Analysis of industrial safety solutions that have transformed nuclear power by 2019

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Abstract. Safety of nuclear power plant elements relies on a range of national and international norms in the field of atomic energy use. Some of these norms is based not only on operation experience of nuclear units but also on statistics of failures among elements of nuclear facilities. Several well-known disasters occurred at nuclear power plants in USSR and Japan shows that its consequences may affect other countries. Therefore, failures analysis is performed not only nationally but also internationally – by International Atomic Energy Agency. However, different kind of failures: affecting and non-affecting safety of the nuclear unit still occur in Russia. This study is focused on statistical analysis of failures among nuclear power plant components with regards to its impact on unit safety assessed on the International Nuclear Event Scale. The analysis of industrial safety solutions that transformed the nuclear power industry was carried out for the period from 1992 to 2018. Though general decreasing trend can be noted within the that period, failures with safety impact occurred in 2 out of 3 years and non-impacting failures stabilized at around 61 events per year.

1. Introduction

Process modelling on supercomputers has changed various industries: automotive, aerospace, nuclear and other. It significantly saves cost and gives precise estimation of modelled parameters when physical prototyping is not profitable or even not desirable due to some reasons [1]. An illustration of digitalization in nuclear engineering is modelling of operation of the entire nuclear power plant (NPP) unit [2] or its some particular systems [3] on supercomputers. Another example is modelling of accidents [4] and failures of NPP elements [5]. Though complexity of such models is high and, therefore, verification of such models is extremely difficult, it is still possible to verify some probabilistic safety assessment studies using statistics of events with minor impact on reactor safety. Importance of this
reconsideration has increased due to design of new NPP projects for remote usage and territories such as nuclear icebreakers, underwater nuclear gas stations in Arctic, and other [6].

Every nuclear unit in operation continuously generates a large stream of data which includes information about errors. Unpredicted hidden defects, human factor or even abnormal environmental condition are factors of failure appearance. One of important tasks of JSC Rosenergoatom, Russian nuclear power plant operator, is to collect and analyze operational data from its units in order to improve its safety and reliability. In this regards, the most important dataset is the annual failures record of components of national NPPs. The term “failure” in this article corresponds with the term “Anticipated operational occurrence at the NPP” [7] and implies a deviation from established operation limits or conditions.

Project revision based on lessons learned from failures is essential and take place in Russian codes in the field of atomic energy use [8]. Another example of the failure prevention approach is the probabilistic safety assessment introduced by Farmer [9], then developed in the United States [10], internationally recognized by International Atomic Energy Agency (IAEA) experts and NPP operators throughout the world [11-13] and adopted in Russia [14]. As it was agreed among IAEA experts, classification of accidents and failures must be uniform and quantitative.

In accordance with some Russian norms, the operator obliged to report to the government, other sanitary organizations and municipal officials upon failures which resulted in accident at the NPP with a release of radioactive substances [15, 16]. When a failure has occurred, Rosatom classifies it in retrospective by its impact on unit’s safety using the International Nuclear and Radiological Event Scale (INES) in accordance with [17]. In contrast to such strict national recommendations, information sharing upon INES occurrences among IAEA members is not mandatory. Though “member states in general agree that events rated at Level 2 or above and events attracting international media attention need to be communicated internationally through the IAEA [18].

Though application of INES [18] is “focuses on the degradation of the approved design rather than the adequacy of the approved design against some particular standard” (p.2), it is possible to estimate trends of failure appearance. On second, analysis of failure’s cause and effect may provide insights about application of norms in the field of atomic energy use, quality of component design and in some cases about the safety culture which is shared among operational stuff of the nuclear unit.

Rostechnadzor, Russian authority in the sphere of environment, industry and Nuclear energy usage field, provides regulation and control in specified domains. Like Rosenergoatom, the regulator publishes failure statistics with the cause analysis [19]. The reporting period, however, is quite short and starts from 2004 year because of unknown reasons. This limitation put some constrains on accuracy of the assessment. So, failure statistics of Rosatom [20] which has been published in open sources since 1992 might give more precise trend estimation even analysis of causes is absent there.

Taking into account the fact that operation of the NPP unit is relied on thousands of components, a probability of failure of one of them is tiny small. On the other hand, multiple factors such as component’s life span, system configuration, national standards and other may significantly increase the likelihood of the deviation-from-normality occurrence. These factors burdens classification and collection of failure events [21] which is also interfering with correct cause and trend analysis.

2. Purpose of the research
Actual study aimed at deriving insights from statistics of annual failures of Russian nuclear power plants components with regard its impact on unit safety which assessed on the INES scale.

3. Methods
The data set will be analyzed using several statistical methods such as: least squares method, correlation analysis, boxplot diagram and Durbin-Watson statistical test. The research is based on the data which was gathered from annual reports of JSC Rosenergoatom available [20] and also reports of the company’s executives [22].

Figure 1 illustrates the annual failures spread between years 1992 and 2018 inclusive with separation of events by its impact. Observing the graph, a steady decline of all failures within the period from 1992
to 2002 has changed to weak fluctuation around some value in the consequent period. Non-affecting safety failures have dropped significantly from 165 events per year in 1992 to 67 events per year in 2001. Since 2002 its number stabilized at some level.

Failures affecting safety have dropped in 16 times (from 32 failures a year to 2 between years 1992 and 1996 respectively) and then fluctuated until 2004. Since 1995 its value does not exceed 5 events by year. It is remarkable that from 2004 to 2008 failures were absent. Then, fewer than 5 errors per year occurred from 2009 until 2016 excluding 2014.

4. Combined analysis of failures on the INES scale: affecting and non-affecting the NPP safety

The similarity between trends admitted above can be expressed through the coefficient of correlation $\rho$ which can be found from the following equation:

$$
\rho = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} = \frac{5889.788}{178.052 \cdot 40.396} = 0.820.
$$

High value of the correlation coefficient indicates a relatively strong positive relationship between both types failures. This circumstance does not necessary signify the same cause of failures, but points out on the possibility of further analysis.
Figure 1. Spread of annual number of failures by its impact on the safety of Russian nuclear power plant units between years 1992 and 2018: • - failures of the level 0 and below scale; × - failures of levels 1÷3.

5. Failures of the level 0 and below INES scale analysis
On first, it is possible to derive the mathematical model, approximating the dataset, applying the least square approach (LSA). As it can be noted from the graph, data points are negatively distributed along anticipated curve. Thus, application of the binominal model of third extent will be more precise in comparison with the linear model.

According to the approach, sum of squares of deviations between actual values of the dependent variables and the values predicted by the model. This could be transformed into following equation:

\[ \sum_{i=1}^{n} \delta^2 = \sum_{i=1}^{n} (y_i - (a \cdot x_i^3 + b \cdot x_i^2 + c \cdot x_i + d))^2. \]  \hspace{1cm} (1)

I order to estimate unknown coefficients \(a, b, c, d\), the equation (1) could be partially differentiated with respect to each coefficient. Then, equalize each equation to zero and move all its multiples with \(y_i\) to the right hand side it will be solved using the Cramer approach. Substituting computed coefficients into the equation (1) gives us the model equation:

\[ y = -0.012x^3 + 0.815x^2 - 18.070x + 168.246. \]

Model quality \(r^2\) could be estimated from the following equation:

\[ r^2 = \frac{\sum_{i=1}^{N}(y_i - \hat{y})^2}{\sum_{j=1}^{N}(y_j - \bar{y})^2} = \frac{42270.90}{45134.07} = 0.935, \]

where

\[ \sum_{i=1}^{N}(y_i - \hat{y})^2 \text{ - sum of squares of deviations between predicted values and average value of the data set;} \]

\[ \sum_{j=1}^{N}(y_j - \bar{y})^2 \text{ - sum of squares of deviations between actual values and average value of the data set.} \]

Though the model precision is relatively close to 1 which means high quality of the model, a residual analysis will be conducted in order to estimate the prediction errors effect. Figure 2 illustrates the distribution of residuals by time.
Figure 2. Residuals plot.

Since no obvious correlation observed between values, the Durbin-Watson statistic [23] will be used to detect presence of autocorrelation among neighboring residuals. The test consist of determining whether or not the autocorrelation parameter $\rho$ is equal to zero. If it is true, then The value of Durbin-Watson criteria $d_w$ could be determined from the following equation:

$$d_w = \frac{\sum_{i=2}^{N} (e_i - e_{i-1})^2}{\sum_{i=1}^{N} e_i^2} = \frac{3297.068}{2058.406} = 1.602,$$

where

$e_i$ – residual at the time $i$.

Then, the $d_w$ value will be compared with the bounds of Durbin-Watson statistic taken for the following parameters: one variable $Y$, number of observations in the data set $N=27$, and the significance level $\alpha = 0.05 \%$. Since $d_w > d_{Wu}=1.47$, neighboring residuals have no autocorrelation.

Following approach will be used for analysis of the annual failures number spreading in time: on first it will be calculated the mean and the standard deviation; on second – five basic characteristics, namely $x_{\text{min}}, Q_1, \text{Median}, Q_3, x_{\text{max}}$, ascending by value will be depicted on the box diagram. Since the population size is small (the number of observations $N=27$), it is possible to analyze the whole population without taking sample. The mean $\mu$ could be found from the following equation:

$$\mu = \frac{\sum_{i=1}^{N} x_i}{N} = \frac{1644}{27} = 60.889 \text{ (failures per year)}.$$
$X_i$ – n-observation of the variable $X$,

$\sum_{i=1}^{N} X_i$ – sum of variables of the population.

It is possible to estimate the standard deviation $\sigma$ of the population using following equation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} (X_i - \mu)^2}{N}} = \sqrt{\frac{31702.667}{27}} = 34.266 \text{ (failures per year)}. \quad (3)$$

So, the value of annual failures is fluctuating around 60.889 failures per year with the deviation of 34.266 from the mean in most.

Estimation of the basic characteristics of the spread in accordance with [24] yields following result: $Q_1 = 38$, $Median = 44$, and $Q_3 = 78.5$ failures per year. Minimum value $x_{min} = 28$ failures per year; maximum value $x_{max} = 165$ failures per year. Figure 3 illustrates the spread of failures of the level 0 and below scale on the box plot.

![Box plot](image)

**Figure 3.** Failures of the level 0 and below scale between years 1992 and 2018 box plot.

Analyzing the boxplot, it can be concluded that the spread is asymmetrical and right-skewed. So, it is worth to estimate outliers using the empirical rule [24] which can be found from the equation:

$$\mu \pm 2\sigma = 60.889 \pm 2 \cdot 34.266 = (-7.644; 129.421). \quad (4)$$

Thus, two datum, $x_{1992} = 165$ and $x_{1993} = 130$, exceed the interval. But, taken into account limited period of the observation in comparison with the whole lifespan of the VVER technology (1964-present) [25], these observations shall not be excluded from the consideration.

6. Failures of the level 1 and higher by the INES scale analysis

Failures of the levels 1÷3 by the INES scale between years 1992 and 2018 (population A) also contains $N_A = 27$ elements. Applying equations (2) and (3), it is possible to estimate the mean $\mu_A = 3.926$ and the standard deviation $\sigma_A = 7.774$ failures per year respectively.

Testing the population A for outliers using the equation (6) gives an interval $(-11.623; 19.474)$. Though two data points: $x_{1992} = 32$ and $x_{1993} = 29$ failures per year lies outside of the interval, they will be considered in this study due to the reason mentioned above.

Thus, due to asymmetrical data spread, it is worth to use histogram instead of the box plot for analysis of the population A. In this case, the data will be sorted by value. The number of intervals will be found from the following equation [26]:

$$k = \log_2 N + 1 = \log_2 27 + 1 = 5.755 \approx 6. \quad (5)$$
where
k – number of bins,
N – number of the elements in the population.

Taken into account presence of outliers, bin width will be set to 1. The histogram on the Figure 4 illustrates the data distribution. In result of the regroupment the data which is shown on the Figure 5, one may see that failures affecting NPP’ safety occurred every 2 years out of 3. Furthermore, it is observed more than 3 failures annually in a third time periods.

*Figure 4.* Failures affecting safety of Russian NPP between years 1992 and 2018 by frequency.

*Figure 5.* Failures affecting NPP’ safety after regroupment.

7. Results and discussion
General trend on failures decline on the Figure 1 t on safety can be explained by project and element revision which is based on lessons learned from failures, occurred within operation of NPPs. It can be argued that this is fair particularly for failures of levels from 1 to 3 within the periods 1992-1996, 2004-2008. Several periods of failure numbers fluctuation between years 1997-2001 and 2009-16 are
outstanding. Though this paper is focused on trend comprehension rather than causes exploration, it can be supposed that failure origins are hidden defects, low efficiency of reactive measures resulting in codes modification or human errors.

Similar tendency on event decline can be observed failures of the level 0 and below scale within the period from 1992 to 2002. Though, stabilization of failure frequency in the subsequent period is also remarkable, and its origins are likely similar to that of level 1-3 failures stated above.

8. Conclusion
1. Study of the annual failures statistics of Russian nuclear power plants components without impact on safety on the INES scale shows decreasing tendency within the period from 1992 to 2002 with stabilization in the consequent period up to 2018 at approximately 61±34 failures per year.
2. Relatively strong correlation between both types of failures: impacting and non-impacting safety indicates on the possibility of further analysis of causes.
3. Within the observed period, failures impacting safety occurred in 2 out of 3 years, though positive tendency on failure disappearance can be observed since 2004.

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