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# Probabilistic Approach to Determining the Tendency to Destroy a Nuclear Reactor Vessel in the Presence of Metal Defects

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## Abstract

The metal of the reactor vessel is subject to aging mechanisms caused by radiation exposure, high temperatures, and thermohydraulic variable loads. After decades of operation under these conditions, defects form in the metal structure. In addition to the well-known deterministic methods of testing and monitoring the metal, new approaches have been increasingly sought in recent years. The presentation in this article has two main goals: 1) To determine whether a probabilistic model is suitable for determining the tendency for breaking the metal of the casing, in the presence of defects; 2) How to use the probabilistic approach to conduct technical diagnostics of the condition of the metal of the case.

## Keywords

Reactor, Defects, Probabilistic Approach

## 1. Introduction

The policy of each NPP is to ensure safe production of electrical energy as well as security of supply. The operating temperatures in the primary circulation circuit are 270˚C - 330˚C, and the fluid pressure reaches 17.5 MPa. The metal of the reactor vessel is subject to neutron and temperature brittleness, fatigue, wear and intergranular corrosion [1]. At the current level of development of nuclear technologies, the influence of each influencing mechanism has been studied separately from other mechanisms in laboratory conditions. The complex (synergistic) interaction of degradation mechanisms and their impact on objects has not yet been studied. These influencing factors change the mechanical properties of the metal and reduce the bearing capacity of the structure. After several decades of operation of the nuclear unit, it is usually necessary to revalidate the strength analyses of the equipment to ensure its safe operation [1] [2]. The neutron flux produced by the chain reaction of the decay of uranium fuel in the core of the hull causes neutron and thermal brittleness of the metal. Neutrons, with their small mass and high energy values, penetrate deep into the crystalline metal lattice of the case [3]. They easily "knock" atoms out of their equilibrium positions-this is how vacations are created. Vacations are point defects and cause weakening of interatomic bonds, **Figure 1(a)**. Vacations migrate into the metal structure, can accumulate in cavities in the metal, which in turn leads to changes in the dimensions of the material (swelling). Atoms from the surface boundary between individual grains or blocks in grains also represent defects. This type of defect is the mosaic structure. Each grain consists of separate defect-free blocks, or Sub grains with dimensions of the order of $10^{-6}$ - $10^{-8}$ m, which make small angles between themselves. Sub grains at the borders are perceived as surface defects (the red zone of **Figure 1(b)**) and here the vacations, knocked out atoms, and impurity atoms (of the elements Phosphorus and Sulphur) accumulate. In these zones, weak interaction bonds are created between the building blocks. The space here between the crystal grains in the metal structure is susceptible to intergranular corrosion. In short, neutrons cause point, surface and volume defects in the structure of metals, as well as intergranular corrosion.

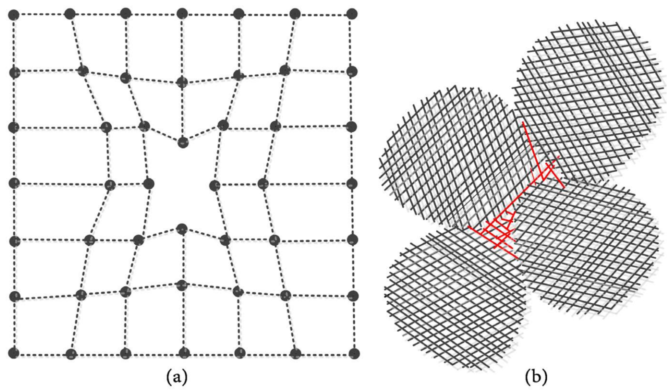



**Figure 1.** (a) Scheme of vacation in the crystal metal lattice. (b) Scheme of a mosaic structure in real metal.

Neutron and thermal effects cause changes in the mechanical properties of metals. The values of strength $6_B$ and yield strength $6_S$ increase. In cases of prolonged irradiation (over two decades) with neutron fluence, the value of the yield strength $6_S$ can be increased up to three times and practically approach the strength limit $6_B$. The convergence of these two boundaries means that in the load-resistance diagraph ("6-ε") the dragging site is "lost"; the metal loses its tough-plastic structure and reaches states of ultimate strength even at small values of deformation. The risk of brittle fracture increases sharply. The "6-ε" diagram for non-irradiated metal is shown in **Figure 2(a)**, and the same diagram for irradiated metal is shown in **Figure 2(b)**.

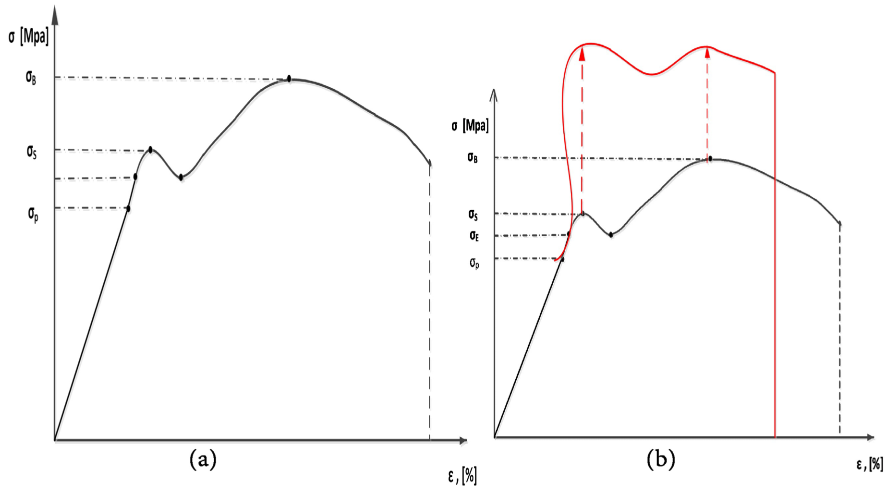



**Figure 2.** (a) Load-resistance diagram of a metal, without neutron and thermal irradiation. $\sigma_P$ -limit of proportionality; $\sigma_E$ -limit of elasticity; $\sigma_S$ -limit of yield; $\sigma_V$ -tensile strength; $\varepsilon$ -strain value; (b) Load-resistance diagram of a metal, with neutron and thermal irradiation. $\sigma_P$ limit of proportionality; $\sigma_E$ -limit of elasticity; $\sigma_S$ -limit of yield; $\sigma_V$ -tensile strength; $\varepsilon$ -strain value.

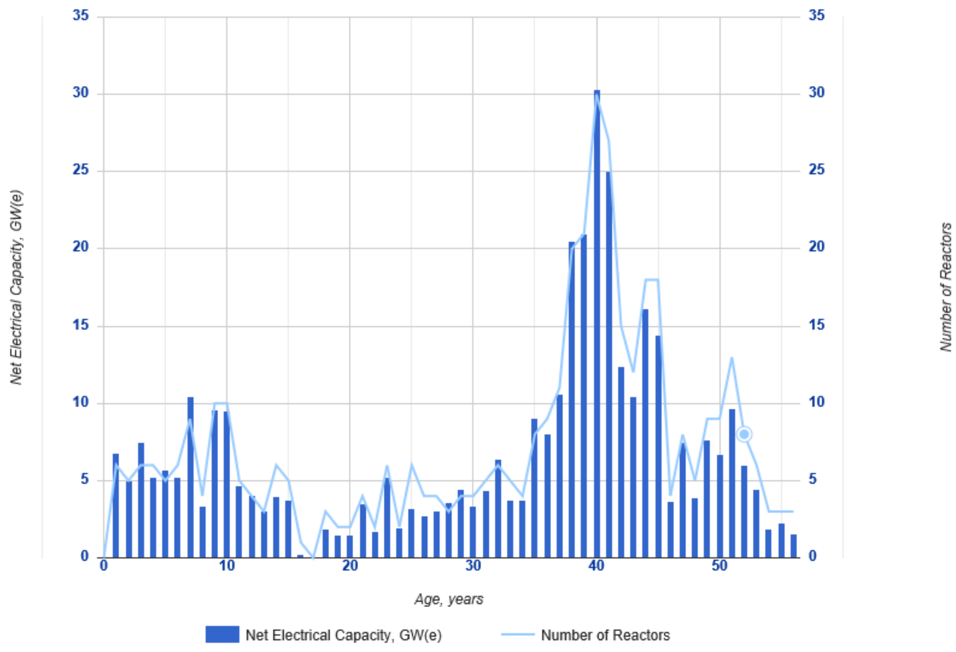



**Figure 3.** Number of nuclear reactors and years of their operation, worldwide.

Metal fatigue is caused by thermohydraulic loads during the operation of nuclear facilities. The reasons for metal fatigue are the thermal and mechanical stresses that vary in value and sign. The mechanisms of degradation of mechanical properties of the metal, typical for nuclear installations, are known [1] [2] [4]. However, the synergistic effect of the interaction of many influencing factors has not yet been studied. The processes of modification of mechanical properties are considered in the design and operation of the plant. To ensure the safe operation of a nuclear reactor, different standards apply in different countries [5]-[7]. The regulatory and technological documents, however, were prepared and put into effect 30 - 40 years ago. Since then, a lot of knowledge and operational experience has been accumulated on metal aging. Most of the nuclear power plants have been in operation for more than 3 decades. As of 2024, of all the nuclear reactors in operation in the world, 164 reactors have been in operation for 40 years or more [8], **Figure 3**. Inevitably, for the "obsolete" units, a decision must be made to extend the service life or to close and decommission them.

The combination of factors: 1) the outdated regulatory framework, 2) ensuring the reliability of the nuclear power plant, 3) mechanisms of degradation of mechanical properties of the metal, which inevitably lead to compromising the bearing capacity of the structures, 4) the long-term operation of the many nuclear units in the world, 5) the need to extend the service life of nuclear capacities, which is formed by the scarcity of energy resources in the world—all this leads to an increase the importance of technical diagnostics of the condition of equipment in nuclear power plants. The methods for testing the metal are given by the manufacturer of the equipment and are defined in the technological regulations of the unit [9]. These methods are mainly deterministic—visual, capillary, ultrasound, and eddy current control methods. Deterministic is the algorithm that will always give the same result at a certain input. The assessment of the final state is whether the measured indicator is less than the limit values [7] [9]. In recent years, however, probabilistic methods for assessing resource indicators have been increasingly applied. Probability is a quantitative assessment of the possibility that an event will occur, based on the available information. One of the most important indicators determining the integrity and functionality of the facility are the defects found in the metal from operational non-destructive testing. This article discusses the parameters of defect indications and discusses whether statistical distributions are applicable. The presentation describes a method of applying a probabilistic method for assessing the condition of the metal of the reactor vessel, and processing statistical data on defects in the metal.

## 2. Materials and Methods

The objects of the assessment are metals of welded joints from the inner and outer surfaces of reactor vessels, type VVER 1000. Two real units are considered. There are areas with potential for destruction in the sites and the reasons for this are:

1) Welded sections have a heterogeneous metal structure (base metal zone, thermal impact zone and welded metal zone); heterogeneity in structures is one of the general causes of defects.

2) The welded compounds located opposite the reactor core are subjected to the brittle effects of neutron fluence with high values.

3) Defects in the welded joints have been found.

The focus of the current study is solely on welded joints, since no defects were recorded in the base metal of the reactorc. The reactor materials are austenitic steels and ferrite-pearlite steels with austenitic surfacing coating. Austenitic steels are corrosion-resistant, have appropriate technological properties and operate up to temperatures of 700˚C. Steels of type 08X18H10T are radiation-resistant. Alloyed pearlite chromium-molybdenum-vanadium steel 15X2NMFA has two layers of austenitic overlay. Steels of the type 15X2MFA, 15X2NMFA, A542, A543, A508 have resistance to radiation brittleness, high strength and good ductility ( $R_e = 500 - 900 MPa$ ), but are not corrosion-resistant [7]. The reactor vessels have an internal diameter of 3580 mm and a wall thickness of 140 mm [10]. The objects were tested by ultrasonic method [11]-[16]. The characteristic data for each defect are its dimensions, equivalent area, location and type. Since ultrasonic testing registers indications of defects, we speak of indications later in the text. Systematization of the indications of defects found during ultrasonic non-destructive testing of the external and internal surfaces of the reactor vessels has been carried out. Systematization means that a sample is made for all indications that are above a specified level of fixation of the ultrasound signal, reflected by the incompleteness. The entire statistical evaluation period covers 26 years. The data for all indications recorded by ultrasound control for 26 years were processed. For each indication, the value of the equivalent area $S_{eqv}$ of the defect indication is divided by the maximum allowable area $S_{norms}$ of defects for this facility, determined by the norms [9].

The normalized value of the equivalent area of the indication is obtained $\frac{S_{eqv}}{S_{norms}}$. In case $\frac{S_{eqv}}{S_{norms}} < 1$, the facility is suitable for safe operation. In case $\frac{S_{eqv}}{S_{norms}} \ge 1$ the indication has reached the maximum amount allowed by the regulations. The data for $\frac{S_{eqv}}{S_{norms}}$ are ranked in ascending order of variations. On the basis of the set of inconsistencies and by representing their dimensions in probability networks, it is possible to estimate the moment in time when one or more indications will reach critical dimensions and a failure of the facility will follow. Hypothetically, we choose the Weibull distribution as an appropriate physical model for estimating the state of objects [17]. The random variable is indicated $y_i = \frac{S_{eqv}}{S_{norms}}$. In the two-parameter Weibull distribution, the distribution function is:

$$F(y) = \frac{\beta}{\eta} . \left(\frac{y}{\eta}\right)^{\beta-1} . e^{-\left(\frac{y}{\eta}\right)\beta} \tag{1}$$

The function determines the probability that the defect will reach critical dimensions and the metal will rupture; β and η are distribution parameters. $F(y)$ probabilistic networks are built for the development of indications. Reliability Function, which determines the probability that the metal will not tear due to defects is:

$$R(y_i) = 1 - \hat{F}(y_i) \tag{2}$$

Probability density Function:

$$f(y_i) = \frac{\hat{R}(y_i) - \hat{R}(y_{i+1})}{\Delta y_i} = \frac{1}{(n+0.4).\Delta y_i} \tag{3}$$

Failure Intensity Function:

$$\lambda(y_i) = \frac{f(y)}{R(y)} \tag{4}$$

## 3. Results

The data for $y_i$ of the indications of the object "Welded Joint on the Outer Surface of the Reactor Vessel of the Power Unit" are ranked in ascending order of variation, Table 1. Ranking means that the units are ordered in ascending order according to the meanings of an unmetered characteristic.

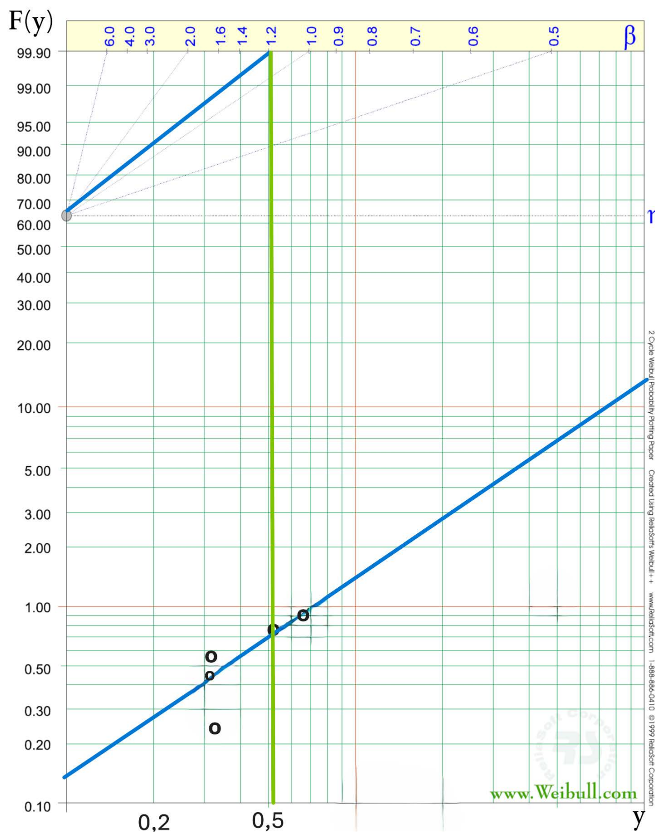
Table 1. Ranked data for defects of the object "Welded joint on the outer surface of the reactor vessel of the power unit".

| | Ranked data | | | | | |
|---|---|---|---|---|---|---|
| | $y_i$ | $\hat{F}_i(y_i)$ | $R(y_i)$ | $\Delta y_i$ | $f(y_i)$ | $\lambda(y_i)$ |
| 1997 | 0.26 | - | - | - | - | |
| | 0.33 | 0.26 | 0.73 | 0.07 | 2.23 | 3.04 |
| | 0.33 | 0.42 | 0.58 | 0.07 | 2.23 | 3.86 |
| | 0.33 | 0.58 | 0.42 | 0.07 | 2.23 | 5.29 |
| | 0.53 | 0.73 | 0.26 | 0.2 | 0.78 | 2.94 |
| | 0.66 | 0.89 | 0.10 | 0.13 | 1.20 | 11.5 |
| 2002 | 0.64 | | | - | - | - |
| | 0.66 | 0.18 | 0.82 | 0.02 | 5.32 | 6.49 |
| | 0.66 | 0.29 | 0.71 | 0.02 | 5.32 | 7.46 |
| | 0.68 | 0.39 | 0.61 | 0.02 | 5.32 | 8.77 |
| | 0.73 | 0.5 | 0.5 | 0.05 | 0.47 | 2.13 |
| | 0.74 | 0.61 | 0.39 | 0.01 | 10.64 | 27.03 |
| | 0.78 | 0.71 | 0.29 | 0.04 | 2.66 | 9.26 |
| | 0.85 | 0.82 | 0.18 | 0.07 | 1.52 | 8.40 |
| 2006 | 0.86 | 0.92 | 0.07 | 0.01 | 10.64 | 142.8 |
| | 0.5 | 0.075 | - | - | - | - |
| | 0.54 | 0.18 | 0.82 | 0.04 | 2.66 | 3.25 |
| | 0.64 | 0.29 | 0.71 | 0.1 | 1.06 | 1.49 |
| | 0.65 | 0.39 | 0.61 | 0.01 | 10.64 | 17.54 |
| | 0.70 | 0.5 | 0.5 | 0.05 | 2.13 | 4.25 |

**Continued**

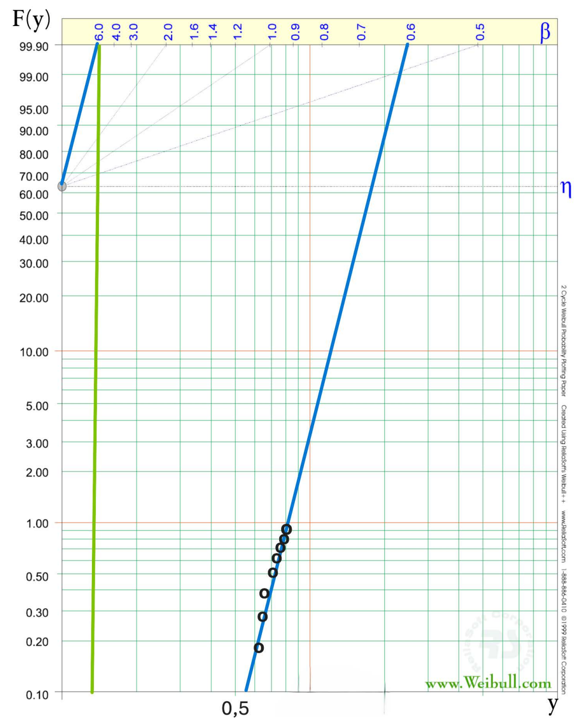
| | | | | | | |
|---|---|---|---|---|---|---|
| | 0.78 | 0.61 | 0.39 | 0.08 | 1.33 | 3.38 |
| | 0.8 | 0.71 | 0.29 | 0.02 | 5.32 | 18.52 |
| | 0.82 | 0.82 | 0.18 | 0.02 | 5.32 | 29.41 |
| | 0.86 | 0.92 | 0.07 | 0.04 | 2.66 | 35.71 |
| | 0.71 | 0.09 | - | - | - | - |
| | 0.96 | 0.23 | 0.77 | 0.25 | 0.54 | 0.70 |
| | 1.39 | 0.36 | 0.63 | 0.43 | 0.31 | 0.49 |
| 2010 | 1.39 | 0.5 | 0.5 | 0.43 | 0.31 | 0.63 |
| | 1.96 | 0.63 | 0.36 | 0.57 | 0.23 | 0.65 |
| | 5.35 | 0.77 | 0.23 | 3.39 | 0.04 | 0.17 |
| | 17.07 | 0.90 | 0.094 | 11.72 | 0.01 | 0.12 |
| | 0.71 | 0.09 | - | - | - | - |

The data for the object "Welded joint on the outer surface of the reactor vessel of the power unit" are plotted in probability networks of the Weibull distribution, Figures 4-7.



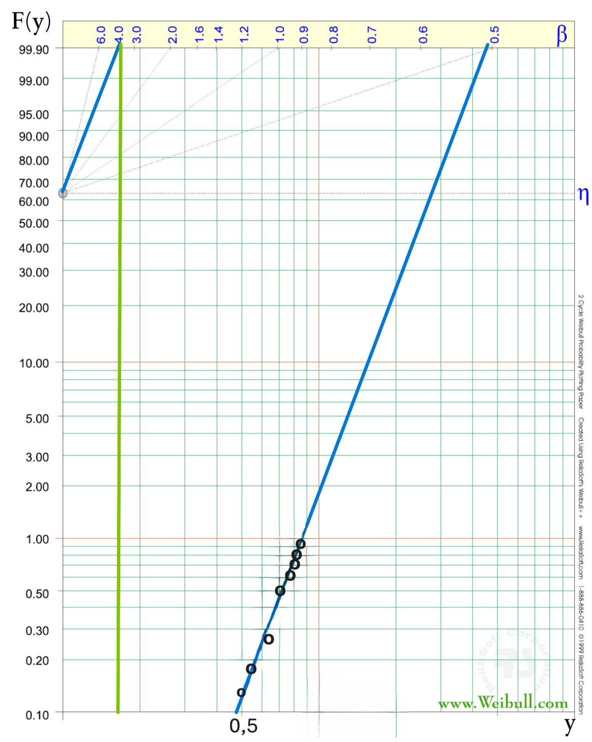

$\beta = 1.2$ ; $\eta = 0.51$ .

Figure 4. Example of Grafical models of Weibull data distribution for indications of the object "Welded joint on the outer surface of the reactor vessel of the power unit" 1997.




$\beta = 6$; $\eta = 0.14$.

**Figure 5.** Example of Grafical models of Weibull data distribution for indications of the object "Welded joint on the outer surface of the reactor vessel of the power unit" 2002.




$\beta = 4$; $\eta = 0.17$.

**Figure 6.** Example of Grafical models of Weibull data distribution for indications of the object "Welded joint on the outer surface of the reactor vessel of the power unit" 2006.

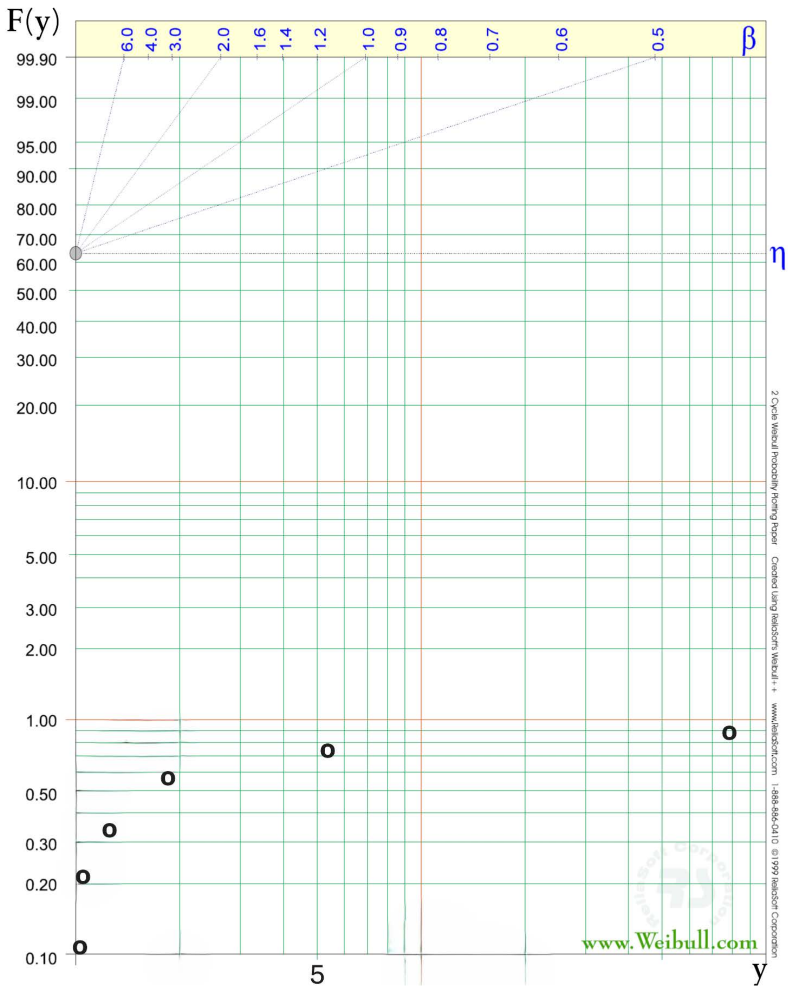



**Figure 7.** Example of Grafical models of Weibull data distribution for indications of the object "Welded joint on the outer surface of the reactor vessel of the power unit" 2010.

An analysis of the obtained graphical patterns is carried out. In case the approximation line is straight, then the Weibull two-parameter distribution is applicable. Linearity is found in **Figures 4-6**. This means that the hypothetically selected Weibull distribution is suitable for analyzing the state of the metal of the reactor vessel based on the development of defects in the metal. For the 2010 data, a parabola is observed, which means that it is appropriate to apply a three-parameter Weibull distribution or another type of distribution, **Figure 7**. The parameters of the distribution can be graphically determined, **Table 2**.

**Table 2.** Parameter values $(\beta, \eta)$ of the Weibull distribution, graphically obtained from **Figures 4-6**.

| | Parameter values $(\beta, \eta)$ | | |
|---|---|---|---|
| From Figures | **Figure 4** (1997) | $\beta_1 = 1.2$ | $\eta_1 = 0.51$ |
| | **Figure 5** (2002) | $\beta_2 = 6.0$ | $\eta_2 = 0.14$ |
| | **Figure 6** (2006) | $\beta_3 = 4.0$ | $\eta_3 = 0.17$ |

Once the parameters $(\beta, \eta)$ of a two-parameter Weibull distribution are known, it is possible to determine the probability values of $F(y)$ the function of metal rupture due to defects in the metal. These values can be determined graphically (by Figures 4-6) or computationally (1). Let the values of F (the function y) be determined by a graphical method, taking a certain indication, $y_1$. It is logical to expect that the area of the indication will increase in subsequent years of operation of the unit, Table 3.

Table 3. Stubs on $y_1$ and on $F(y_1)$.

| | | $y_1$, from Table 1 | $F(y_1)$ |
|---|---|---|---|
| Data sample year | (1997) | 0.33 | 0.41% Figure 4 |
| | (2002) | 0.66 | 0.28% Figure 5 |
| | (2006) | 0.54 | 0.19% Figure 6 |

Table 3 shows that the values of $F(y_1)$ decrease as the operating time increases.

## 4. Discussion

When the reactor service life increases, there are two possible scenarios—the defects may not change or increase in area. This depends on the loads and the operating time. The loads themselves can also change over time. And as the area of defects increases, the function of the failures of the facilities also changes. Table 3 shows that with an increase in the years of operation, the values of the function $F(y)$ decreases or in other words, the probability of destruction of the facility in case of established incompleteness decreases.

## 5. Conclusion

The final effect of the degradation of the mechanical properties of the equipment (aging effects) is the loss of operability of components and systems, which compromises the safety of the nuclear unit. Tracking trends in the demolition of facilities is extremely important. The probabilistic approach for determining the values of the function $F(y)$ is a quick and easy way to monitor the condition of an object for which indications of defects in the metal have been found. The two-parameter Weibull distribution is suitable for application in the case under consideration. The values of the function $F(y)$ decrease with increasing years of operation of the facility. The defects are in a stable state and do not develop (at the time of the last statistical sample). During the first 28 - 30 years of operation of the reactor vessel, the Weibull distribution is suitable for describing the probabilistic characteristics of facilities based on resistance to the development of incompleteness in the metal. During further operation of the unit (over 30 years), the processes of degradation of the material are intensified due to an increase in neutron and thermal brittleness. In such a case, it is assumed that the values of the function $F(y)$ will increase with the years of operation of the facility.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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