SOME PERFORMANCE INDICATORS OF PWR STEAM GENERATORS

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Abstract

The monitoring of operational performance is a crucial aspect of the management of equipment operation and maintenance in many industries, including nuclear and thermal power plants. Monitoring involves the collection and analysis of data on the operation. PWR steam generators operating experience is sufficiently abundant to enable a systematic analysis of steam generator degradation and failure mechanisms. The data allows the development of corrective measures and overall improvement of power plant effectiveness and safety performance. Raw data used in present analysis come from experience at various nuclear power plants collected in the IAEA Power Reactor Information System (PRIS) and published in the agency's annual reports on operating experience since 1971.

In this paper, we analyze steam generators in operation, e.g., their malfunctions during the plant life cycle with the aim of identifying characteristics of failure rate and repair rate. These are necessary parameters to determine the reliability and availability of steam generators and their effect on the safety and efficiency of the nuclear power plant. We analyzed IAEA available data for period from 1971 to 2000. Each steam generator was analyzed individually during plants' lifetime. The data on steam generator failures are presented in uniform format, allowing the consistency in failure classification and data reporting. Operational aspects of steam generators were tracked through plant lifetime and the failure rate λ and repair rate μ with associated boundaries were calculated. The empirical probability distribution of failure rates and repair rates were observed. General trends in performance indicators (λ, μ) were analyzed, from the point of their influence on plant reliability and availability.

Introduction

The steam generators (SG) in the pressurized water reactor (PWR) are large tube-in-shell heat exchangers that use the heat from the primary reactor coolant to produce steam in the secondary side and thus drive turbine generators. The primary reactor coolant passes through a large number of small diameter tubes and boils water on the outside of the tubes to make steam. Steam generator tubing provide safety barrier between the radioactive primary side and the non-radioactive secondary side. In order to perform such safety function, it is important that the steam generator tubing is free of cracks or any other degradation mechanisms. Any degradation which impairs such safety function, i.e. which may lead to either single or multiple tube rupture, or to consequential failure and/or leakage under certain accidental conditions, is consider as a significant safety concern. The primary reactor coolant is at a higher pressure than the secondary coolant. Any leakage from flaws in the tubes can result in release of radioactivity to the environment outside the reactor containment through the pressure relief valves, the condenser off-gas, or other possible paths in the secondary system.

In the early days of design of generation I, II or III nuclear power plants, it was assumed that the operational life cycle of steam generators would be the same or to that of the other key components in the reactor primary heat transport system (reactor vessel, core, piping, primary coolant pumps, etc.). However, widespread degradation of the steam generator tubing that has occurred at a number of plants has shown this original assumption was incorrect or at least too optimistic. Observed degradations can be attributed to a number of factors ranging from shortcomings in the design codes manufacturing processes, or water chemistry, and unanticipated mechanisms of material and component degradation resulting from high temperature, high fluid flow, cycling loads and presence of corrosive species. As a result, the extent of the damage to steam generator tubes has resulted in significant losses in efficiency and abandonment or replacement of steam generators well before their design lifetime. Furthermore, steam generator problems have ranked only behind fuel outages as the most significant contributor to lost power generation. Steam generators have therefore represented one of the largest problems in terms of reliability, availability and unanticipated cost that nuclear industry has had to face to date.

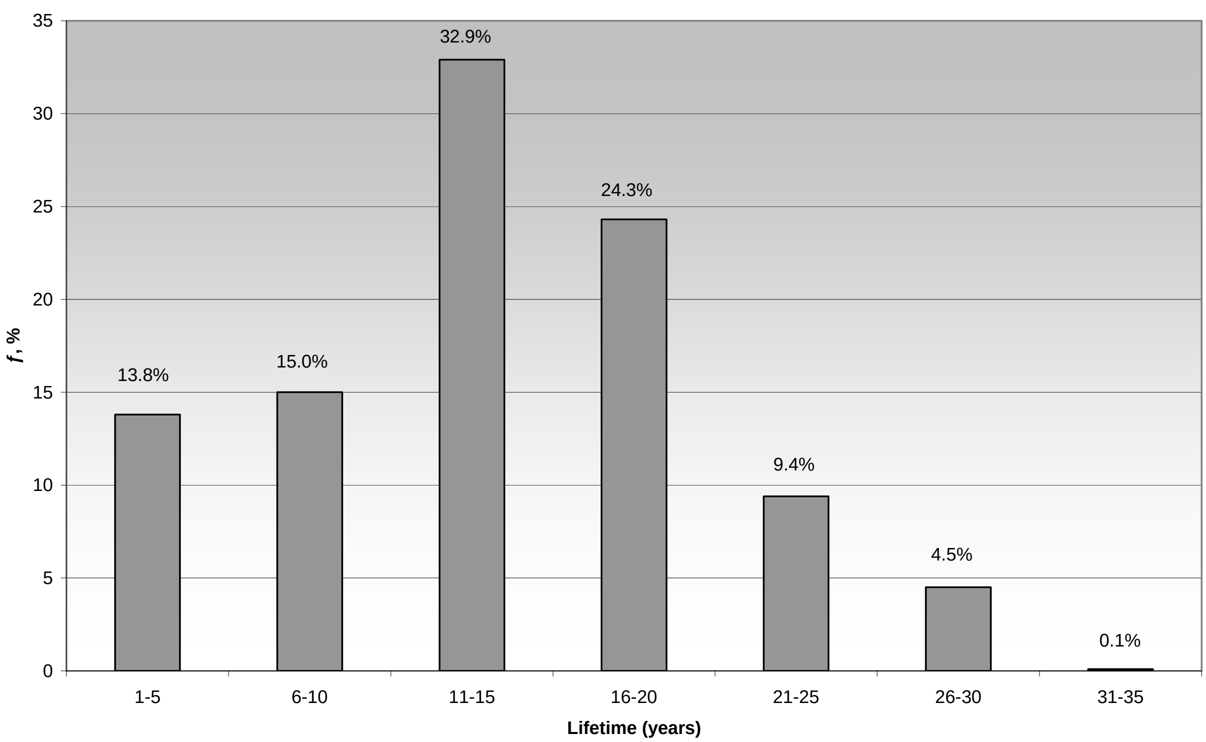
Traditionally, tube plugging rate is the most commonly used indicator of the extent of tube failure degradation. However, the tube plugging rate does not provide the whole information about the extent of degradation and its impact on steam generator and power plant performance. This paper seeks to identify the more appropriate steam generator performance indicators, namely the failure rate and the repair rate.

Performance Indicators

A systematic approach to analyze the operating experience of equipment is one way of examining and improving their operational effectiveness. To this effect, the monitoring of operational performance is a crucial aspect of the management of equipment operation and maintenance in many industries, such as nuclear and thermal power plants, chemical and process systems. Monitoring involves the collection and analysis of data from plant components operation. Methods which are typically used to analyze equipment failure include determination of failure rate and repair rate for individual failure modes [1, 2]. In safety analyses and risk studies of nuclear power plants or their components, failure / repair rates or probabilities of generic components are commonly used parameters. Usually it is assumed that the failure/repair rates or probabilities do not have a fixed value but are rather following given statistical distribution. Then, the failure/repair rate of particular component is chosen randomly from this distribution as input data for Probabilistic Safety Analysis and evaluation the effectiveness of nuclear units. However, we have to note here that in order to obtain reliable data for operational behavior of generic equipment we must use operational data from a large number of components.

About half of total number of currently operating nuclear power plants is PWR type contributing to about 60% of the total energy production up to the end 2000. Therefore, PWR system generators have operating experience which is sufficiently abundant to enable reliable and systematic analysis of their malfunctions. Raw data, used in this analysis, are of those operating nuclear units collected within the IAEA Power Reactor Information System (PRIS) and published in the Agency's annual reports on operating experience since 1971 [3]. The source data on component failures in the PRIS database were presented in the following format: data of particular failure, outage duration and type of failure, etc. Thus, failure classification and data reporting were consistent for all nuclear units. In present paper, data for 799 steam generators (SG) from the onset of their commercial operation were analyzed. The analysis of SG performance indicators was performed along two timeframes: over unit lifetime and over calendar years. The failures and repairs were monitored individually and considered within each unit lifetime period and for each calendar year during lifetime. Figure 1 shows distribution of the number of steam generators over an operational lifetime. About 70% of analyzed SGs have operational lifetime in the range between 60,000 h and 160,000 h.

Figure 1:Lifetime Distribution of PWR Steam Generators (vertical, U-tube) at the end of 2000



Two main performance indicators of individual steam generators were used in current analysis, namely:
Mean Time to Failure (MTTF),

$$MTTF = \sum t_i / (r+1) \text{ [h]}, \qquad i=1, r \qquad (1)$$

and
Mean Time to Repair (MTTR),

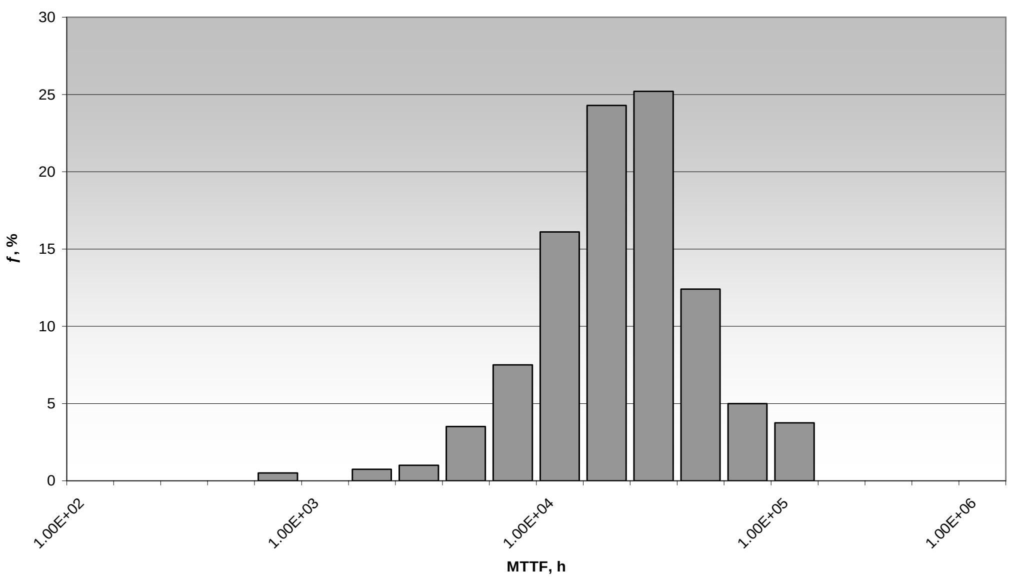
$$MTTR = \sum \tau_i \; / \; r, \text{ [h]} \qquad i=1, r \qquad (2)$$

Distributions of both of these performance indicators, based on operational data of 799 steam generators up to 200, are shown on Figures 2 and 3. MTTF values are within narrow interval from 10^4 to 10^5 hours, while MTTR values are seen uniformly distributed within whole available interval from 10^1 to 10^4 hours. The main characteristics the MTTF and MTTR distributions are shown in Table 1.

Table 1 The PWR Steam Generators operational performance for period 1971 – 2000.

Number of Steam Generators			799
Total Operational time for SG population, h			$75.548\ 10^6$
Total Repair Time for SG population, h			$1.364\ 10^6$
The characteristic values of indicators for single SG	Lower bound	Median	Upper bound
t_L, h – Lifetime operational period	21,990	93,824	185,058
τ_L, h – Lifetime repair time	2	296	8,835
TTF, h – Time-to-Failure	1,347	10,614	73,259
TTR, h – Time-to-Repair	6	62	2,294
$MTTF_L$, h – Mean Time-to-Failure	5807	23,709	90,820
$MTTR_L$, h – Mean Time-to-Repair	2	89	1,246

Figure 2: Distribution of MTTF (Mean Time To Failure) of Individual PWR Steam Generators (vertical, U-tube) at the end of 2000



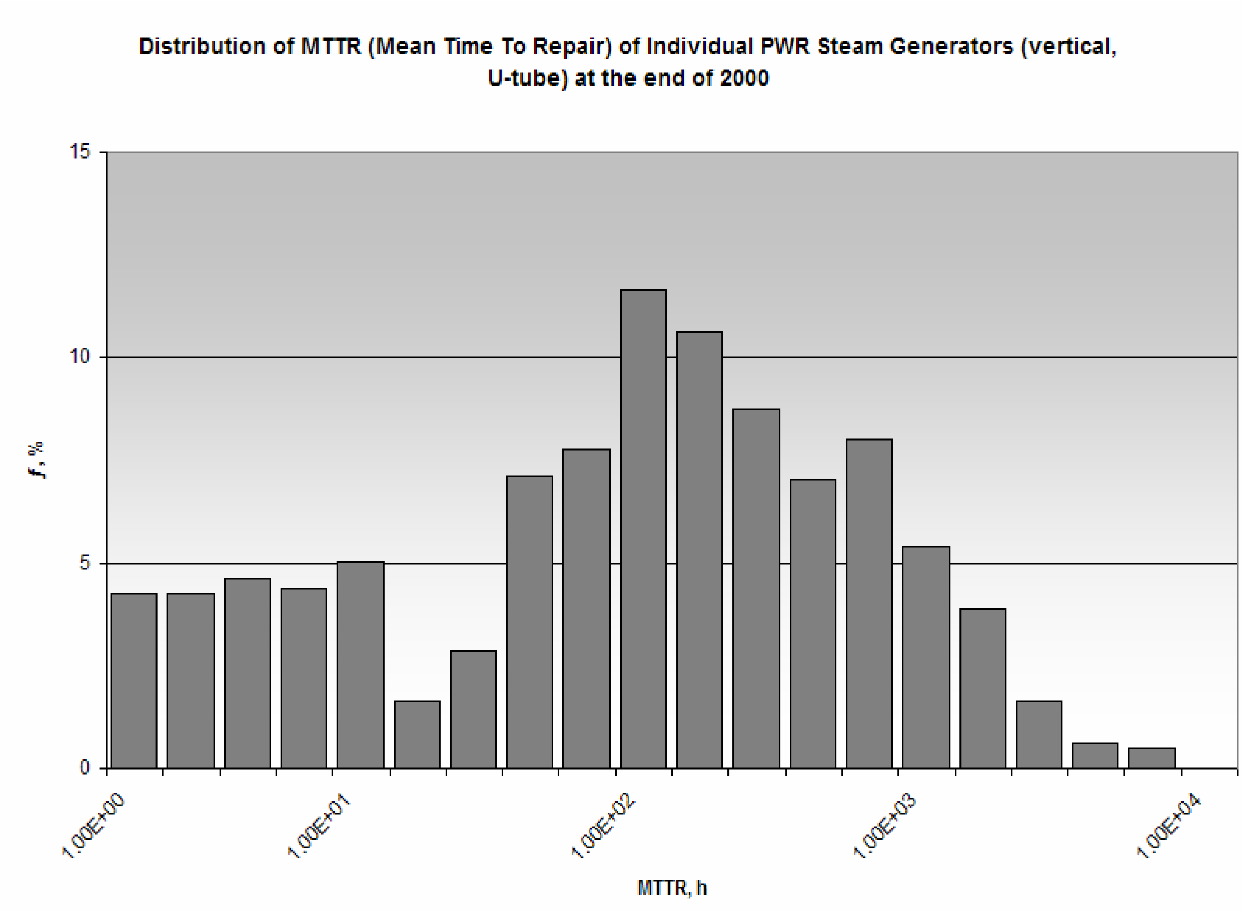


Figure 3

The Prime Performance Indicators

Steam generators are vital components of nuclear steam supply system for which there is no ready off-the shelf replacement. Should they breakdown the nuclear unit must be shutdown and SG repaired, consequently steam generators are considered as repairable components. As already discussed, the data on SG malfunctions as reported in reference [3] were used. Further, for the purpose of present analysis, only SG malfunctions which resulted in unplanned shutdown and outage of nuclear unit were considered. Our approach in the analysis of SG failures was aimed towards determination of steam generator failure rates and repair rates during nuclear unit cumulative lifetime as well as per each calendar year of operation. The failures rate and repair rates could be considered as the prime performance indicators, since they provide basis for determination of deduced performance indicators (reliability, availability, etc). We followed well established and broadly accepted approach to calculate the failure and repair rates [2], in the same fashion as applied in related references [4-7], based on equations (1) and (2), i.e.,

Failure rate,

$$\lambda = 1/\mathrm{MTTF} = (r+1)/t, \ [h^{-1}] \qquad (3)$$

Repair rate,

$$\mu = 1/\,\mathrm{MTTR} = r/\ \{\Sigma\ \tau_L\},\ [h^{-1}] \qquad (4)$$

The steam generator failure/ repair rates per calendar years are defined as a probability of failure/ repair in the unit time, assuming that the SG was in working condition at the beginning and at the end of calendar year. On the other side, the lifetime (or cumulative) SG failure/ repair rates are defined as a probability if failure/ repair in the unit time, for the lifetime period of operation.

Figure 4 shows the distribution of steam generator failure rate over lifetime, based on empirical data from operating steam generators in the period between 1971 and 2000. One can observe that the median value of the failure rate steadily decreases during initial period of operation, then relatively stabilizes around median value of 5.0 * 10^{-5} [h^{-1}] in the period between 10th and 23rd year of operation. Data shows that after 23rd year of lifetime operation median value of the failure rate sharply decreases due the equipment old age but also due to a relatively small number of steam generators in operation (well below hundred) at this age of their lifetime which directly affected calculation. Overall, it appears that the most probable empirical value of steam generator failure rate over lifetime is in the order of 5.0 * 10^{-5} [h^{-1}].

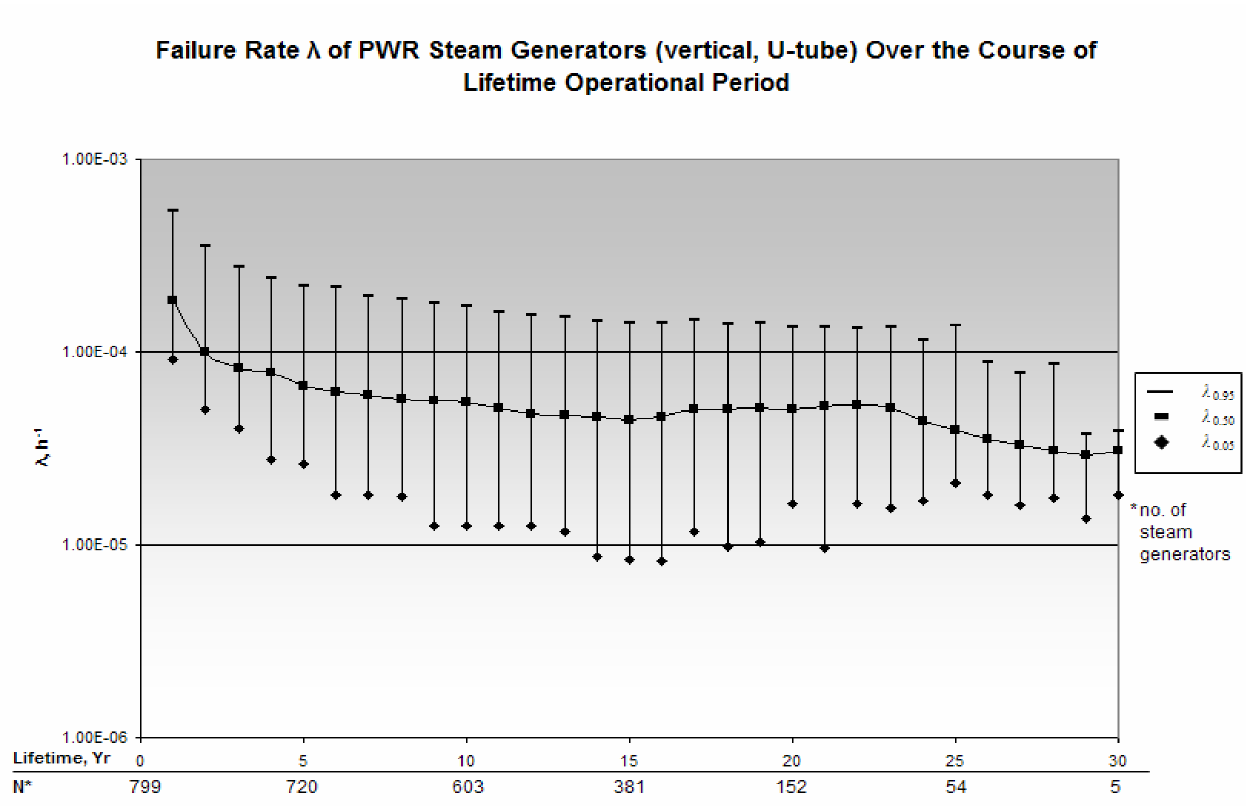


Figure 4

Figure 5 shows the distribution of steam generator repair rate over lifetime, based on empirical data from operating steam generators in the period between 1971 and 2000. Sharp decrease of the repair rate in first ten years is a consequence of relatively small number of repairs that need to be performed during initial period of operation. Number of repairs steadily increases up to 10th year of operation resulting in leveling the repair rate within an interval of $7*10^{-3}$ to $1.0*10^{-2}$ [h^{-1}] which characterizes remaining life of a generic steam generator.

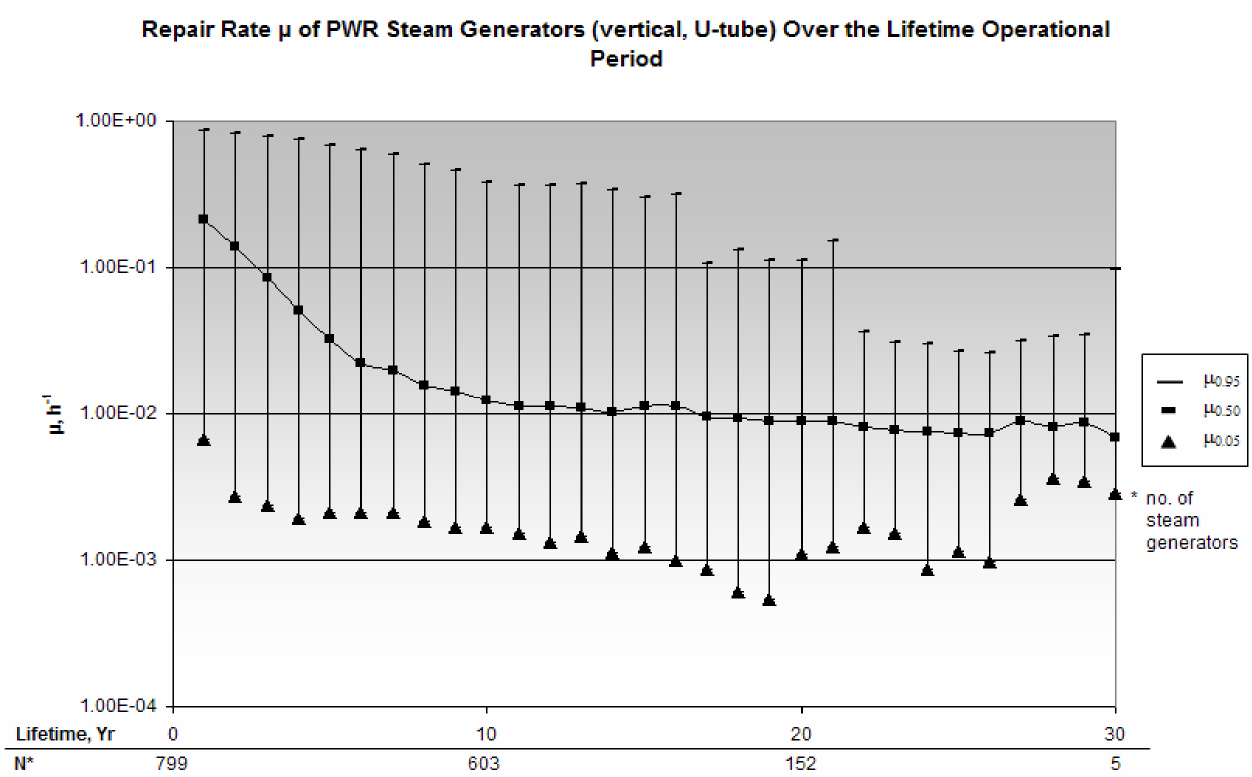


Figure 5

Conclusions

Traditionally, tube plugging rate is the most commonly used indicator of tube failure degradation. However, tube plugging rate does not provide the whole information about the extent of degradation and its impact on steam generator and power plant performance. In this paper we analyzed steam generators in operation, e.g., their malfunctions during the plant life cycle with the aim of identifying characteristics of failure rate and repair rate. These are necessary and more informative parameters if we are to determine the reliability and availability of steam generators and their effect on the safety and efficiency of the nuclear power plant. Data for 799 steam generators in operation from 1971 to 2000 were analyzed. Operational presence of the analyzed steam generators is tracked through a plant lifetime and the failure rate λ as well as the repair rate μ with associated boundaries were calculated. The empirical probability distribution of failure rates and repair rates were observed and general trends in performance indicators (λ, μ) from the point of their influence on plant reliability and availability were captured. Overall, it appears that the most probable empirical values of steam generator failure and repair rates over lifetime are in the order of $5.0 * 10^{-5}$ [h^{-1}] and within an interval of $7*10^{-3}$ to $1.0*10^{-2}$ [h^{-1}], respectively.

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