APPLICATION OF THE “LEAK BEFORE BREAK” CONCEPT ON NPP UNITS OF THE FIRST GENERATION WITH WWER-440 REACTORS. IMPROVEMENT OF LEAK DETECTION SYSTEMS CONSIDERING NEW ELABORATED APPROACHES

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Introduction

The essence of the Leak Before Break (LBB) concept consists in a fact that the design of NPP components and its materials assure that a total destruction of the component having a through wall crack is impossible without a preliminary existence of the stable leak of the working medium. Such a leak can be detected in advance before the moment when crack length reaches its critical size and the crack becomes unstable. LBB concept should be applied to the pipelines of the main circulation circuit in order to assure a safe and reliable operation of Nuclear Power Plants (NPP) and this application is an urgent task in a frame of NPPs’ design service life prolongation.

Analysis of the design features of WWER 440/230 reactor assembly shows that there are three typical problems concerned with safety assurance of the reactor assembly:

- restricted capacity of the Emergency Reactor Cooling System;
- restricted number of the mounted piping wipe restraints;
- common insufficiency of the design information.

In order to guarantee the WWER NPP’s safety in a common case it should be demonstrated that a break of the primary circuit piping can be excluded. For this purpose in Russia it have been issued a “Leak before break application guide for NPP piping” R-LBB-01-99 [1]. This regulative document contains the main requirements of the LBB concept and reflects the international approaches (US approaches – NUREG 1061.3 [2], SRP 3.6.3 [3]) as well as the accumulated experience in Russia and abroad regarding the practical application of the LBB methodology to the systems of nuclear power units.

Within IAEA activities considering WWER-440/230 safety analysis the LBB concept applicability is a fact of a major importance confirming NPP safety in a common case. LBB concept should be considered as technically justified approach which aims an increase of NPPs operational safety and reliability. LBB concept implementation allows to take on timely actions in order to prevent accidents with piping ruptures and, as a consequence, to save the third physical barrier on a path of ionizing radiation and radioactive substances propagation to the environment.
LBB concept general requirements

Substantiation of the LBB concept applicability on WWER-440 NPPs implies a comprehensive analysis and calculations of the main coolant piping (MCP) – main circulation lines (MCL) and surge lines (SL), including:

- all circumferential and longitudinal welds;
- all main equipment nozzle welds - up to safe ends and dissimilar welds - including the Pressurizer;
- all branch nozzles - up to the auxiliary line weld - including the Surge Lines;

According to R-LBB-01-99 Guide [1] in a frame of the estimation of LBB concept applicability to the considered main coolant piping it is necessary to demonstrate an implementation of such main technical principles as the Principle of a high quality and the Principle of a controllable operation. In order to meet these principles it is necessary to carry out a comprehensive assessment of piping metal properties, manufacturing and mounting technologies, pre-service inspection, as well as the previous operation experience.

An approach for a mechanistic assessment of piping rupture is used for a demonstration that such events as guillotine break with double-side leak and catastrophic pipe rupture are impossible for the piping which satisfy LBB requirements. In a Figure 1 there are presented general principles of the substantiation of the LBB concept applicability to the primary circuit piping.

Implementation of the LBB calculative substantiation should be carried out in accordance with R-LBB-01-99 [1] requirements by use of M-LBB-01-93 procedure [4]. Preliminary a stress calculation is to be carried out in order to determine stress values in every weld joint of considered pipelines. There are considered different loading modes under Normal Operation Conditions (NOC) and for a case of the Safe Shutdown Earthquake (SSE).

In every weld joint it is postulated a crack with a length $2l_p$, which is determined by a set flow rate through the crack in NOC modes. The postulated flow rate is determined by a sensitivity of existing Leak Detection Systems (LDS), which should be less than 3,8 l/min according to LBB requirements. When the length of the through-wall crack $2l_p$ – which can be detected by LDS – is calculated it is set a margin coefficient 10 for a flow rate. It means that the length $2l_p$ is calculated by a flow rate which is 10 times bigger than the actual LDS sensitivity. On a next stage a calculative analysis of a stability of the postulated through-wall crack is to be done in order to exclude a possibility of piping ruptures under maximum loads.

Calculation of critical crack lengths is done for the stress values in NOC and SSE modes. For Maximum Acceptable Stresses (MAS), which occur in NOC+SSE modes, and for loads, which 1,4 times exceed loads in NOC+SSE there are calculated critical lengths $2l_{c1}$ and $2l_{c2}$ correspondingly by means of fracture mechanics methods.

Calculation results satisfy the crack stability criterion if the following conditions are met simultaneously:

- $l_{c1} / l_p > 2$ – for loads under MAS=NOC+SSE
- $l_{c2} / l_p > 1$ – for loads under MAS=1,4·(NOC+SSE)
In a case when pointed out conditions are not met there should be used more precise calculative methods or the possibility of using more sensitive leak detection systems should be considered.

**FIG. 1. General principles of the substantiation of the LBB concept applicability to the primary circuit piping.**
Margin coefficients 2 for the crack length and 10 for the leak flow are safe coefficients which take into account uncertainties in metal properties, physical nature of the postulated crack, loading conditions, leak detection and calculative methods.

An Integral Leak Detection System should guarantee forming of a precautionary and emergency signal on a reactor control board in a case of leak detection above the level set for the definite NPP type. After that the NPP unit have to be moved to the reactor cooling and reactor shutdown modes. In operational instructions the time between the ultimate leak detection and the reactor shutdown should be set. For the time being there are available single methods of leak detection which combines both optimum leak detection sensitivity, ability to determine a leak location and small leak rates. As a result, for LBB concept implementation at least three independent, redundant and diverse systems, based on different methods must be used on NPP to monitor a leakage in the main coolant circuit. According to LBB requirements a sensitivity of the integrated leak detection system is to be 3.8 l/min or less, an accuracy of leak localization is to be ± 2m, response period and the time interval for a leakage detection should not exceed 1 hour.

**LBB concept application on Armenian NPP, Unit 2**

In recent years there were fulfilled works on substantiation of LBB concept applicability for Kola NPP – Units 1, 2, Novovoronezh NPP – Units 3, 4 with WWER-440 reactors and Balakovo NPP – Unit 1 with WWER-1000 reactor. The obtained experience allowed to carry out the substantiation of the LBB concept applicability for Armenian NPP – Unit 2 on much more higher technical level and to propose new technical approaches which make possible LBB concept implementation.

In the frame of the Contracts between the European Commission (Contracting Authority) and the Consortium composed by Ansaldo Energia Divisione Nucaleare (Italy), Empresarios Agrupados Internacional (Spain) and CTC “CMSLM” (Centre of Material Science and Lifetime, Russia) the Tacis Project A1.01/00A “Leak Before Break (LBB) Application to Armenia NPP Unit 2” [5] was carried out in a period of 2004-2005 years.

The Project consisted of two main parts.

The main objective of the Part 1 was to apply the Leak-Before-Break (LBB) concept to Main Coolant Loop / Surge lines piping (MCL/SL’s) of the Unit 2 Nuclear Power Plant located in Armenia, which consists of a WWER-440 Model 270 Unit, Soviet type reactor (a version of the WWER 440/230 type). A list of main works executed in a frame of Part 1 is as follows:

- adaptation of the US reference methodology - the NUREG 1061.3 / SRP 3.6.3 approach - to the Armenian country; in order to match the local Regulatory Documents which, due to the lack of Armenia specific rules, are the Russian ones;
- collection of reliable and well documented set of basic design and actual plant specific input data for the MCP/SL’s piping (e.g. geometry, layout, material properties and loading conditions), in order to be able to cope with the requirements of LBB concept application;
- evaluation of the structural behavior of the MCL /SL’s piping and supports;
- verification of the possibility to apply the LBB concept the MCL/SL’s piping according to the chosen methodology; calculation of detectable and critical crack lengths for
all the postulated longitudinal and circumferential trough wall cracks and assessment of related margins;
• evaluation of the effectiveness and reliability of the Leak Detection Diagnostic System, taking into account the In-Service Inspection (ISI) programs (methodologies and qualification) in order to validate the LBB concept;
• preparation of a list of recommendations to enhance/upgrade the existing ISI and LDS in order to implement the recommended improvements.

The main objective of the Part 2 was to define a Leak Detection System that meets the requirements for the application of the Leak-Before-Break methodology to the Main Coolant and Surge Lines (MCL/SLs) piping of the Armenian NPP Unit 2. A list of main works executed in a frame of Part 2 is as follows:

• obtaining the characteristics and arrangement of the existing LDS;
• determination of a set of interim critical crack sizes for the locations of concern (the most likely locations);
• exploration the ability of the existing LDS to cover the leaks of the cracks defined;
• definition of the standard leak as the minimum detectable flow rate for the locations of concern and explore the ability of the existing LDS to cover the leaks of the cracks defined;
• verification of the existing LDS coverage of the LBB methodology requirements and standard leak;
• definition the existing LDS upgrading measures required to cover the above findings (with existing methods or by defining additional methods).

Hereinafter there are presented measures which are necessary and sufficient for the LBB concept implementation on Armenian NPP, Unit 2 as well as proposals concerning the implementation of principally new Leak Detection Systems are performed.

Calculative recommendations

Surge Lines are the most critical components concerned with necessity of LBB requirements fulfilment. The main problem of LBB concept application on SL is as follows:

• At present the LBB concept - according to requirements of US SRP 3.6.3 [3], hence considering the Normal Operating Conditions and the seismic SSE loads - cannot be fully applied to Surge Lines piping without the application of additional upgrading measures, since the crack length margins are below the required value of two by a rather large amount.
• For Surge Lines, even using the partial application of LBB concept in Normal Operating Conditions only, no circumferential welds satisfy the criteria imposed by the NUREG 1061.3/ SRP 3.6.3 methodology [2, 3].
• Considering the proposed in the Tacis Project measures for SL construction modifications/upgrading: 1) hardware upgrading; 2) complete (or partial) Surge Line pipe material replacement – the most optimal way is position of hardware upgrading from the point of view of making minimum changes in the initial SL design and optimization of the financial costs.

Analysis of results of calculations, carried out in accordance with LBB requirements, allows to make the following conclusions:
The main cause why Surge Lines do not meet LBB requirements is due to the low level of stresses in a Normal Operation Conditions (NOC). As a consequence of this, large sizes of the postulated cracks were obtained: length of the detectable crack in the most critical zones is about 1/4 of the SL section. So, to meet LBB margins, critical crack length should be about 1/2 of the SL section. Evaluative calculation shows, that such a big critical crack is not able to hold even internal SL pressure. Actual calculations show, that in NOC and SSE conditions for the most of welds critical cracks lengths are lower than detectable cracks lengths even if LDS sensitivity of 0.5 gal/min is considered. So, margin of 2 can not be reached.

Additionally conservative assumptions in calculation approach effects on a critical cracks lengths: absolute (by modulus) sum of the loads and selection of the most conservative calculation approach.

- Increase of Leak Detection Systems sensitivity more than 1,9 l/min by use of new high-sensitive LDS can not solve the problem existing for SL (large detectable cracks corresponding to detectable flow with margin of 10) is seen to be low effective measure to reach required margin of 2 between critical and detectable cracks lengths. In spite of probable application of the high-sensitive systems safe margin of 2 can not be reached without hardware upgrading of SL piping construction.

- Non-rigid construction of Surge Lines is causes high level of stresses in SSE condition. Therefore additional supports are needed to reduce stressed state in SSE – mounting of hydraulic shock absorbers (HAS) on two lines will partially resolve this problem. Nevertheless, it should be noted, that when SL were considered only in NOC (without additional SSE loading) LBB concept is not applicable for SL. So, mounting only additional HAS on SL can not in a fully solve the existing problem and save margin of 2 won’t be reached using LDS with 1,9 l/min sensitivity.

As the main upgrading measure it is recommended to mount one rigid support on each leg of SL on an average distance between pipe ends. Supports should be mounted taking into consideration features of the floor building construction. This measure will cause considerable increase of loads in NOC and loads decrease in SSE.

- In the case of additional rigid supports mounting on SL it was proposed to carry out the further work on LBB concept application for SL (with proposed LDS sensitivity 1,9 l/min) in a way as follows:
  - Preliminary selection of the places for rigid supports mounting on SL taking into consideration features of the floor building construction. Recalculation of all SL welds by use of LBB approach.
  - Calculative analysis of the necessity of additional hydro shock absorbers (HSA) mounting on SL to reduce loads in SSE.
  - To elaborate, substantiate and approve Project of rigid supports and HSA mounting on SL of ANPP, Unit 2.
  - To carry out stress substantiation of the project of additional supports and HSA mounting in the modes of NOC failure and in emergency conditions.

In order to analyze changing of the metal service properties of austenitic pipelines it was carried out an analysis of metal condition after long time operation during 200 000 hours and additional laboratory researches [6, 7] for 300 000 hours of operation. Executed researches had shown that changing of metal mechanical properties lies within 10-15 % compared to the initial metal state before operation. Nevertheless crack resistance and impact toughness
properties can reduce on 40 % and more as a result of long time operation. The obtained results mean that changing of mechanical characteristics, which strictly determine the metal state, have to be taken into account when piping stress calculations are being done for the period after 30 years of operation.

**Recommendations for Leak Detection Systems**

Leak Detection Systems existing on ANPP, Unit 2 were not designed for the application of the LBB concept and do not meet strict LBB requirements in a full scope.

Presently progressive development of science and technologies allows to propose principally new approaches as regards to development and installation on NPP of a new high-sensitive Leak Detection Systems meeting LBB requirements in a full scope concerning leak detection, location and sensitivity performances.

It was proposed several different ways for ANPP which could be followed during LBB application for the primary circuit piping on Unit 2:

Way №1: Application of one new Leak Detection System and full (or partial) modernization of two LDS already existing on ANPP, Unit 2: Acoustic Leak Monitoring System (ALMS) and Radiation Monitoring System (RMS) (obligatory application of RMS is prescribed by LBB requirements).

Way №2: Application of several new Leak Detection Systems and full or partial modernization of LDS already existing on ANPP, Unit 2.

A brief description of new LDS proposed for implementation on Armenian NPP, Unit 2 on a base of vision-based and acoustic inspection methods is presented below.

When the pipeline leaks, the hot water from the piping will change the temperature and humidity of the surrounding medium, e.g. the insulation (rock wool), and the surface temperature of the insulation will increase to saturation temperature (approx. 100ºC). A Vision Based Monitoring System (VBMS) using infrared cameras can detect the temperature changes. Therefore the Vision-Based Monitoring System should be designed to monitor the surface temperature of the piping for the piping MCLs and SLs covered by the monitoring system.

The cameras have to be placed permanently inside the Containment to monitor water/steam leakage from the defined pipe routing sections of the main coolant lines and of the surge lines. The method allows to monitor big surfaces, practically all the visible part of the compartment can be observed.

On a horizontal section of a pipe a “hot spots” will have a tendency of stretching to a top and bottom points of section as a result of processes of steam convection and hot condensate water drain. As a consequence, the “hot spots” will be visible from all sides of observation.

Appearance of “hot spots” can be registered automatically in such a way, as this procedure is already realized in vision-based security systems (detectors of alien objects).
By use of sizes and growth rates of the “hot spots” it was done the evaluation of flow rates. Temperature evaluation of the insulation cover from the outside. Heat transfer coefficient of condensation is 5.000..10.000 W/(m²·°С) Air heat transfer coefficient of the convection is 50..150 W/(m²·°С). Relation of temperature drops in wall regions is inversely to relation of heat transfer coefficients, so, in the “hot spot” insulation cover temperature will be close to steam temperature (98…93°С).

Evaluation of registration time: for 1 kg of the insulation (glass wool with density 200 kg/m³, physical volume of 1 kg is 1/200 m³ or 5 liters). To fill this volume by the steam it is necessary 3 g of the steam: steam density under 100 °C is 0.598 kg/m³, volume of 1 kg of glass wool will be filled by 1/200 m³ * 0.598 = 3 g of the steam. Required time is 3 seconds if leak rate is 1 g/second.

In accordance with IEC-1250-1994 classification acoustic method had received the highest grade on capability of leak location determination compared to such methods as humidity monitoring and gas-aerosol activity control.

In Russia exists an experience of operation of the system based on monitoring of acoustic noise in compartments for coolant leak detection. On Leningrad NPP it is installed and successfully operated Automated System of Leak Detection (ASLD) using acoustic microphones installed in RBMK reactor compartments. Previously there were carried out acoustic noise measurements and full-scale reactor experiments, which confirmed a possibility of detection, location and determination of leak flow rate.

It should be mentioned that physical conditions (temperature, humidity, pressure) in RBMK compartments are much tough compared to conditions in WWER compartments. Nevertheless ASLD shows successful operation on RBMK reactors.

Carried out investigations show that when leak with 1 gpm flow rate occurs emitted level of a sound pressure is 95-100 Db in a range of frequencies 6…10 kHz. Acoustical absorption by piping insulation can be estimated as 40 Db for a dry insulation and as 20…30 Db for wet one. Acoustic attenuation in a compartment with close packed piping is about 5 Db/m. Unfortunately data of background acoustic noises in WWER compartments are not available. Using data of acoustic noise measurements in compartments of RBMK-1000 reactor (Leningrad NPP) is was shown: background noise in a range of 6…10 kHz is 65-68 Db – for water piping boxes, and 42-45 Db – for steam water piping boxes. A region of the acoustic sensor sensitivity considering the above mentioned scatter of background noises should be 0.5…8 m, i.e. minimum number of sensors for the whole compartment is 80…25. If sensors will be connected into groups close to piping minimum number of sensors on the average should be 36 …24.

It is expedient to mount sensors in WWER MCL-SL compartments in a line for each loop between hot and cold legs. Neighbor sensors should be mounted equidistantly (or symmetrically) from the known sources of noise (RCP, MIV). For each loop sensors should be placed with maximum possible identity relatively loops equipment location (in order to compare signals received on different loops). Analog-digital mainline of one loop have to be organized as close-loop desirably took out of the containment boxes. Number of sensors on one loop depends on optimization of location and desired sensitivity of the system. On the average it is necessary to mount 4-12 sensors on each loop. It is obvious, that sensitivity of
the system reduces if level of background noises increases and distance between a sensor and possible leak location grows.

The base of a method of small leaks monitoring by microphones consists in a principle that on a weld joint it is mounted a hermetical camera in which there are mounted extra-sensitive acoustic microphones. These microphones register acoustic signal which forms due to leak occurrence.

Sensitivity of any acoustic system reduces due to increase level of background noises, and spacing interval growth from the sensor up to probable location of a leak.

In a view of generalizing of the experimental data and expertise of work, it is expedient:

Application of non-contact sensors (microphones)

- the sensor does not injure metal of pipeline;
- there is no problem of poor ultrasonic contact of the sensor with object;
- the sensor does not overheated by the wall of the pipe line;
- the leak beams in air of energy more, than in walls of a tube.

- Monitoring only of potential - dangerous locations found during the LBB calculations.
- Location of the sensor (microphone) close to a possible location of leakage allows to maximize the ratio signal / noise.
- Screening of a sensor - leak system from exterior extraneous noises - making an acoustic camera around the monitored weld. The coating of acoustic camera, besides the deafening function implements also the function of thermal insulation.

The measuring of acoustic background noises in WWER-440 compartment were not spent, but in view of the given measuring data held in RBMK compartments, it is possible to suspect, that the level of acoustic background noises does not exceed 70.. 80 dB (in practice 55 … 70 dB).

Acoustic camera (contains a monitored weld and sensors) is surrounded with thermal insulation, which one reduces exterior background noise on 30.. 40 dB (for fibrous materials by thickness 200 mm). In the worst case the background noise in camera will be 50 dB.

According to data of acoustic leak monitoring system the maximal background noise in metal of the pipe line is 58 dB. In the worst case, from metal of tube to the acoustic camera will be beamed the part of sound energy of pipeline metal proportional to the ratio of acoustic impedance of metal and air which is 1.6 10-4. Hence, the acoustic emission of metal of the pipeline to the in air of acoustic camera can be neglected.

In assumption, that the leak signal should exceed the level of background noises on 10 dB. In this case the noise level of minimum warranted detectable signal of leak in acoustic camera will be 60 dB. The decay of a acoustic signal on path from leak to microphone within the bounds of camera can be neglected because of very small spacing interval between the signal source and the sensor. Extrapolating the data of studies of leaks acoustic performances to the field of small flow rates it was found, that to the level of 60 dB will match a leak with flow
rate 1.5 … 3 l/h (for frequencies 10..6 kHz). The sensitivity of the system to leak flow rate at the worst background situation comes to 1 g/sec – i.e. drop leak.

Acoustic cameras mounted on weld joints can be also used as Leak detection system based on measuring of Nitrogen 16 activity. This method is know-how of Armenian specialists. Gas medium is delivered to a impermeable camera through the pulse tubes by use of electromagnetic valves which switch one of the cameras to the detection unit of N16 activity. Pumping of the gas medium is done by air-exhauster installed outside MCL-SL compartments. Using real coolant activity (N16) and data obtained in detection unit it is possible to determine leakage flow rate in the considered weld joint. In that case if ANPP decides do apply LDS by microphones CMSLM considers expedient using in cameras also inspection method of Nitrogen 16 activity. To receive more detail information on this method, please refer to Armenian NPP.

**Conclusion**

Application of the Leak Before Break concept to the primary circuit piping on WWER NPPs is a significant measure which aims an increase of NPPs reliable and safe operation.

In this paper there are presented main results of the design-experimental researches with regard to the substantiation of the LBB concept applicability on Armenian NPP, Unit 2 with WWER-440 reactor.

It is shown, that Surge Lines are the most critical components concerned with necessity of LBB requirements fulfilment and satisfaction to the set margin coefficients. As a result upgrading measures are necessary – mounting of additional supports and hydro shock absorbers on surge lines This measure will cause considerable increase of loads in NOC and loads decrease in SSE. After that calculative substantiation of LBB requirements satisfaction should be done.

Fulfilled analysis of the metal state of austenitic piping weld joints have shown that the degree of the metal mechanical properties degradation due to a thermal-power ageing lies within the acceptable level.

Leak Detection Systems existing on Armenian NPP, Unit 2 were not designed for the purposes of the LBB concept application. Therefore it is necessary to fulfill hardware and software upgrading of the existing LDS by means of changing of the current systems composition as well as application of new methods for signals processing.

Presently progressive development of technologies allows to propose principally new approaches as regards to application of new high-sensitive Leak Detection Systems meeting LBB requirements in a full scope concerning leak detection, location and sensitivity performances. Tree new leak detection methods were considered and analyzed:

- vision based monitoring system;
- system of the acoustic noises detection in MCL/SL compartments;
- detection of small leaks by acoustic microphones.

Implementation of new modern leak detection systems on NPPs in accordance with LBB
requirements allows to increase NPP safe operation and comprehensively update the leak monitoring system.

The described work was fulfilled in a complex way on a high technical level, was favored by the work contractor – European Commission. Results of the project have been recommended for distribution on WWER-440 and WWER-1000 power units.

REFERENCES