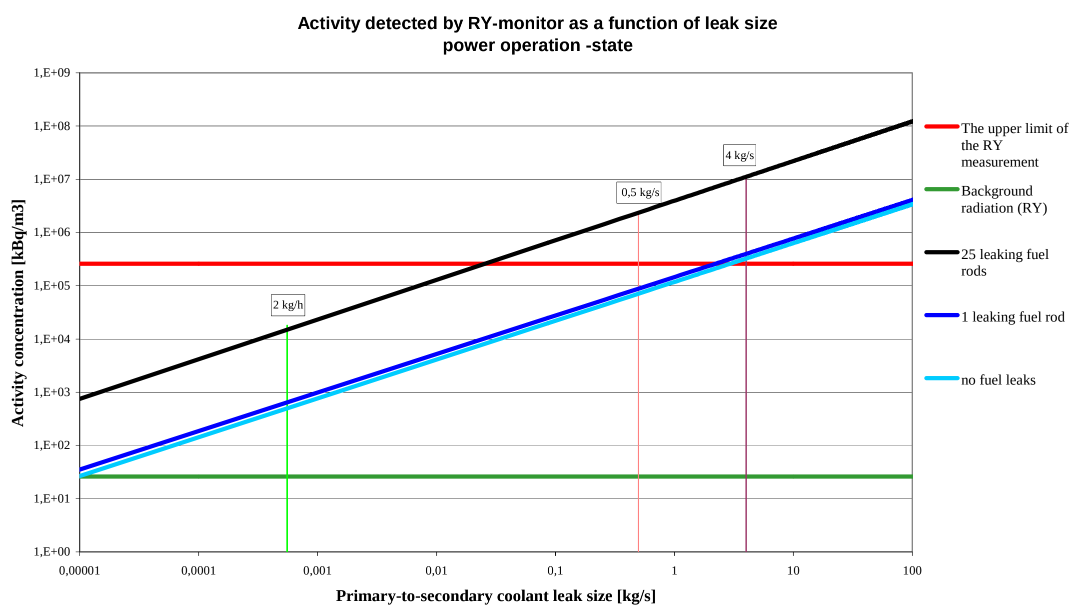

Figure 8. The relationship between leak size and activity detected by RY-monitor, power operation.

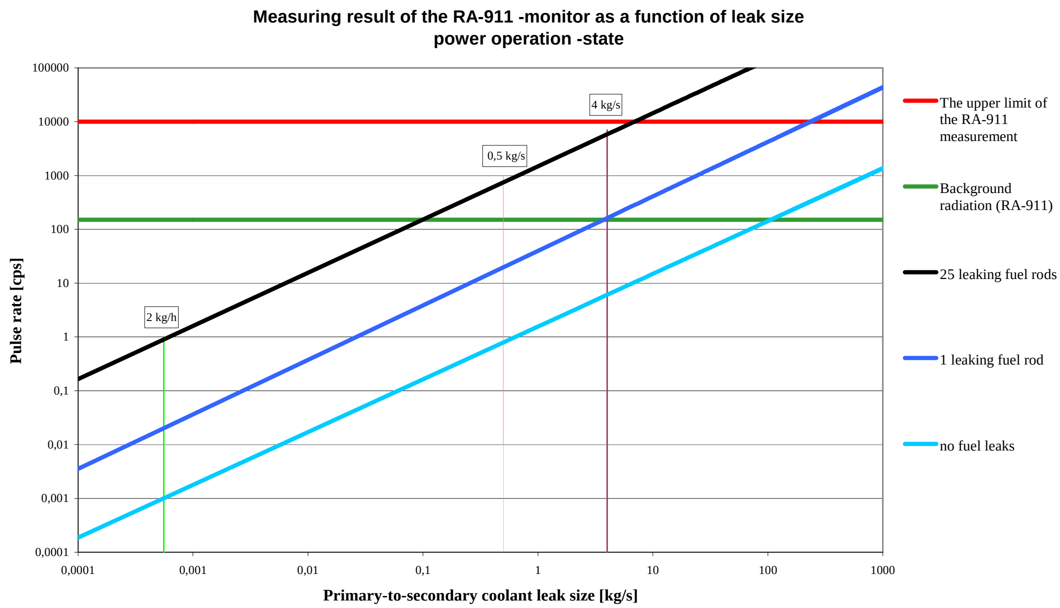

Figure 9. The relationship between leak size and measurement of the RA-911-monitor, power operation.

Figures 10-11 are graphs of hot standby -cases:

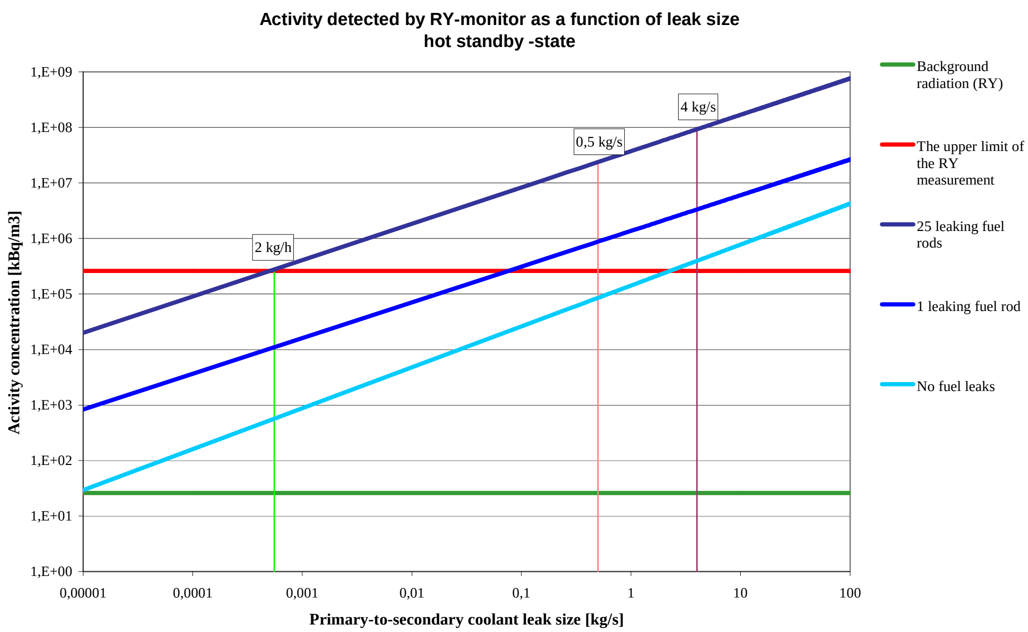

Figure 10. The relationship between leak size and activity detected by RY-monitor, hot standby

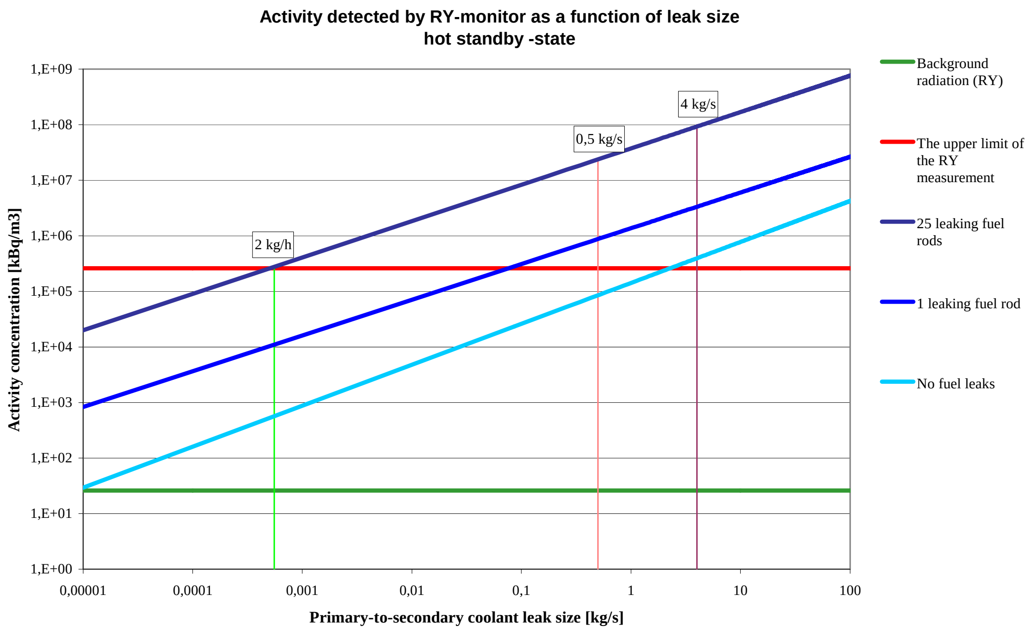

Figure 11. The relationship between leak size and measurement of the RA-911-monitor, power operation.

The study proved that leak sizes those require incident specifications (> 0,5 kg/s) - according to Loviisa NPP guidelines - can be identified with dose rate measurements. However interpretation of the results is not always clear, especially when there is a possibility of leaking fuel rods-problem. The spiking phenomenon has a significant effect to the activity levels therefore identification of primary-to-secondary coolant leak needs also the measuring information of TV04-dose rate monitor.

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[2] R. A. Shaw (project manager), Iodine spiking, EPRI NP-4595, May 1986

[3] APROS - The Advanced Process Simulation Environment, web pages, VTT, 15.5.2008, http://apros.vtt.fi/