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# JUSTIFICATION OF HYDRAULIC TEST PRESSURE REDUCTION FOR NPPS PRIMARY CIRCUIT USING STRUCTURAL RELIABILITY APPROACH

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## ABSTRACT

In the Ukraine, the pressure of the periodical hydrostatic strength test (HT) for series Water-Water Energetic Reactor (WWER-1000) nuclear power plants (NPPs) exceeds the normal operation pressure by more than 1.5 times. Such HT pressure is one of the highest values among HT those adopted in many countries. The implementation of the modern nondestructive test (NDT) methods for the NPP equipment as a certain alternative of the HT, as well as application of the quantitative assessment of the HT effectiveness, permits a reasonable HT pressure reduction. To justify such reduction, a quantitative risk-informed assessment of HT effectiveness for HT pressure reduction has been performed. A probabilistic analysis method is based on the exponent distribution law for defects' depth and lognormal law for their aspect ratio taking into account different laws of the defects' growth. The fracture probability is calculated as the share of defects with higher critical sizes at normal operational mode (NOM) and HT. Limit load models are used for the determination of critical size of defects. The variation in reliability is assessed as the difference between fracture probabilities under NOM conditions after HT performed with routine and reduced pressures. The obtained probabilistic and deterministic results furnish a technical solution for HT pressure reduction for WWER-1000 NPPs.

## INTRODUCTION

Hydraulic strength testing has been used as a traditional method to verify the structural integrity of pressure vessels and piping.  Applying a load higher than the component would experience during service is a well established procedure for screening out manufacturing and material defects before the product is delivered. Successful HT qualitatively demonstrates the equipment reliability.

The efficiency of HT as a destructive inspection method was first clearly demonstrated in the early 1950s in the pipeline industry of the USA, Kiefner and Maxey (2000). Detection of defects during HT increased reliability as their subsequent removal significantly reduced the frequency of pipelines' accidents in the further operation.

With the advent of practical fracture mechanics, the theoretical justifications of HT parameters are made possible. A presupposition of HT efficiency evaluation is: because the HT load pressure is greater than the normal operating pressure, HT detects critical defects of a smaller size that those that would be detected during normal operation mode. The main advantage of HT is that: a) a critical defect detected during HT should be repaired and will not cause failure during operation; b) a possible undetected defects of smaller size will not attain their critical size during the operation until the next HT.

The modern point of view regarding HT with an analysis of its advantages and disadvantages is summarised in a report NASA (1994). There are two types of HT: acceptance tests and periodical testing during operation. Pressure level of the acceptance testing is grater than that of the periodical and 1.2-1.5 times greater than the NOM pressure. From the report the following two important conclusions can be made, namely: a) the absolute advantage of acceptance testing; b) the preferred implementation of the brittle fracture mechanisms at HT that causes more cases of failure. Thus, HT is much more effective for components and structures, which operate under conditions of brittle fracture (low temperature, brittle materials). Besides that, HT have a number of limitations. First, HT can be considered effective for the axial defect detection. The axial stress caused by internal pressure is much smaller than the circumferential stress. Therefore, circumferential defects can withstand a very high HT pressure. Second, HT is efficient for relatively long defects. A short and very deep axial defect can withstand high HT pressure and then failure during operation by a leak mechanism. Third, a successful HT is not a complete evidence of the strength relative to NOM and emergency modes. During HT the maximum load is not necessarily attained at the same points as the maximum load during other modes due to various stress distributions.

In the CIS countries for WWER NPPs, HT pressure 1.5 times higher than the operating pressures since the beginning of operation. Such high level of pressure would be justified if HT provides detection of the defects. But the statistics shows the opposite: most defects are detected by NDT. This fact, as well as high cyclic damage level, due to HT has caused many countries to reduce HT pressure (especially in the cases when the operation life of NPPs should be extended). For example, in the Czech Republic, Skoda JA a.s. (2005), justification of the pressure reduction is based only on the deterministic analysis. For Bulgarian NPP a probabilistic analysis is used, Grigoriev et al, (2005).

At present, the principles of the IAEA SF-1 (2006) and the IAEA guide INSAG-25 (2011) are the basis for variation of control parameters (including HT). According to these guides risk-based approaches are required to be used alongside deterministic analyses for the quantitative performance evaluation for any technical activities. The justification of HT pressure reduction for the primary circuit of Zaporizhya NPP Unit 1 is carried out in accordance with the general methodology prescribed by the IAEA guides. A deterministic analysis was used for many aspects but in the present paper includes only those associated with probabilistic analysis. Analysis was performed to evaluate the HT efficiency and fracture probability changes due to pressure reduction.

## GENERAL METHODOLOGY OF PROBABILISTIC ASSESSMENT

Within the probabilistic analysis justification of change of HT pressure has been performed to evaluate HT efficacy for defects detecting. The analysis has been conducted for the main elements of the primary circuit (replaceable) for which the HT is a useful testing method. Some parts of the evaluations are performed in the deterministically, while other parts are performed probabilistically.

The deterministic part of the evaluation includes: selection of the defining elements; determination of the defect critical sizes; determination of the number of defects. The probabilistic part of the evaluation includes: statistical analysis of the distribution of crack parameters; analysis of the probability of defect detection; determination of the defect growth rates; formulation of reliability criterion.

In the probabilistic analysis the following conservative assumptions were used:
- The defects are semi-elliptical surface cracks;
- A conservative exponential density distribution is used to predict the number of defects at a given depth. The distribution is conservative for depths exceeding 3 mm;
- To determine the number of defects, the maximum value of the defect density obtained from statistics or quality assessment standards is used;
- It is assumed that all defects in the base metal (BM) and welds grow over time;

- Somewhat conservative defect growth rates are assumed. The assumed growth rates are higher than those recommended for analysis by the VERLIFE (2008);
- It is assumed there is a non-zero probability of omitting a large defect in the expression for the probability of defect detection;
- The appearance of cracks is assumed to be equally probable in both axial and circumferential directions.

The probabilistic analysis of the change of HT effectiveness at reduced HT pressures is evaluated for normal operation mode (NOM). These conditions are chosen because the maximum decrease of HT effectiveness is observed at NOM.

*The choice of the defining elements*

All elements of the primary circuit were considered. Few the criteria used to select the equipment that was analyzed included materials of construction, operating temperature, pressure load, the existence of aging mechanisms or defects, and the nominal diameter.

Equipment in the coolant circuit operates under more severe conditions than other connected system, which are usually closed by shut-off valves under normal operation. For each type of material, the equipment and piping with high nominal hoop stresses were analyzed. Critical equipment that must operate without defects or failure, referred to as defining elements, were also analysed. Finally, pipes with a nominal diameter greater than 90 mm were considered, because safety analyses determined that breaks in these pipes could lead to water hammer.

Table 1 shows the equipment that was considered in the probabilistic analysis. The loading factor k is determined as the ratio of allowable stress to the nominal hoop stress at NOM.

Table 1: Defining elements for probability analysis.

| Element | Material | $D$, мм | $s$, мм | $k$, |
|---|---|---|---|---|
| Pressuriser (Pr) | 10GN2MFA | 3330 | 165 | 0.797 |
| Main circulation pipeline (MCP) | 10GN2MFA | 990 | 70 | 0.546 |
| Reactor coolant pump (RCP) | 06Kh12N3DL | 3170 | 250 | 0.434 |
| Pressurised surge line (PSL) | 10GN2MFA | 426 | 40 | 0.401 |
| Injection pipeline (IP) | 08Cr18N10T | 219 | 19 | 0.7 |
| Steam dumping pipeline (SDP) | 08Cr18N10T | 245 | 18 | 0.839 |
| Heat exchange tubes (HET) | 08Cr18N10T | 16 | 1.5 | 0.387 |

*Critical sizes of defects*

Determination of the defect critical sizes is aimed at: a) demonstration of detection of the defects by HT in comparison with the possibilities of NDT; b) further determination of the fracture probability.

To determine the critical sizes of defects, the ductile strength criterion $\sigma_r = \sigma_u$ was used, where $\sigma_u$ is the minimum ultimate strength, $\sigma_r$ is the reference stress determined on the basis of the limit load model Orynyak and Ageev (2009). Here the following circumstances have been considered: a) at NPP HTs are conducted under conditions that exclude brittle fracture; b) HT can not detect defects could lead to failure by the brittle mechanism during pressurised thermal shock (PTS) scenarios at a higher level of stress (at much smaller sizes) than that one during HT. A comparative analysis has been carried out to justify the use of these models. It has been shown that for ductile materials and loading conditions of NOM and HT the defect critical sizes calculated using ductile strength models are smaller than the critical sizes of the brittle fracture.

Critical size of the defect is determined using the formula for the reference stress in a thick-walled cylinder with an axial crack on inner surface under internal pressure $p$:

$$\sigma_r = \frac{pR_m}{\alpha_p s} \tag{1}$$

where $R_m$ is the mean radius; $s$ is the wall thickness $\alpha_p$ is the strength reduction factor, which is determined according to Orynyak and Ageev (2009) as:

$$\alpha_p = \frac{1+4/3\lambda^2 yz}{1+4/3\lambda^2 z} \tag{2}$$

where the following notion is introduced for the convenience:
$y = \left(\ln\left(R_2/R_a\right)+W\right)/\ln\left(R_2/R_1\right)$, $z = R_1\left(\ln\left(R_2/R_1\right)-\ln\left(R_2/R_a\right)-W\right)/s$, $\lambda = c/\sqrt{R_m s}$, $R_a = R_1 + a$,
$W = s^2(1-(p/\sigma_u \ln(R_2/R_1))^2)/4(2R_1+a)(R_1+a/2+s/2)$

in the formulas: $R_1$ and $R_2$ are the inner and outer radius, respectively, $c$ is the defect half-length, $a$ is the defect depth.

Fig. 1 shows the critical defect size curves for main circulation piping (MCP) at the routine (24.5 MPa) and reduced (19.6 MPa) HT pressure, as well as at NOM (15.7 MPa). It also contains curve that separates critical defect size into two zones, which correspond to the leak and break fracture mechanisms. The curve is obtained from the condition of equation the strength reduction factors for surface $\alpha_p$ (2) and for through-wall defects $\alpha_{th}$ Orynyak at al. (2015). The empirical formula for strength reduction factor of through-wall defects had been developed in Battelle Memorial Institute Kiefner at al. (1973): $\alpha_{th} = 1/M(\lambda)$, where $M(\lambda)$ is some function, such that it increases with $\lambda$ and $M(0)=1$. It was taken from the solution of Folias (1967) for the stress intensity factor for a through axial crack in a cylinder, i.e. $M(\lambda) = (1+1.61\lambda^2)^{0.5}$.

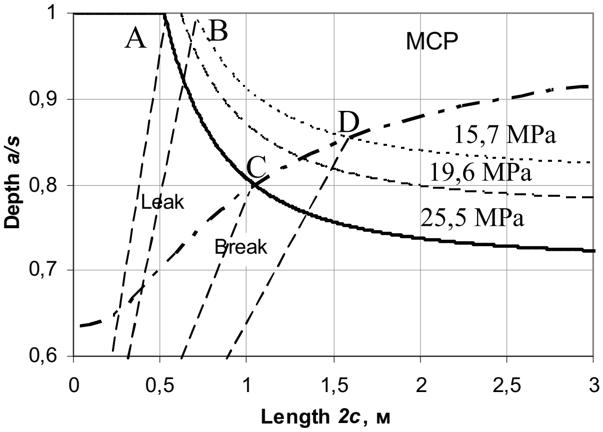

Figure 1. Critical defect sizes under HT and operation modes.

For all elements of Table 1, the critical defect depths for routine and reduced HT pressures, as well as for the operating pressure, were determined. From diagrams similar to Fig. 1 the averaged values of critical defect depths for discrete ranges of defects shapes were obtained. The defect shape $\beta$ is the ratio of length to depth, $\beta=c/a$.

*Number of the defects*

For the determination of the expected number of defects the greater value of two sources were used: the literature data of defect density Grigoriev et al. (2005), NUREG/CR-6471 (2008) and the maximum allowable defect density according to the standard for in-service inspection PNAE G-7-010-89 (1989). Data from first references were mainly used to determine the number of defects in the BM, date from the standard used to determine the defect in the welds. Table 2 shows the expected defects densities and the expected number of defects calculated for defining elements.

Table 2: The defect density and the number of defects.

| Element | Zone | Defect density | Surface of BM/or weld running meter | Expected number of defects |
|---|---|---|---|---|
| MCP | BM | 125 def/m$^2$ | 452 m$^2$ | 28250 |
| | Weld | 80 def/r.m. | 138,7 r.m. | 5549 |
| RCP (4) | BM | 125 def/m$^2$ | 84 m$^2$ | 5250 |
| | Weld | 80 def/r.m. | 26,4 r.m. | 1055 |
| Pr | BM | 150 def/m$^2$ | 105 m$^2$ | 7875 |
| | Weld | 100 def/r.m. | 52 r.m. | 2600 |
| PSL | BM | 125 def/m$^2$ | 23,6 m$^2$ | 1475 |
| | Weld | 70 def/r.m. | 22,8 r.m. | 797 |
| SDP | BM | 110 def/m$^2$ | 7,36 m$^2$ | 405 |
| | Weld | 60 def/r.m. | 11,6 r.m. | 348 |
| IP | BM | 110 def/m$^2$ | 19 m$^2$ | 1045 |
| | Weld | 60 def/r.m. | 11,6 r.m. | 455 |
| HET * | BM | | | 304 |

*Statistical distribution of the crack parameters*

Statistics of the detected defects at Ukrainian NPP is not sufficient for the representative sample to determine the probability distribution of defect sizes for the primary circuit equipment. The primary circuit equipment and RPV are made of similar materials namely pearlitic steel alloys. Therefore, the RPV defect statistics for the base metal and welds can be taken from literature NUREG/CR-6471 (2008). The distribution laws of depths and shapes of defects from the U.S. NRC data and verified using the statistics of the defect found in the WWER-1000 RPVs at the Ukrainian NPPs.

As in Orynyak at al. (2014), an exponential law of the defects depths density distribution is used:

$$f(x) = 1/a_0 \exp(-x/a_0), \tag{3}$$

where $a_0$ is the parameter of the exponential distribution ($a_0$=1,98 mm for BM and $a_0$=2,05 mm – for welds).

The law of depth distribution of the defects Eq. (3) has been verified on the basis of statistics of the detected defects in RPVs of Unit 1 and 3 of Zaporizhya NPP. This statistics has been adjusted for the probability function of the defect detection (5). It is shown Orynyak at al. (2014) that the distribution of the defects depth Eq. (3) is conservative with respect to the actual defects depth distribution. Data Khaleel and Simonen (2000) are used for the pipes made of stainless steel 08Cr18Ni10Ti (see. Table 2). It has been conservatively approximated using an exponential law with the distribution parameter $a_0$= 0.65.

The shape of the defect $\beta=c/a$ (half-length to depth ratio) is taken as a probabilistic value and described using the lognormal distribution law according to NUREG/CR-6986 (2009)

$$f(\beta)=\begin{cases}0 & \beta<1\\ \dfrac{C}{\lambda\beta\sqrt{2\pi}}\exp\left[-\dfrac{1}{2\lambda^2}(\ln\beta/\beta_m)^2\right] & \beta\geq 1\end{cases} \tag{4}$$

where the initial distribution parameters are taken as follows: $\lambda$ = 0,5382; C = 1,419; $\beta_m$= 1,136. It should be noted that the distribution of the defect shape eq (4) has been obtained based on the statistics of the detected defects in NPPs class 1 pipelines. In paper Orynyak at al. (2014) it is shown that for the defect shapes $\beta$ > 2.5 (lengthy defects) Eq. (4) gives a greater probability than the data obtained based on the real statistics. Thus the use of Eq. (4) leads to conservative probabilistic assessment, since the longer defects increases the fracture probability.

It is assumed that the distribution of the defect shapes (4) is maintained during the growth of defects till their critical size (Fig. 2). It can be justified using the well-known fact that there are stable forms of crack growth. It makes it possible to assess the HT efficiency.

A diagram of the critical defect sizes Fig.1 can be divided into several ranges of the defect shape. Point A in Fig. 1 corresponds to the defect shape when the surface critical defect becomes through under HT conditions. Point B is similar to A, however, under normal operating conditions. Point C corresponds to the defect shape at the boundary between the leak and break fracture types under HT conditions. Point D is similar to C, but for NOM.

Table 3 shows the conditional probabilities $V$ of the defects shapes according to eq (4) for the ranges considered. These results, as well as analysis of leak and break zones in Fig. 2b allow one to make some conclusions.

Table 3: Conditional probability of critical defects shape ranges.

| Interval in Fig.2b | Range of values shape β | Conditional probability of the shape $V$ |
|---|---|---|
| 1. To A | $\beta < 3{,}75$ | 0.969 |
| 2. A-B | $3{,}75 \leq \beta < 5{,}5$ | 0.0279 |
| 3. B-C | $5{,}5 \leq \beta < 9{,}2$ | 0.00275 |
| 4. C-D | $9{,}2 \leq \beta < 11$ | 0.000081 |
| 5. After D | $\beta \geq 11$ | 0.000021 |

The first range of the defects shapes (to point A) exhibits the greatest value of the conditional probability of the shape, 97% (i.e corresponds to the highest number of defects). For such defect shapes the HT is useless since the critical defect sizes at HT and NOM are the same (they are independent of the pressure). The expected fracture character of such defects is considered to be leak. HT is helpful for the second and third form ranges (A-B-C) (~3.1% of the defects). The expected fracture character for both HT and NOM modes is regarded to be leak. For the fourth range (C-D) the number of defects is less than 0.1%. The fracture mechanism for such shapes of the critical defects is break for HT mode and leak for NOM. Finally, for the most extended defects (after point D) the conditional shape probability is the smallest (the minimum number of defects). The expected fracture character of critical defects of that range is considered to be break. From the analysis it can be concluded that HT: a) is efficient only for the detection of 3-4% defects of critical sizes; b) increases the proportion of break fracture in comparison to the operation mode.

*Probability of defect detection*

For the analysis the exponentially dependent function of defect detection probability is used:

$$F_d = (1-\varepsilon)\cdot(1-\exp(-x/b)) \tag{5}$$

As in NUREG/CR-6986 (2009), the probability of omitting a large defect is taken into account. The value ε = 0.02 is assumed, that corresponds to the average quality level for NDT for the UI. The parameter *b* is determined using approximation of the data of NDT quality. For instance, for the UI of RPV Khaleel and Simonen (2000) *b* = 3.2 mm, for UI of the medium-quality pipelines NUREG/CR-6986 (2009) - *b* = 5.41 mm, for eddy current inspection of HET Grigoriev (2006) - *b* = 0.54 mm.

*Defect rate growth laws*

In the probabilistic analysis the irregular defect growth rate law is used. It is assumed that the defect growth rate of the crack-like defects is proportional to its size (depth a): $da/dt = \mu a$. Then the defects depths probability (3) taking into account growth with time can be described by the following:

$$f(x,t) = \frac{1}{a(t)}\exp\left(-\frac{x}{a(t)}\right),\quad a(t) = a_0\exp(\mu\cdot t)\,, \tag{6}$$

For the equipment where UI is used, the growth rate parameter $\mu$ was determined using the higher of the two values, one obtained on the basis of analysis of the real defects statistics or one base on known defects rate growth dependences, for instance, $da/dt = C(\Delta K_I)^m$. The material constants C and m dependent on the load ration R and environment are given VERLIFE (2008).

A conservative postulation of the epistemic growth rate law is used for the cases when there is no defect statistics or when NDT inspection is not adequate for the defect sizes determination, and when the defects growth rate cannot be evaluated. In this case, the growth rate parameter is determined from the assumption that the fracture probability of element would be 5% for leak and break mechanisms up to 30 years of operation. Table 4 presents the parameter $\mu$ for different elements as well as the models were used.

*Reliability criterion*

The decision criteria EPRI TR-1 12657 (1999) were used is to ensure that the cumulative change in Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) is less than 1E-7 per year per system and lE-8 per year per system, respectively.

Risk change is measured by change CDF or change LERF as:

$$\Delta\text{CDF} = \Delta P \cdot \text{CCDP} \tag{7a}$$

$$\Delta\text{LERF} = \Delta P \cdot \text{CLERP} \tag{7b}$$

where $\Delta P$ is the change in fracture probability of the system caused by the change HT pressure; CCDP and CLERP are the conditional core damage probability and conditional early release probability, respectively. CCDP and CLERP values are determined based on a numerical Probabilistic Safety Analysis (PSA) associated with the systems (piping) failure.

Table 4: Growth rate parameter values.

| Element | $\mu$, 1/year | | |
|---|---|---|---|
| | Norms | Statistical | Epistemic |
| MCP + RCP | 0.00093 | 0.000857 | - |
| Pr | 0.0055 | 0.000116 | - |
| PSL | 0.00033 | - | 0.026 |
| IP | 0.00036 | - | 0.0384 |
| SDP | 0.00048 | - | 0.0394 |
| HET | - | 0.0242 | - |

## FRACTURE PROBABILITY CALCULATION

Fracture probability during operation after HT is determined as the probability of the depth of defect, which is not detected during HT with the critical depth $a_{cr}^{HT}$, so that it will exceed the critical depth at NOM $a_{cr}^{NOM}$ until the next HT. Then the fracture probability of at least one defect in the period between HTs Δt (for a random year of operation *t*) is defined as

$$P_{0;1}(t) = \sum_{i=1} ((P_{N,i}^{NOM}(t) - P_{N,i}^{HT}(t - \Delta t)) \cdot V_i \tag{8}$$

where $V_i$ is the conditional probability of the defect shape, *i* is the number of the defect shape, *N* is the number of defects, *t* is the operation time, $\Delta t$ is the HT time interval. The index "0" denotes the fracture probability at NOM after HT with routine pressure, "1" denotes the fracture probability after HT with reduced pressure. The probability for 1 year is determined as the average value: $P_{0;1} = P_{0;1}(t)/\Delta t$. Fracture probabilities $P_N^{NOM}(t)$ and $P_N^{HT}(t)$ for the corresponding modes are calculated from the common formula.

$$P_N(t) = 1 - \exp(-N \cdot P(t)) \tag{9}$$

based on the fracture probability for a single defect $P^{NOM}(t)$ and $P^{HT}(t)$. The values $P^{NOM}(t)$ and $P^{HT}(t)$ are determined from the distribution and density eq (6) as:

$$P(t) = \exp(-\frac{a_{cr}}{a_0 \exp(\mu t)}) \cdot \tag{10}$$

In the eq (10) the correspondent critical defect sizes $a_{cr}^{NOM}$ and $a_{cr}^{HT}$ for each discrete defect shape *i* should be use.

## RESULTS AND DISCUSSION

The methodology presented above was used to evaluate the efficient of HT and to assess the change of fracture probability with pressure reduction for main circuit piping and structures. Analyses were performed with respect to Zaporizhya NPP Unit 1. The results of the total fracture probability calculation for leak and break of the base metal and welds of each element are shown in Table 5. Failure probabilities have been obtained for a 30-year operation without carrying out the HT as well as for operation with HT of the routine and reduced pressure. In Table 5, the fracture probability change $\Delta P = P_0 - P_1$ caused by the HT pressure reduction is shown. Sign "-" denotes the decrease of reliability (increase of the fracture probability).

The same values for the fracture probabilities of MCP indicate that all defects, which have attained their critical sizes, would be detected during HT with the routine as well as with the reduced HT pressure. During 4-year period between the HT the defect, which has withstood the last HT, does not grow to its critical size of NOM, because even with the conservative postulation the defects growth rate is very low.

From comparisons of the fracture probabilities for defining elements without $P^{NOM}$ and with HT $P_0$ , $P_1$ it can be concluded that HT does not significantly reduce the failure probability. The values of these probabilities are of the same order. Hence, HT cannot be efficient action to increase reliability. Generally, reduction of HT pressure increases the fracture probability, but such increase is an insignificant, which is less than the baseline values by 2 orders of magnitude. Risk change values $\Delta$CDF were calculated according to Eq. (7) from the known changes the fracture probabilities $\Delta P$ and the conditional core damage probabilities. The calculated values $\Delta$CDF for the defining elements analyzed satisfy the criterion of acceptable risk changes.

Table 5: Results of fracture probability calculation.

| Element | $P^{NOM}$ | $P_0$ | $P_1$ | $\Delta P$ | $\Delta$CDF |
|---|---|---|---|---|---|
| MCP | 2,126E-12 | 2,004E-12 | 2,004E-12 | 0 | 0 |
| Pr | 3,104E-25 | 2,954E-27 | 3,041E-27 | -8,7E-29 | ~0 |
| PSL | 5,191E-02 | 5,159E-02 | 5,187E-02 | -2,85E-04 | 1,15E-08 |
| IP | 4,964E-02 | 4,933E-02 | 4,952E-02 | -1,86E-04 | 7,52E-09 |
| SDP | 4,976E-02 | 4,915E-02 | 4,941E-02 | -2,52E-04 | 1,02E-08 |
| HET | - | 4,082E-02 | 4,112E-02 | -2,97E-04 | 3,67E-08 |

## CONCLUSIONS

A physically based methodology for justification of the pressure reduction with periodic HTs for the primary circuit of NPP equipment and pipelines was developed. It involves both deterministic and probabilistic analyzes.

It was shown that for NPP as a means of material defects detection the periodic HT has a low effectiveness and HT is regarded as an inefficient method for the material defect detection.

HT pressure reduction does not practically increase the fracture probability during operation, and satisfies the criteria of risk change. These results and conclusions provide a justification of the pressure reduction for the periodical HT of the NPP primary circuit.

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