About leak detection systems in the framework of LBB concept application at Russian NPPs

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Application of "leak before break" concept to reactor coolant circuit is obligatory for RF NPPs and the success depends also on fulfilment of requirements to the leak detection systems specified in RF national standard. During 1999-2020 requirements to the leak detection systems were permanently improved in regulatory documents. The most important changes in requirements have been done according to the Federal law on ensuring the uniformity of measurements. Paper gives comparative analyses of these evolutionary changes of requirements as well as details of their implementation during design and manufacturing of leak detection systems to supply NPP Units with VVER-440/1000/1200 and RBMK-1000 reactor facilities. Recently approved in the Russian Federation, the Federal norms and rules (FNR) in the field of atomic energy use ensure the continuity of the general requirements for reactor coolant leak monitoring (detection) systems (LDS) at nuclear power plants (NPPs) in relation to the previously valid regulatory documents.

***Keywords**: leak before break concept, leak detection system, certificates of approval of the type of measuring instrument, certified measuring procedure.*

1. Introduction

Actual Russian Federal Norms and Rules (FNR) in the field of nuclear energy use [1-3] ensure continuity of general requirements for reactor coolant leak monitoring (detection) systems (LDS) at nuclear power plant (NPP) in relation to former regulatory documents [4-6].

Specific requirements for LDS were first defined in normative guidelines on the "leak before break" (LBB) concept [7] for use at Russian NPPs. The guideline [7] had been developed by the analogy with international practice of the LBB concept application: the publications [8-9] contain references to LDS manual [10].

2. Requirements to LDS in 1999-2018

The Federal Law on the unity of measurements No.102 [11] (2008) led to changes in the technical policy of Russian nuclear power industry. Indicator-type LDS (as was actually the case in [7]) gradually began to be replaced by measurement-type LDS with technical requirements providing explicitly the necessary characteristics of measurement accuracy.

It should be noted that the regulatory documents on LBB concept applications [7, 12-13] did not take into account the requirements for the LDS of the primary coolant, which were specified in paragraph 5.2.5 PNAE G-01-036-95 (NP-006-98) [6] in relation to the detection of minimum leak through the pressure boundaries of the first circuit of the VVER type reactor: "specify the minimum amount of leakage that can be detected by the methods used." This requirement is fully contained in the current document NP-006-16 [3] in subsection 5.2.6 of the mandatory Annex No. 3.

The application of this requirement under the conditions of a complete ban on the operation of the NPP Unit with through wall defects in equipment and pipelines [14] provided the way to effective LDS transfer from the indicator status to the measuring one by metrological confirmation of the LDS characteristics: sensitivity Q_0 (one of the main parameters used in the algorithms for proving the LBB concept in [7, 12-13]) and the minimum leakage detected value Q_{min} (should be evaluated for the LDS application).

The relationship of these parameters through the relative measurement error of leak flow rate δ can be written as $Q_{min} = (1 + \delta)Q_0$.

The normative guideline [12] specified, as metrological requirement, that "the relative error in measuring the leak flow rate (relative to the measured value) is not more than ± 50 %".

Also [12] contained the requirement that "the LDS must ensure the reliability of leak control at a level not lower than 0.9. The reliability indicator of the LDS leak control must be justified in the design documentation for the system". The document [13] defined the indicator value equal to 0.8.

In contrast to [12], [13] the national standard on the LBB concept application (GOST R 58328-18 [15], valid from 01.01.2019), has no any mention of the reliability indicator of the LDS leak control.

The requirements for the lower limit of LDS sensitivity Q_0 – 1.9 kg/min for pipelines with $150 \le D_{nom} < 750$ mm and 3.8 kg/min for pipelines with $D_{nom} \ge 750$ mm – are coincide in the regulatory documents [12-13, 15].

Results of comparing the LDS requirements specified by documents on LBB concept applications are presented in detail in table 1.

3. Characteristics of VVER type LDS

For NPP Units with VVER-440/1000, JSC IPPE developed LDS for the primary (SACT and SCTV) and secondary (SACT-2K, SCTV-2K and SCTV-2P) circuits in accordance with the technical specifications [16-17]. The LDS are characterized by relative error of ±50% for the leak flow rate measurements (table 2). The listed LDS subsystems provide monitoring of leaks for pipelines under thermal insulation (except for SCTV-2P) using acoustic sensors and humidity control sensors, determining the leak location or the distance from the acoustic sensor to the leak location with absolute error ±2 m. The SCTV-2P subsystem is able to locate leak position up to the compartment of the NPP Unit. Certificates of approval of the type of measuring instrument (CATMI) have been issued for LDS subsystems of acoustic control and humidity control (table 2). These certificates confirm the minimum leakage detected value Q_{min} at least 1.5 l/min. So requirements of the [1-6] and [12-13, 15] are fulfilled.

Table 1. Comparison of requirements for LDS in Russian normative guidelines from 1999 year to present time

Requirements for LDS	**RD 95 10547-99**	**RD EO 1.1.2.05.0939-2013**	**RD EO 1.1.2.05.0939-2016**	**GOST R 58328-2018**
LDS status	p.8.6.1: diagnostic system	p.5.3.3: measurement system for technical diagnostics		
Requirement for intervention of the NPP Unit control panel operator in the operation of LDS	p.8.6.2: no requirements			
Requirement to separate leaks from identified and unidentified sources	yes	5.1.2	no	no
Number of subsystems in LDS	3	p.5.3.1.1, item 2: 3 for primary circuit 2 for secondary circuit	p.D.1.8 at least 3	p.B.1.2 and p.B.1.3 2 + 1 (LDS Integral Level)
Should leak monitoring be performed based on the radiation activity parameter?	p.8.5, item 1: yes	no	p.D.1.8: yes	p.B.1.3: yes
Requirements for LDS Integral Level when NPP unit operating at rated power:	Yes	yes		p.B.2.3
- leak rate sensitivity is not worse	p.8.5, item 3: - 3,8 l/min (for the reactor cooling circuit) - 19 l/min (for steam pipelines)	p.5.3.1.5: - 3, 8 kg/min (for main circulation pipelines) - 1,9 kg/min (for other pipelines)	p.D.2.2, "a": - 3, 8 kg/min ($D_{nom} \geq 750$ mm) - 1,9 kg/min ($150 \leq D_{nom} < 750$ mm)	p.B.2.3, item 1: - 3,8 kg/min (228 kg/hour) for pipelines $D_{nom} \geq 750$ mm; - 1,9 kg/min (114 kg/hour) for pipelines $150 \leq D_{nom} < 750$ mm
- the upper range of leak flow measurement	not established	not established	p.D.2.2, "b)": at least 19,0 kg/min	p.B.2.3, item 2: at least 19,0 kg/min
- the time interval of the detection and measurement of leaks	p.8.5, item 3: no more than 1 hour	p.5.3.1.5: no more than 1 hour (as possible)	p.D.2.2., "v)" no more than 1 hour	p.B.2.3, item 3: no more than 1 hour
- the relative error of a leak flow measurement	don't need to specify	p.5.3.1.5: reduced (modified) to the measured value, no more than ± 50%	p.D.2.2, "g)": no more than ± 50%	p.B.2.3, item 4: no more than ± 50%
- error in measuring the leak location coordinates	p.8.5, item 3: recommendation ± 2 m	p.5.3.1.5: ± 2 m	p.D.2.2, "d)": no more than ± 2 m or ½ of placing sensors step	B.2.3, item 5: ± 3 m, but no more than ½ of placing sensors step
The requirement to LDS at the lowest recorded flow rate of unidentified leakage	no	p.5.3.1.5: - 230 kg/min (for main circulation pipelines) - 114 kg/min (for other pipelines)		no
The requirement to LDS to function in the mode of hydraulic (pneumatic) tests	p.8.1, paragraph 2	no	p.D.1.13	no
The requirement to LDS to function in regimes of NNUE and accident situation	no	p.5.1.2		no
The requirement to LDS to detect and identify leaks of equipment and pipelines when the unit is	no	no		p.B.1.1

Requirements for LDS	RD 95 10547-99	RD EO 1.1.2.05.0939-2013	RD EO 1.1.2.05.0939-2016	GOST R 58328-2018
operating in start-up (stop) modes)				
Need to approve the type of measuring instrument on LDS	no	p.5.3.4.1: yes	p.D.3.3 [5)]: yes	p.B.2.5: yes
Separate requirement for approval of the type of measuring instrument to measuring channels	no	no	p.D.3.2 [4)]: yes	no
Requirements for reliability of leak detection	p.8.6.1: requirements to minimize: - the probabilities of false operation; - probability of missing an event	p.5.3.2: not less than 0.9	p.D.2.2, "e": not less than 0.8 (in the flow rate range from the lower limit to the middle of the measurement range); below 0.9 (if the flow rate is above the middle of the measurement range)	no
Requirement to LDS to specify the minimum leakage value that must be detected using the methods used (from NP-006-98 and NP-006-16)	no	no	no	p.6.2.3
The method for measuring leak parameters should be developed in accordance with the requirements of GOST R 8.932-2017	no	no	no	p.B.2.1
LDS software must be verified and passed the procedure for confirming compliance with the requirements of GOST R 8.654-2009	no	no	no	p.B.2.2
Requirement for certification LDS software/software tool in Rostechnadzor bodies in accordance with current requirements	no	p.5.3.3: yes	no	no
Seismic qualification requirement for each LDS subsystem	p.8.7.1, item 4: yes; p.8.9 - see below[1]:	no	no	no
Requirement for identification and seismic qualification of AC power sources for each LDS	p.8.7.1, item 6: yes p.8.9 - see below[2]	no	no	no
The requirement to ensure the possibility of calibration of measuring channels in the operating mode	p.8.10: yes	no	no	no

Table. 2. The list of CATMI for LDS of NPPs with VVER type reactor

Reg. ID	Name of measuring instrument	Valid until/ Verification interval	The system consists of LDS[3] / Technical specification	Q_{min} / δ[4]	Limits of permissible absolute error in determining the leak site
55686-13	Acoustic LDS with acoustic signal measurement channels Manufacturer (Vendor): IPPE JSC https://info.metrologu.ru/grsi/grsi_225869.html	28.11.2018; 09.04.2023 / 2 years	Technical specification E.091.7372.05 TU	1,5 l/min ±50%	±2m (Limits of permissible absolute error in determining the distance from the acoustic sensor to the leak site)

[1] The drainage level monitoring system and at least one of the three leak monitoring subsystems must be qualified to perform the design functions corresponding to the maximum design earthquake for NPP Unit;

[2] The earthquake-resistant LDS must be powered from a earthquake-resistant AC power source

[3] LDS in the table 2 meet the requirements of NP-006-98, NP-006-16 and p.6.2.3 of GOST R 58328-2018.

[4] Q_{min} – Minimum detectable amount of coolant flow through a leak; δ – Limits of permissible relative error in determining the flow rate of the coolant through a leak, %

Reg. ID	Name of measuring instrument	Valid until/ Verification interval	The system consists of LDS[3] / Technical specification	Q_{min} / δ[4]	Limits of permissible absolute error in determining the leak site
55687-13	LDS with relative humidity and temperature measurement channels Manufacturer (Vendor): IPPE JSC https://info.metrologu.ru/grsi/grsi_226346.html	28.11.2018; 11.04.2023/ 2 years	SCTV, SCTV-2K / Technical specification E.091.7326.01 TU	1,0 l/min ±50%	±2m
			SCTV-2P / Technical specification E.091.7326.01 TU		«-» accurate to the room

4. Characteristics of RBMK type LDS

Full-scale LDS for RBMK NPP Units - ASOTT - were developed by NIKIET JSC. The details of certified measuring procedures (CMP) for full-scale LDS at four RBMK NPP Units are provided in table 3.

The CMPs (FR.1.29.2016.24188 ÷ FR.1.29.2016.24191) contain formulas to calculate flow rate measurement error as applied to individual subsystems and LDS as a whole. The formulas are the same for Units of the first and second generations of RBMK NPPs, which have differences in layout of technological equipment. The formulas do not take into account presence or absence of thermal insulation on piping outer surface. Calculations using these formulas, as applied to full-scale LDS give for the lower flow rate boundary 114 kg/h the corresponding relative error equal to ±75%, and for the upper boundary 1140 kg/h the corresponding relative error equal to ±65%. In other words, the threshold of ±50% specified by the regulatory documents [12-13, 15] has been exceeded.

For LDS of other two RBMK NPP Units (Smolensk NPP Unit 1, Kursk NPP Unit 3) CATMI have been issued also (tables 4 and 5). Formulas to calculate flow rate measuring errors of individual subsystems and LDS as a whole specified in the CATMI (tables 4 and 5) are similar to the ones specified in CMP (table 3). Therefore, the estimates given above are valid and also do not meet the requirements of regulatory documents [12-13, 15].

Table 3. The list of CMP for LDS of NPPs with RBMK type reactor

Registration ID	Name of the CMP	Certificate of attestation	Issue date	Measurement range, kg/hour	Number of measuring channels[1]
FR.1.29.2016.24191	Measurement procedure for measuring mass flow and determining the leak location coordinates using the coolant full-scaled automatic leak detection system of Smolensk NPP Unit 2 https://fgis.gost.ru/fundmetrology/registry/16/items/297039	01.00225-2011.201/056-2015	18.12.2015	114 ÷ 1140	4
FR.1.29.2016.24190	Measurement procedure for measuring mass flow and determining the leak location coordinates using the coolant full-scaled automatic leak detection system of Kursk NPP Unit 4 https://fgis.gost.ru/fundmetrology/registry/16/items/297038	201-007/01.00225-2011/2016	29.04.2016	114 ÷ 1140	4
FR.1.29.2016.24189	Measurement procedure for measuring mass flow and determining the leak location coordinates using the coolant full-scaled automatic leak detection system of Kursk NPP Unit 2 https://fgis.gost.ru/fundmetrology/registry/16/items/297037	201-005/01.00225-2011/2016	08.04.2016	114 ÷ 1140	3
FR.1.29.2016.24188	Measurement procedure for measuring mass flow and determining the leak location coordinates using the coolant full-scaled automatic leak detection system of Kursk NPP Unit 1 https://fgis.gost.ru/fundmetrology/registry/16/items/297036	201-008/01.00225-2011/2016	13.04.2016	114 ÷ 1140	3

Table 4. The list of CATMI for LDS of Smolensk NPP Unit 1 with RBMK type reactor

Registration ID	Name of CATMI /Technical specification	Data of the approval certificate of CATMI	Valid until / Verification interval	Measurement range, kg/hour	Number of measuring channels
57990-14	Full-scaled automatic leak detection system of reactor coolant of Smolensk NPP Unit 1 / No technical specifications https://fgis.gost.ru/fundmetrology/registry/4/items/370946	RU.E.29.004.A №56250 / 23.07.2014	unlimited / 1 year	114 ÷ 1140	4

[1] Measuring channel which characterized the specific way to leak detection (for example, humidity etc.)

Table 5. The list of CATMI for LDS of Kursk NPP Unit 3 with RBMK type reactor

Registration ID	Name of CATMI/Technical specification	Data of the approval certificate of CATMI	Valid until / Verification interval	Measurement range, kg/hour	Number of measuring channels
58802-14	Subsystem of ASOTT-V (ASOTT-humidity) of Kursk NPP Unit 3 / TU 4389-007-73555750-2012 https://fgis.gost.ru/fundmetrology/registry/4/items/371903	RU.E.29.004.A №57125 / 20.10.2014	unlimited / 1 year	114 ÷ 1140	-
58803-14	Subsystem of ASOTT-T (ASOTT-Temperature) of Kursk NPP Unit 3 / TU 4389-008-73555750-2012 https://fgis.gost.ru/fundmetrology/registry/4/items/371904	RU.E.29.004.A №57153 / 20.10.2014	unlimited / 1 year	114 ÷ 1140	-
58804-14	Subsystem of ASOTT-A of Kursk NPP Unit 3 / TU 4389-006-73555750-2012 https://fgis.gost.ru/fundmetrology/registry/4/items/371905	RU.E.29.050.A №57154 / 20.10.2014	unlimited / 1 year	114 ÷ 1140	-
58805-14	Subsystem of ASOTT-Ac (ASOTT-acoustic) of Kursk NPP Unit 3 / TU 4389-009-73555750-2012 https://fgis.gost.ru/fundmetrology/registry/4/items/371906	RU.E.29.004.A №57155 / 20.10.2014	unlimited / 1 year	114 ÷ 1140	-
58806-14	Full-scaled automated LDS of Kursk NPP Unit 3 / TU 4389-010-73555750-2012 https://fgis.gost.ru/fundmetrology/registry/4/items/371907	RU.E.29.004.A №57156 / 20.10.2014	unlimited / 1 year	114 ÷ 1140	4

Information and formulas provided in CMPs (table 3) for each LDS measuring channel to assess flow rate measurement error and values of Q_{min} as applied to individual subsystems and LDS as a whole are given in table 6. Estimations of flow rate measurement error and values of Q_{min} for a set of G values are provided in table 7.

Table 6. Measuring channel set for ASOTT-P for NPPs with RBMK type reactor

Measuring channel / ASOTT-P	Measurement range, kg/hour	Limits of the relative measurement error interval corresponding to P = 0.95
Measuring channel of mass leak flow rate based on direct temperature measurement (subsystem ASOTT-T)	114 ÷ 1140	$\delta = \pm\left(0{,}2 + \frac{4{,}2 \cdot (G_B - G_H)}{G + 5{,}88 \cdot (G_B - G_H)}\right) \cdot 100$
Measuring channel of mass leak flow rate based on direct temperature and humidity measurement (subsystem ASOTT-V)	114 ÷ 1140	$\delta = \pm\left(0{,}2 + \frac{3 \cdot (G_B - G_H)}{G + 4{,}88 \cdot (G_B - G_H)}\right) \cdot 100$
Measuring channel of mass leak flow rate based on the results of direct measurements of the volume activity of radioactive aerosols (subsystem ASOTT-A)	114 ÷ 1140	$\delta = \pm\left(0{,}2 + \frac{4{,}2 \cdot (G_B - G_H)}{G + 5{,}88 \cdot (G_B - G_H)}\right) \cdot 100$
Measuring channel of mass leak flow rate based on the results of direct measurements of the sound pressure level (subsystem ASOTT-A)	114 ÷ 1140	$\delta = \pm\left(0{,}2 + \frac{3{,}58 \cdot (G_B - G_H)}{G + 5{,}38 \cdot (G_B - G_H)}\right) \cdot 100$
Measuring channel of mass leak flow rate based on the measurement results ASOTT-P	114 ÷ 1140	$\delta = \pm\left(0{,}3 + \frac{1{,}58 \cdot (G_B - G_H)}{G + 3{,}38 \cdot (G_B - G_H)}\right) \cdot 100$

* G – value of the measured mass leak flow rate, kg/hour; GB and GH – upper and lower level of measurement range of mass leak flow rate, kg/hour; P - confidence probability.
The time between the leak occurrence and the output of the measurement result with the specified error does not exceed 1 hour

Table 7. Calculating of Q_{min} as [G_{min} x (1+δ)] for ASOTT-P of NPP Units with RBMK type reactor

			G_H	114 kg/h	114 kg/h	114 kg/h	114 kg/h
			G_B	1140 kg/h	1140 kg/h	1140 kg/h	1140 kg/h
			G	114 kg/h	228 kg/h	627 kg/h	1140 kg/h
ASOTT-T	KNPP-4	FR.1.29.2016.24190	δ	± 90,0 %	± 89,0 %	± 85,0 %	± 80,0 %
	SNPP-2	FR.1.29.2016.24191					
ASOTT-V	KNPP-1	FR.1.29.2016.24188	δ	± 80,0 %	± 79,0 %	± 75,0 %	± 70,0 %
	KNPP-2	FR.1.29.2016.24189					
	KNPP-4	FR.1.29.2016.24190					
	SNPP-2	FR.1.29.2016.24191					
ASOTT-A	KNPP-1	FR.1.29.2016.24188	δ	± 90,0 %	± 89,0 %	± 86,0 %	± 80,0 %
	KNPP-2	FR.1.29.2016.24189					
	KNPP-4	FR.1.29.2016.24190					
	SNPP-2	FR.1.29.2016.24191					
ASOTT-Ak	KNPP-1	FR.1.29.2016.24188	δ	± 85,0 %	± 84,0 %	± 80,0 %	± 75,0 %
	KNPP-2	FR.1.29.2016.24189					
	KNPP-4	FR.1.29.2016.24190					
	SNPP-2	FR.1.29.2016.24191					
ASOTT-P	KNPP-1	FR.1.29.2016.24188					

	KNPP-2	FR.1.29.2016.24189	δ	± 75,0 %	± 74,0 %	± 70,09 %	± 65,0 %
	KNPP-4	FR.1.29.2016.24190					
	SNPP-2	FR.1.29.2016.24191					
ASOTT-P	KNPP-1	FR.1.29.2016.24188	Q_{min}	200,0 kg/h	396, 0 kg/h	1063,0 kg/h	1883,0 kg/h
	KNPP-2	FR.1.29.2016.24189					
	KNPP-4	FR.1.29.2016.24190					
	SNPP-2	FR.1.29.2016.24191					

Information and formulas provided in CATMI (tables 4 and 5) for each LDS measuring channel to assess flow rate measurement error and values of Q_{min} as applied to individual subsystems and LDS as a whole are given in table 6 due to the fact that they are the same for CATMI and SMP. Estimations of flow rate measurement error and values of Q_{min} for a set of G values are provided in table 8.

Table 8. Calculating of Q_{min} as [G_{min} x (1+δ)] for ASOTT-P of SNPP Unit 1 and KNPP Unit 3

			$G_{\text{н}}$	114 kg/h	114 kg/h	114 kg/h	114 kg/h
			$G_{\text{в}}$	1140 kg/h	1140 kg/h	1140 kg/h	1140 kg/h
			G	114 kg/h	228 kg/h	627 kg/h	1140 kg/h
ASOTT-T	SNPP-1	57990-14 / RU.E.29.004.A №56250	δ	± 90,0 %	± 89,0 %	± 85,0 %	± 80,0 %
	KNPP-3	58803-14 / RU.E.29.004.A №57153					
ASOTT-V	SNPP-1	57990-14 / RU.E.29.004.A №56250	δ	± 80,0 %	± 79,0 %	± 75,0 %	± 70,0 %
	KNPP-3	58802-14 / RU.E.29.004.A №57125					
ACOTT-A	SNPP-1	57990-14 / RU.E.29.004.A №56250	δ	± 90,0 %	± 89,0 %	± 86,0 %	± 80,0 %
	KNPP-3	58804-14 / RU.E.29.050.A №57154					
ASOTT-Ak	SNPP-1	57990-14 / RU.E.29.004.A №56250	δ	± 85,0 %	± 84,0 %	± 80,0 %	± 75,0 %
	KNPP-3	58805-14 / RU.E.29.004.A №57155					
ASOTT-P	SNPP-1	57990-14 / RU.E.29.004.A №56250	δ	± 75,0 %	± 74,0 %	± 70,1 %	± 65,0 %
	KNPP-3	58806-14 / RU.E.29.004.A №57156					
ASOTT-P	SNPP-1	57990-14 / RU.E.29.004.A №56250	Q_{min}	200,0 kg/h	396,0 kg/h	1063,0 kg/h	1883,0 kg/h
	KNPP-3	58806-14 / RU.E.29.004.A №57156					

The results discussed above indicate existing deviations from the requirements of [15] at seven RBMK NPP Units and absence of official data for LDS status of Leningrad Units 2-4 with RBMK.

The non-compliance of LDS at NPP Units with the requirements of GOST R 58328-2018 [15] violates compliance of these NPP Units with the requirements of paragraph 3.3.3 of NP-001-15 [1] and, consequently, non-compliance with the requirements of paragraph 21 of NP-010-16 [18] remains uncompensated by improper LBB application. This situation as well as other deficiencies in the LBB concept applications at NPP Units as stated in the report [19] seems worth to be discussed with the Utility and NPP staff.

5. Conclusion

The article considers the evolution of requirements to LDS in Russian regulatory documents in 1999-2020.

The article provides details about LDS status at VVER and RBMK NPPs as certified measuring instrument for LBB application according to GOST R 58328-2018.

Some deviations from the actual requirements are highlighted and recommended for further discussion and improvement.

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