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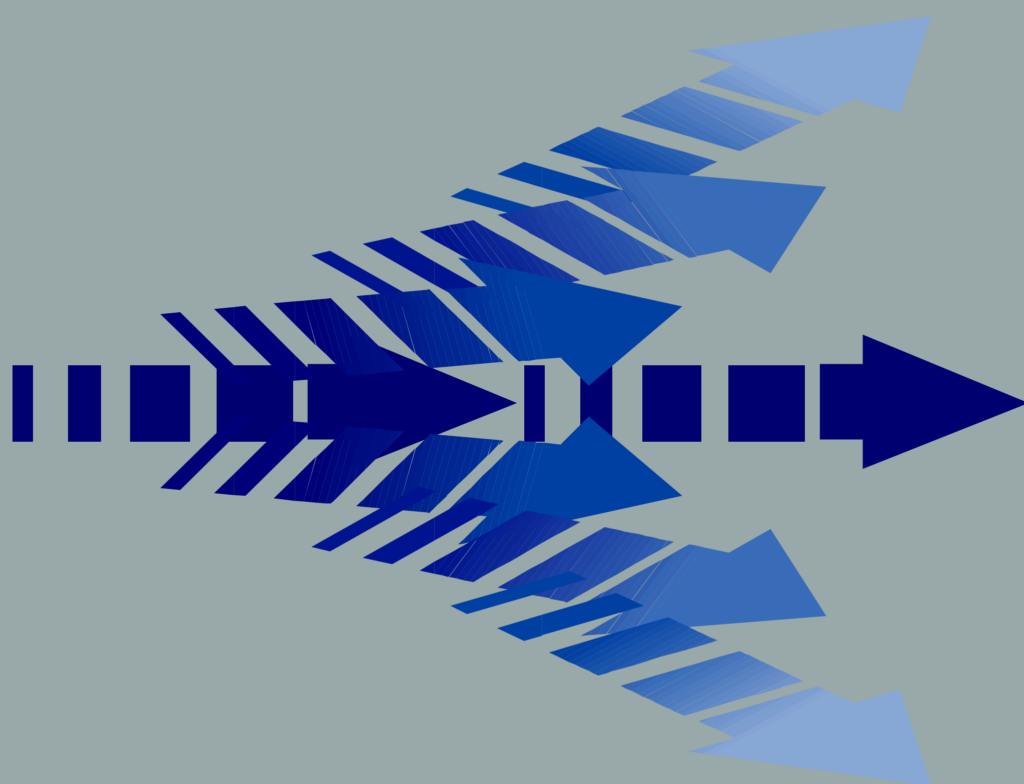
# RELIABILITY ANALYSIS AND ASSESSMENT OF HYDROPOWER EQUIPMENT



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# *RELIABILITY ANALYSIS AND ASSESSMENT OF HYDROPOWER EQUIPMENT*

By

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For

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# PREFACE

This report was completed as a product of the U.S. Army Corps of Engineers' Risk Analysis for Water Resources Investments Research Program managed by the Institute for Water Resources which is a unit of the Water Resources Support Center. The report conforms to the basic planning model and to the analysis recommendations presented in "Economic and Environmental Principles and Guidelines for Water related Land Resources Implementation Studies" (P&G).

The purpose of this research project was to develop and present an assessment methodology for use in producing time-dependent reliability and hazard functions of hydropower equipment. The development of these hydropower reliability functions is a required step in pursuit of conducting the technical and economic analyses necessary to complete a major rehabilitation study.

This report was prepared by the authors under terms of a contract with the U.S. Army Corps of Engineers Institute for Water Resources. Bilal M. Ayyub and Mark P. Kaminskiy are of the University of Maryland, College Park. Dr. David A. Moser, besides being a co-author, was the contract manager for the report and is the manager of the Risk Analysis for Water Resources Investments Research Program. The Chief of the Technical Analysis and Research Division is Mr. Michael R. Krouse and the Director of IWR is Mr. Kyle Schilling.

# SUMMARY

A major rehabilitation program as defined by the US Army of Corps of Engineers (USACE) is a program for reliability or efficiency improvement. A reliability rehabilitation project consists of structural or mechanical work on USACE operated facility such as locks, dams, and hydropower plants. The objective of reliability rehabilitation projects is to determine capital expenditure to replace structures in a cost effective method. Hydropower equipment and plants are, therefore, included within these major rehabilitation programs. A justification for rehabilitation needs to include rigorous technical and economic analyses in order to successfully compete for limited appropriation funds. The technical analysis for hydropower equipment such as generators needs to include reliability assessment of the equipment.

In this study an assessment method of the time-dependent reliability and hazard functions of hydropower equipment is developed. Life data of equipment can be classified into several types. For hydropower equipment, complete data or right censored data are commonly encountered. The 1993 inventory of generators as provided by the USACE include also failure and replacement records. A preliminary examination of these records revealed that the average age at failure is 28 years. Also, the average age of equipment based on this 1993 inventory is 24 years. Generators were grouped by plant-on-line date and power to produce 12 groups. The life data of generators within each group were analyzed. Reliability functions were developed, and models based on nonlinear numerical curve fitting using an exponential function with a second-order polynomial tail were proposed. Early-life special models and late-life prediction (extrapolation) models were also developed. The effect of manufacturer on generator reliability was investigated. It can be concluded that the differences between the reliability values of the General Electric USACE and Westinghouse USACE generators are, in general, statistically insignificant.

The above reliability and hazard functions can be viewed as marginal functions that do not account for the particular condition of a piece of equipment, but they provide average or generic results for a group or stratum. In the practical use of hazard functions in investment decision analysis, a generic function might not be sufficient for a particular piece of equipment. Hence, the generic function needs to be modified by conditioning on a particular piece of equipment, resulting in a modified hazard function. By conditioning on a particular piece of equipment, the physical or performance condition of the equipment is introduced as a factor for modifying the generic function. The US Army Corps of Engineers (USACE) maintains information on test results of a particular piece of equipment that are aggregated to obtain a condition index. The test results and the condition index are needed to perform this modification.

Once a generic hazard function and a condition index are obtained for a particular piece of equipment, they can be combined to obtain the modified hazard function using Bayesian techniques. Reliability functions were developed for groups of generators that were defined by the date of having the plant on line and the power rating of the generators. The resulting reliability functions are called herein the group reliability functions. These reliability functions can be used as prior information in the Bayesian techniques to obtain plant-specific reliability functions by utilizing new plant information on generator failures or censoring to obtain plant reliability functions as posterior reliability functions. Then, methods are presented to obtain a unit (i.e., generator) specific reliability function based on a plant (or group) reliability function and the condition index of the unit. Two models were presented based on binomial and exponential parameters. Examples were used to demonstrate the use of these methods.

The suggested methods in this study were demonstrated using hydropower generators. Other similar hydropower equipment types can be treated using similar methods.

# Table of Contents

# 1. INTRODUCTION AND BACKGROUND

## 1.1. Background and Problem Statement

A major rehabilitation program is defined in the US Army of Corps of Engineers (USACE) Guidance for Major Rehabilitation Projects as a program for reliability or efficiency improvement (USACE 1993a). A reliability rehabilitation project consists of structural or mechanical work on USACE operated facility such as locks, dams, and hydropower plants. The objective of reliability rehabilitation projects is to determine capital expenditure to replace features of structures in a cost effective method. Hydropower equipment and plants are, therefore, included within these major rehabilitation programs that are funded by specific U.S. Congressional appropriations (Norlin 1993). A justification for rehabilitation needs to include rigorous technical and economic analyses in order to successfully compete for limited appropriation funds. The technical analysis for hydropower equipment such as generators needs to include reliability assessment of the equipment.

The definition of hydropower equipment reliability (Norlin 1993) is "The extent to which the generating equipment can be counted on to perform as originally intended. This encompasses (1) the confidence in soundness or integrity of the equipment based on maintenance costs and forced outage experience, (2) the output of equipment in terms of measured energy, power, efficiency, and availability, and (3) the dependability of the equipment in terms of remaining service life (retirement of the equipment)." Reliability assessment of hydropower equipment has gained added importance due to the aging inventory of USACE equipment. A significant fraction of equipment inventory is approaching or beyond an initial design life of forty to fifty years (Mlakar 1993). Therefore, there is a need to develop procedures for reliability assessment of hydropower equipment.

## 1.2. Objectives

The general objective of this study is to develop an assessment method of the time-variant reliability and hazard functions of hydropower equipment. The method needs to account for the condition of a particular piece of equipment resulting into equipment-specific reliability and hazard measures as functions of time.

The specific objectives can be expressed as (1) the development of a generic hazard function for a selected hydropower equipment type such as generators, (2) the examination of the condition index that is used by the USACE and its underlying tests, and (3) the development of an aggregation procedure for the condition index. The condition index will be used for modifying the generic hazard function for a particular piece of equipment to produce a modified hazard function.

The suggested methods in this study were demonstrated using hydropower generators. Other similar hydropower equipment types can be treated using similar methods.

# 2. LIFE DATA

## 2.1. Classification of Life Data

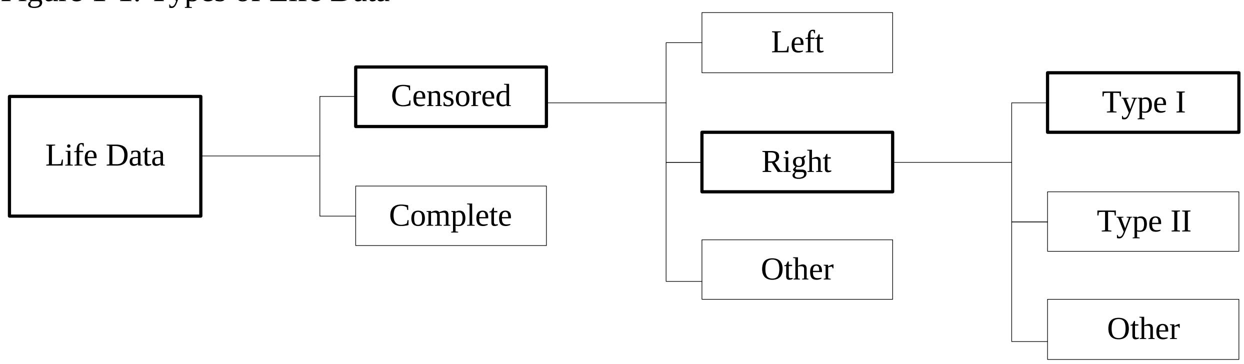
Life data of equipment can be classified into two types, complete and censored data. Complete life data that are based on tested equipment that has failed, and times to failure for the equipment are available based on these tests. Censored life data include some test results that represent only lower or upper limits on times to failure. For example if an equipment did not fail at some time *t*, then *t* is considered to be a lower limit on the time to failure and can be used for estimation. Equipment data that produces lower-limit values on times to failure are called right censored values. In some engineering applications, left censored data with upper-limit values on times to failure might also be available. For hydropower equipment, complete data or right censored data are commonly encountered. Data that include one or more censored observations are called censored data. Other types of data are possible such as interval censoring.

Censored data can be further classified into Type I or Type II data. Type I data are based on observations at a set time, that is, an end to equipment testing is based on a set time. Type II data are based on observations up to reaching a set count for the number of failures. In hydropower equipment, Type I right-censored data are commonly encountered. Figure 1-1 shows a summary of these data types. Other types of data are possible such as random censoring.

Hydropower equipment life data that are of interest herein are commonly based on failures that result in an equipment replacement or major repair and rehabilitation that renders it new. Therefore, hydropower data of interest herein are for non-repairable equipment. The models used in this study are for non-repairable systems, or for repairable systems with time to first failure.

Additional information on life data types is provided by Leemis (1995).

Figure 1-1. Types of Life Data




## 2.2. Hydropower Generators

### 2.2.1. Database of Hydropower Generators

Hydropower generators are used in this study to demonstrate the suggested methods. The 1993 inventory of the USACE of hydropower equipment was used for this purpose. The inventory was obtained from the USACE in the form of a database that consists of the records of 785 hydropower generators provided by USACE. The inventory was limited to generators with power (*P*) more than 5 MW and plant-on-line (*POL*) date after 1930. Appendix A contains a listing of records in the database. Each record is about one generator and consists of the following fields:

1. Plant Name
2. Unit Number
3. Plant-on-Line (*POL*) Date
4. Power (kW)
5. Rewind Date
6. Rewind Rating (kW)
7. Rewind Reason
8. Age at Failure (Years)
9. Age or Exposure Time (Years)

The 1993 inventory of generators as provided by the USACE includes also records of failure and replacement. A preliminary examination of these records revealed that the average age at failure is 28 years. Also, the average age of equipment based on this 1993 inventory is 24 years. A histogram for age of generators at failure (in years) is shown in Figure 2-1a. Also, an age histogram for the 1993 inventory of generators is shown in Figure 2-1b. The large scatter in age at failure (Figure 2-1a) can be attributed to the nature of mixed population of generators in terms of power capacity, usage, models, and operational history.

Figure 2-1a. Histogram for Equipment Age at Failure

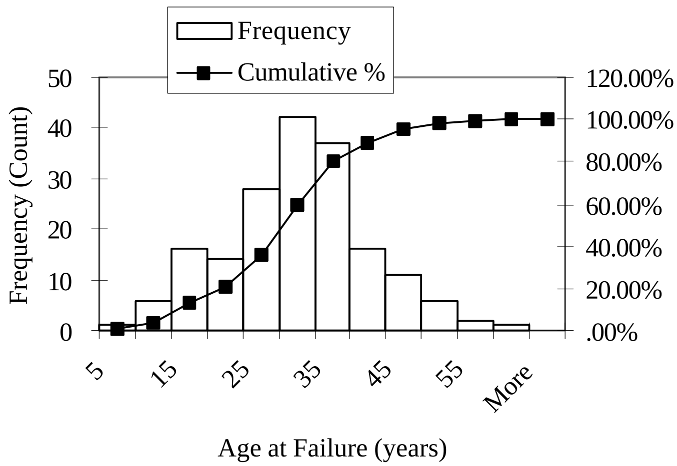
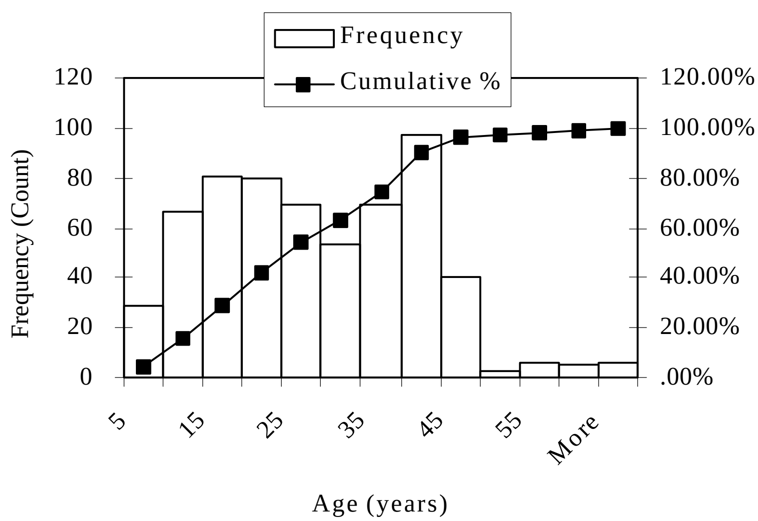



Figure 2-1b. Histogram for Equipment Age




## 2.2.2. Definition of Groups of Hydropower Generators

The age (or exposure time) for generators that appears as a field in the database can be treated either as the time to failure (for equipment that was repaired or replaced) or as the time to censoring (for equipment that was not repaired or replaced). The database includes equipment that has *POL* date in the range 1930 to 1993. Generators that were installed in the thirties are based on technologies and materials that might be different than in the fifties or the nineties. Therefore, the *POL* date (*T*) can be used to stratify the population of generators into groups as follows:

1. 1970 < *T* ≤ 1993
2. 1960 < *T* ≤ 1970
3. 1950 < *T* ≤ 1960
4. 1930 < *T* ≤ 1950

Each group spans 10 years except the first group that spans 23 years because no failures were reported for generators with *T* > 1980. Combining the last 23 years in one group produces some failure records in this time span for analysis purposes. An implied assumption in this group breakdown is that technologies and materials used in manufacturing generators are strongly correlated with *T*, therefore *T* can be used to reflect this effect.

The second factor that can be used for developing these groups is the power rating of generators. A histogram of power rating of hydropower generators is shown in Figure 2-2. The data were divided in the following groups based on power capacity (*P*) in MW:

1. Low Power *P* ≤ 30 MW
2. Medium Power 30 < *P* ≤ 50 MW
3. High Power *P* > 50 MW

The simultaneous stratification of the generators population by *T* and *P* results in 12 groups of low, medium and high power for each of the four time periods for *POL*. The number of units in these groups and the fractions of surviving units in each group are given in Table 2-1. The development of reliability assessment models are based on both variables (*T* and *P*). If one of them is determined to be insignificant, it can be dropped from the models, and the models are revised accordingly. Therefore, the possible model development scenarios are

1. <u>Both *P* and *T* are significant</u>. The result in this case consists of 12 reliability models, each model for a combination of *P* and *T*. Alternatively, one multivariable reliability model can be developed as a function of both *P* and *T*.
2. <u>Either *P* or *T* is significant</u>. The result in this case consists of 3 or 5 reliability models, respectively. Each model in this case is for the different values of the respective significant variable (*P* or *T*). Alternatively, one multivariable reliability model can be developed as a function of either *P* or *T*, respectively.
3. <u>Both *P* and *T* are insignificant</u>. The result in this case consists of one model that is independent of *P* and *T*.

Figure 2-2. Histogram for Power Rating of Hydropwer Generators

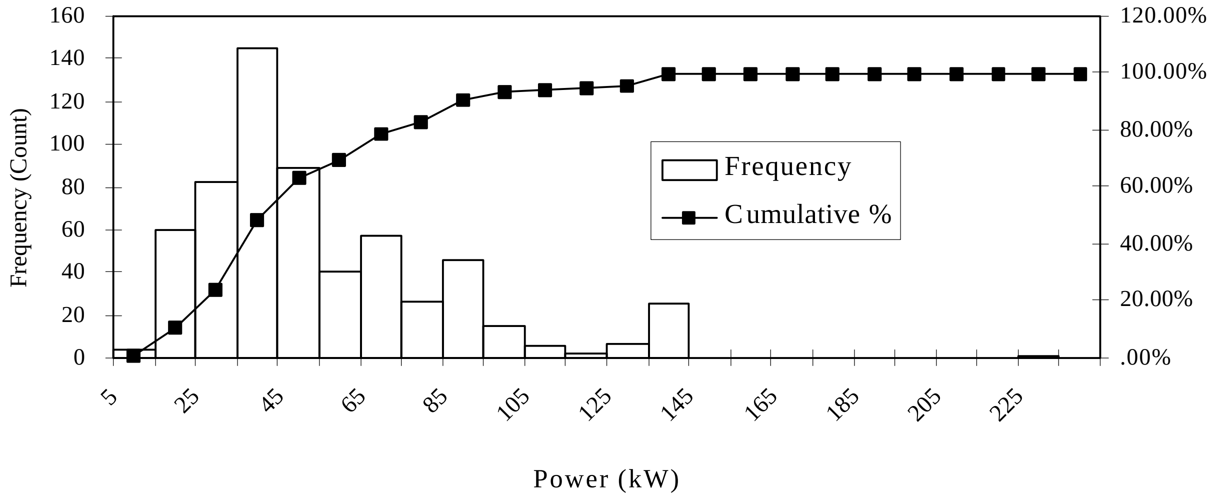



Table 2-1. Definition of Groups of Hydropower Generators

| Group Designation | Plant on Line (*POL* or *T*) in Years | Power Capacity (*P*) in MW | Number *n* of Equipment (Number *r* of Failures) | Fraction of Surviving Equipment [(*n*-*r*)/*n*] |
|---|---|---|---|---|
| 4.1 | 1930 < *T* ≤ 1950 | Low Power (*P* ≤ 30) | 63 (38) | 0.396 |
| 4.2 | 1930 < *T* ≤ 1950 | Medium Power (30<*P*≤50) | 43 (37) | 0.140 |
| 4.3 | 1930 < *T* ≤ 1950 | High Power (*P* > 50) | 17 (11) | 0.353 |
| 3.1 | 1950 < *T* ≤ 1960 | Low Power (*P* ≤ 30) | 84 (17) | 0.798 |
| 3.2 | 1950 < *T* ≤ 1960 | Medium Power (30<*P*≤50) | 62 (17) | 0.726 |
| 3.3 | 1950 < *T* ≤ 1960 | High Power (*P* > 50) | 86 (29) | 0.663 |
| 2.1 | 1960 < *T* ≤ 1970 | Low Power (*P* ≤ 30) | 32 (1) | 0.969 |
| 2.2 | 1960 < *T* ≤ 1970 | Medium Power (30<*P*≤50) | 50 (9) | 0.820 |
| 2.3 | 1960 < *T* ≤ 1970 | High Power (*P* > 50) | 65 (15) | 0.769 |
| 1.1 | 1970 < *T* ≤ 1993 | Low Power (*P* ≤ 30) | 85 (0) | 1.000 |
| 1.2 | 1970 < *T* ≤ 1993 | Medium Power (30<*P*≤50) | 74 (2) | 0.973 |
| 1.3 | 1970 < *T* ≤ 1993 | High Power (*P* > 50) | 124 (4) | 0.968 |

# 3. METHODOLOGY

## 3.1. Reliability Models

Generic reliability and hazard functions need to be developed for an equipment type using corresponding life data. A nonparametric approach based on polynomial cumulative hazard rate function was selected in this study as the basis behind the developed methods. The cumulative distribution function (CDF), $F(t)$, for time to failure (TTF), $t$, and the reliability function, $R(t)$, can be expressed in terms of the cumulative hazard rate function (CHRF), $H(t)$, as follows:

$$F(t) = 1 - \exp(-H(t)) \tag{3-1}$$

and

$$R(t) = \exp(-H(t)) \tag{3-2}$$

The cumulative hazard rate function (CHRF) and its estimates must satisfy the following conditions:

$$H(0) = 0 \tag{3-3a}$$

$$\lim_{t \to \infty}\left(H(t)\right) = \infty \tag{3-3b}$$

$$H(t) \text{ is nondecreasing, that is, } \frac{dH(t)}{dt} \geq 0 \tag{3-3c}$$

The Weibull distribution is a candidate model that can be used to fit the data, but other models can also be used. For example, a series-expansion model or a polynomial model for CHRF can be used to achieve a better fit. The resulting reliability and hazard functions can be viewed as marginal functions that do not account for the particular condition of a piece of equipment, but they provide average or generic results for a group or a stratum.

An initial examination of life data of hydropower generators revealed that a polynomial cumulative hazard rate function needs to be examined in detail because it provided a better fit than the Weibull and exponential models. The polynomial cumulative hazard rate function is given by

$$H(t) = a_0 + a_1 t + a_2 t^2 + \ldots \tag{3-4}$$

The polynomial CHRF is described in many reliability monographs and studies such as Nelson (1982), Lawless (1982), and Bain and Engelhardt (1991). An earlier publication about this model is by Krane (1963). The power of the polynomial is usually set not greater than 2.

## 3.2. Statistical Analysis of Life Data

A preliminary data analysis showed that available life data on generators (as shown in Appendix A) are censored. If the censoring is not taken into account in an analysis, a significant underestimation of an equipment reliability might result. The statistical estimation of the cumulative distribution function (CDF) of time to failure (TTF) for censored data should be based on the Kaplan-Meier (called product-limit) estimation procedure (Leemis 1995, Nelson 1982, and Lawless 1982). The resulting CDF function can be used to compute the reliability (or survivorship) function of the equipment.

The Kaplan-Meier estimation procedure is based on a sample of *n* items, among which only *k* values are distinct failure times with *r* observed failures. Therefore, there are *r* minus *k* (i.e., *r*-*k*) repeated (non-distinct) failure times. The failure times are denoted according to their ordered values (order statistics) as $t_1 \le t_2 \le \ldots \le t_k$, and $t_0$ is identically equal to zero, i.e., $t_0 = 0$. The number of items under observation (censoring) just before $t_j$ is denoted by $n_j$. The number of failures at $t_j$ is denoted $d_j$. Then, the following relationship holds:

$$n_{j+1} = n_j - d_j \qquad (3\text{-}5)$$

Under these conditions, the product-limit estimate of the reliability function ($S_n$) is given by

$$S_n(t) = \begin{cases} 1 & 0 \le t < t_1 \\ \prod_{j=1}^{i} \left( \frac{n_j - d_j}{n_j} \right) & t_i \le t < t_{i+1} \text{ and } i = 1,2,\ldots,k-1 \\ 0 & t_k \le t < \infty \end{cases} \qquad (3\text{-}6)$$

where *t* = time to failure of an equipment. For cases where $d_j = 1$, i.e., one failure at time $t_j$, Eq. 3-6 becomes

$$S_n(t) = \begin{cases} 1 & 0 \le t < t_1 \\ \prod_{j=1}^{i} \left( \frac{n_j - 1}{n_j} \right) & t_i \le t < t_{i+1} \text{ and } i = 1,2,\ldots,k+1 \\ 0 & t_k \le t < \infty \end{cases} \qquad (3\text{-}7)$$

For uncensored (complete) samples with $d_j = 1$, the product-limit estimate coincides with the commonly-used empirical $S_n(t)$ which is defined as follows:

$$S_n(t) = \begin{cases} 1 & 0 \le t < t_1 \\ \dfrac{n-i}{n} & t_i \le t < t_{i+1} \text{ and } i = 1,2,\ldots,n-1 \\ 0 & t_n \le t < \infty \end{cases} \quad (3\text{-}8)$$

Therefore, an estimate of the CDF of TTF can be computed as

$$F_n(t) = 1 - S_n(t)$$

where $F_n(t)$ = estimated CDF of time to failure (TTF). Tables 3-1a, 3-1b, 3-1c, and 3-1d shows the resulting $S_n(t)$ function based on Eq. 3-6 for groups 4, 3, 2, and 1, respectively. Also, the tables show the average power capacity and *POL* date for all generators (failed and non-failed) in the respective groups.

Table 3-1a. Reliability Function Estimate ($S_n(t)$) for Group 4

| Group | Years to Failure | Average Power (kW) | Average POL (Year) | Reliability Value |
|---|---|---|---|---|
| 4.1 | 0 | 21387.31746 | 12/4/42 | 1 |
| 4.1 | 26 | 21387.31746 | 12/4/42 | 0.984126984 |
| 4.1 | 27 | 21387.31746 | 12/4/42 | 0.952380952 |
| 4.1 | 28 | 21387.31746 | 12/4/42 | 0.888888889 |
| 4.1 | 29 | 21387.31746 | 12/4/42 | 0.873015873 |
| 4.1 | 30 | 21387.31746 | 12/4/42 | 0.857142857 |
| 4.1 | 31 | 21387.31746 | 12/4/42 | 0.793650794 |
| 4.1 | 32 | 21387.31746 | 12/4/42 | 0.714285714 |
| 4.1 | 33 | 21387.31746 | 12/4/42 | 0.698412698 |
| 4.1 | 34 | 21387.31746 | 12/4/42 | 0.682539683 |
| 4.1 | 35 | 21387.31746 | 12/4/42 | 0.634920635 |
| 4.1 | 36 | 21387.31746 | 12/4/42 | 0.555555556 |
| 4.1 | 37 | 21387.31746 | 12/4/42 | 0.53968254 |
| 4.1 | 38 | 21387.31746 | 12/4/42 | 0.523809524 |
| 4.1 | 39 | 21387.31746 | 12/4/42 | 0.507936508 |
| 4.1 | 40 | 21387.31746 | 12/4/42 | 0.492063492 |
| 4.1 | 42 | 21387.31746 | 12/4/42 | 0.46031746 |
| 4.1 | 43 | 21387.31746 | 12/4/42 | 0.424908425 |
| 4.1 | 50 | 21387.31746 | 12/4/42 | 0.392223161 |
| 4.1 | 56 | 21387.31746 | 12/4/42 | 0.35656651 |

Table 3-1a. (Cont.) Reliability Function Estimate ($S_n(t)$) for Group 4

| Group | Years to Failure | Average Power (kW) | Average POL (Year) | Reliability Value |
|---|---|---|---|---|
| 4.2 | 0 | 36912.90698 | 1/27/45 | 1 |
| 4.2 | 12 | 36912.90698 | 1/27/45 | 0.976744186 |
| 4.2 | 13 | 36912.90698 | 1/27/45 | 0.930232558 |
| 4.2 | 14 | 36912.90698 | 1/27/45 | 0.906976744 |
| 4.2 | 15 | 36912.90698 | 1/27/45 | 0.88372093 |
| 4.2 | 19 | 36912.90698 | 1/27/45 | 0.860465116 |
| 4.2 | 20 | 36912.90698 | 1/27/45 | 0.813953488 |
| 4.2 | 21 | 36912.90698 | 1/27/45 | 0.790697674 |
| 4.2 | 22 | 36912.90698 | 1/27/45 | 0.744186047 |
| 4.2 | 24 | 36912.90698 | 1/27/45 | 0.720930233 |
| 4.2 | 25 | 36912.90698 | 1/27/45 | 0.651162791 |
| 4.2 | 26 | 36912.90698 | 1/27/45 | 0.627906977 |
| 4.2 | 27 | 36912.90698 | 1/27/45 | 0.604651163 |
| 4.2 | 28 | 36912.90698 | 1/27/45 | 0.581395349 |
| 4.2 | 29 | 36912.90698 | 1/27/45 | 0.534883721 |
| 4.2 | 30 | 36912.90698 | 1/27/45 | 0.511627907 |
| 4.2 | 33 | 36912.90698 | 1/27/45 | 0.488372093 |
| 4.2 | 34 | 36912.90698 | 1/27/45 | 0.418604651 |
| 4.2 | 35 | 36912.90698 | 1/27/45 | 0.372093023 |
| 4.2 | 37 | 36912.90698 | 1/27/45 | 0.348837209 |
| 4.2 | 40 | 36912.90698 | 1/27/45 | 0.325581395 |
| 4.2 | 42 | 36912.90698 | 1/27/45 | 0.279069767 |
| 4.2 | 43 | 36912.90698 | 1/27/45 | 0.255813953 |
| 4.2 | 44 | 36912.90698 | 1/27/45 | 0.223837209 |
| 4.2 | 48 | 36912.90698 | 1/27/45 | 0.149224806 |
| 4.2 | 49 | 36912.90698 | 1/27/45 | 0.074612403 |
| 43 | 0 | 57917.64706 | 1/16/42 | 1 |
| 4.3 | 6 | 57917.64706 | 1/16/42 | 0.9375 |
| 4.3 | 14 | 57917.64706 | 1/16/42 | 0.87890625 |
| 4.3 | 17 | 57917.64706 | 1/16/42 | 0.823974609 |
| 4.3 | 24 | 57917.64706 | 1/16/42 | 0.769042969 |
| 4.3 | 26 | 57917.64706 | 1/16/42 | 0.659179688 |
| 4.3 | 31 | 57917.64706 | 1/16/42 | 0.612095424 |
| 4.3 | 43 | 57917.64706 | 1/16/42 | 0.568374322 |
| 4.3 | 47 | 57917.64706 | 1/16/42 | 0.527776157 |
| 4.3 | 51 | 57917.64706 | 1/16/42 | 0.49007786 |
| 4.3 | 54 | 57917.64706 | 1/16/42 | 0.452379563 |

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Table 3-1b. Reliability Function Estimate ($S_n(t)$) for Group 3

| Group | Years to Failure | Average Power (kW) | Average POL (Year) | Reliability Value |
|---|---|---|---|---|
| 3.1 | 0 | 18334.55952 | 2/12/55 | 1 |
| 3.1 | 5 | 18334.55952 | 2/12/55 | 0.988095238 |
| 3.1 | 22 | 18334.55952 | 2/12/55 | 0.964285714 |
| 3.1 | 23 | 18334.55952 | 2/12/55 | 0.952380952 |
| 3.1 | 24 | 18334.55952 | 2/12/55 | 0.94047619 |
| 3.1 | 25 | 18334.55952 | 2/12/55 | 0.928571429 |
| 3.1 | 26 | 18334.55952 | 2/12/55 | 0.916666667 |
| 3.1 | 28 | 18334.55952 | 2/12/55 | 0.904761905 |
| 3.1 | 30 | 18334.55952 | 2/12/55 | 0.880952381 |
| 3.1 | 32 | 18334.55952 | 2/12/55 | 0.869047619 |
| 3.1 | 34 | 18334.55952 | 2/12/55 | 0.856807512 |
| 3.1 | 38 | 18334.55952 | 2/12/55 | 0.812868665 |
| 3.1 | 39 | 18334.55952 | 2/12/55 | 0.786647095 |
| 3.1 | 40 | 18334.55952 | 2/12/55 | 0.757512018 |
| 3.1 | 41 | 18334.55952 | 2/12/55 | 0.707011216 |
| 3.2 | 0 | 40327.79032 | 7/3/54 | 1 |
| 3.2 | 14 | 40327.79032 | 7/3/54 | 0.983870968 |
| 3.2 | 19 | 40327.79032 | 7/3/54 | 0.967741935 |
| 3.2 | 21 | 40327.79032 | 7/3/54 | 0.935483871 |
| 3.2 | 27 | 40327.79032 | 7/3/54 | 0.919354839 |
| 3.2 | 29 | 40327.79032 | 7/3/54 | 0.903225806 |
| 3.2 | 30 | 40327.79032 | 7/3/54 | 0.85483871 |
| 3.2 | 31 | 40327.79032 | 7/3/54 | 0.790322581 |
| 3.2 | 33 | 40327.79032 | 7/3/54 | 0.758064516 |
| 3.2 | 34 | 40327.79032 | 7/3/54 | 0.741584853 |
| 3.2 | 36 | 40327.79032 | 7/3/54 | 0.723928071 |
| 3.3 | 0 | 68929.06977 | 3/7/57 | 1 |
| 3.3 | 16 | 68929.06977 | 3/7/57 | 0.976744186 |
| 3.3 | 18 | 68929.06977 | 3/7/57 | 0.965116279 |
| 3.3 | 22 | 68929.06977 | 3/7/57 | 0.941860465 |
| 3.3 | 25 | 68929.06977 | 3/7/57 | 0.930232558 |
| 3.3 | 27 | 68929.06977 | 3/7/57 | 0.88372093 |
| 3.3 | 28 | 68929.06977 | 3/7/57 | 0.848837209 |
| 3.3 | 29 | 68929.06977 | 3/7/57 | 0.802325581 |
| 3.3 | 30 | 68929.06977 | 3/7/57 | 0.744186047 |
| 3.3 | 31 | 68929.06977 | 3/7/57 | 0.686046512 |
| 3.3 | 32 | 68929.06977 | 3/7/57 | 0.674418605 |
| 3.3 | 34 | 68929.06977 | 3/7/57 | 0.661693725 |

Table 3-1c. Reliability Function Estimate ($S_n(t)$) for Group 2

| Group | Years to Failure | Average Power (kW) | Average POL (Year) | Reliability Value |
|---|---|---|---|---|
| 2.1 | 0 | 19890.375 | 8/16/66 | 1 |
| 2.1 | 14 | 19890.375 | 8/16/66 | 0.96875 |
| 2.2 | 0 | 38131.6 | 7/5/65 | 1 |
| 2.2 | 11 | 38131.6 | 7/5/65 | 0.98 |
| 2.2 | 14 | 38131.6 | 7/5/65 | 0.92 |
| 2.2 | 19 | 38131.6 | 7/5/65 | 0.88 |
| 2.2 | 21 | 38131.6 | 7/5/65 | 0.82 |
| 2.3 | 0 | 89453.24615 | 9/19/66 | 1 |
| 2.3 | 13 | 89453.24615 | 9/19/66 | 0.969230769 |
| 2.3 | 14 | 89453.24615 | 9/19/66 | 0.953846154 |
| 2.3 | 15 | 89453.24615 | 9/19/66 | 0.938461538 |
| 2.3 | 17 | 89453.24615 | 9/19/66 | 0.907692308 |
| 2.3 | 19 | 89453.24615 | 9/19/66 | 0.876923077 |
| 2.3 | 21 | 89453.24615 | 9/19/66 | 0.815384615 |
| 2.3 | 22 | 89453.24615 | 9/19/66 | 0.784615385 |
| 2.3 | 23 | 89453.24615 | 9/19/66 | 0.768269231 |

Table 3-1d. Reliability Function Estimate ($S_n(t)$) for Group 1

| Group | Years to Failure | Average Power (kW) | Average POL (Year) | Reliability Value |
|---|---|---|---|---|
| 1.1 | 0 | 21362.22353 | 11/10/79 | 1 |
| 1.2 | 0 | 39728.21622 | 2/18/79 | 1 |
| 1.2 | 8 | 39728.21622 | 2/18/79 | 0.984615385 |
| 1.2 | 42 | 39728.21622 | 2/18/79 | 0 |
| 1.3 | 0 | 107545.1613 | 1/27/81 | 1 |
| 1.3 | 6 | 107545.1613 | 1/27/81 | 0.965909091 |
| 1.3 | 7 | 107545.1613 | 1/27/81 | 0.953199761 |

## 3.3. Model Fitting to Data

Three types of models are described herein that correspond to cases as discussed in Section 2.2.2:

1. Individual univariate models for each of the 12 groups, $R(t)$
2. Bivariate models using average plant-on-line dates, $R(t,P)$
3. Trivariate model using average power and average plant-on-line dates, $R(t,P,T)$

The resulting models for the above three cases are valid only within the corresponding ranges of the failure data. For early life prediction and late life (extrapolation) prediction, models and discussion are provided at the end of this section.

### 3.3.1. Individual Univariate Models for Each of 12 Groups of Plant-on-Line and Power Combinations

One of the 12 groups of plant-on-line and power combinations (group 1.1) has no failures. This group without failures is treated using confidence interval estimation for an exponential distribution as discussed at the end of this section. For each of remaining 11 groups as defined in Tables 2-1 and 3-1, the following second-order polynomial exponential reliability function was fitted to the respective reliability ($S_n(t)$) results. Therefore using Eqs. 3-2 and 3-4, the fitted reliability function ($R(t)$) to the data ($S_n(t)$) can be expressed as

$$R(t) = \exp(-(a_0 + a_1 t + a_2 t^2)) \qquad (3\text{-}9)$$

where $t$ is TTF (in years). The least squares estimates of the model parameters were obtained using Quasi-Newton and Simplex minimization methods (Wilkinson et al 1992). Initial estimates of the model parameters were obtained using loglinear regression estimation. The loglinear transformation makes Eq. 3-9 as follows:

$$-\ln(R(t)) = a_0 + a_1 t + a_2 t^2 \qquad (3\text{-}10)$$

Therefore, linear regression analysis can be used to obtain the model parameters based using Eq. 3-10. Then, these model parameters are used as starting (initial) values in least squares minimization methods such as Quasi-Newton and Simplex minimization methods (Wilkinson et al 1992) to obtain better estimates of model parameters. The model parameters and adjusted squared multiple correlation coefficient $R_c^2$ (or multiple $R_c$ for linear first-order cases) for each groups are given in Tables 3-2a, 3-2b, and 3-2c. For group 4.1 (Table 3-2a), two analyses were performed using 19 distinct failures and 17 distinct failures by excluding the last two failures at times 50 and 56 years. These two failures were excluded since equipment replacement was performed for upgrading purposes. They might have been premature replacements in terms of remaining lives. However, they might have been needed for other operational considerations.

For group 1.1 with no failures, an exponential distribution for time to failure based on a homogeneous Poisson Process is used (Nelson 1982). The following upper confidence limit on the hazard rate $a_1$ as defined in Eq. 3-9 with $a_0$ = 0 and $a_2$ = 0:

$$a_{1u} = \frac{c_{a}^{2}(2)}{2T_s} \qquad (3\text{-}11)$$

where $a_{1u}$ = upper confidence limit on the hazard rate $a_1$; $c_{a}^{2}(2)$ = lower percentile of the chi-square distribution at α level with 2 degrees of freedom; and $T_s$ = total censoring time (i.e., time in service) given by

$$T_s = \sum_{i=1}^{n} t_{si} \qquad (3\text{-}12)$$

where $t_{si}$ = censoring time for the $i$th equipment for $i$ -= 1, 2, …, $n$. Using $a$ = 0.5 for group 1.1 where $T_s$ = 1134 years, $n$ = 85, and $c_{a}^{2}(2)$ = 1.3863, $a_{1u}$ was calculated as 0.00061124 years$^{-1}$.

The resulting $a_{1u}$ for group 1.1 is reasonable in comparison with other groups such as group 2.1. Table 3-3 shows the recommended models for each group. The recommended models were selected from the results in Tables 3-2a, 3-2b and 3-2c, and Eq. 3-11. Figures 3-1 to 3-12 show the fitted and observed values of reliability functions for the 12 groups. Figure 3-13 shows the reliability curves ($S_n(t)$) for the 12 groups.

Table 3-2a. Model Parameters Using Loglinear (Second-order Polynomial) Regression for $R(t)$

| Group | Number of Distinct Failures ($k$) | $a_0$ | $a_1$ (year$^{-1}$) | $a_2$ (year$^{-2}$) | Adjusted $R_c^2$ |
|---|---|---|---|---|---|
| 4.1 | 19 | -2.55657 | 0.125233 | -0.00109 | 0.98473 |
| 4.2 | 25 | 0.268153 | -0.03148 | 0.00142 | 0.95772 |
| 4.3 | 10 | -0.05507 | 0.015988 | -1.5E-05 | 0.96222 |
| 3.1 | 14 | 0.044801 | -0.00752 | 0.000334 | 0.95597 |
| 3.2 | 10 | 0.280355 | -0.03058 | 0.000899 | 0.91950 |
| 3.3 | 11 | 0.641829 | -0.06761 | 0.001838 | 0.93241 |
| 2.1 | 2 | na | na | na | na |
| 2.2 | 5 | -0.00038 | -0.00404 | 0.00062 | 0.93005 |
| 2.3 | 9 | 0.000906 | -0.01012 | 0.000939 | 0.99256 |
| 1.1 | 0 | na | na | na | na |
| 1.2 | 2 | na | na | na | na |
| 1.3 | 3 | 0 | -0.00062 | 0.001066 | 1.00000 |

na = not applicable

Table 3-2b. Model Parameters Using Nonlinear (Second-order Polynomial) Regression for $R(t)$

| Group | Number of Distinct Failures ($k$) | $a_0$ | $a_1$ (year$^{-1}$) | $a_2$ (year$^{-2}$) | Adjusted $R_c^2$ |
|---|---|---|---|---|---|
| 4.1 | 19 | -2.299 | 0.1113 | -0.00091 | 0.98379 |
| 4.1 | 17 | -1.71776 | 0.07177 | -0.00028 | 0.98233 |
| 4.2 | 25 | 0.02563 | -0.01068 | 0.001028 | 0.99095 |
| 4.3 | 10 | -0.0472 | 0.015172 | -1.3E-05 | 0.96907 |
| 3.1 | 14 | 0.04129 | -0.00708 | 0.000323 | 0.96884 |
| 3.2 | 10 | 0.27943 | -0.03042 | 0.000895 | 0.93594 |
| 3.3 | 11 | 0.71266 | -0.0738 | 0.001965 | 0.95459 |
| 2.1 | 2 | na | na | na | na |
| 2.2 | 5 | -0.00049 | -0.004 | 0.00062 | 0.96568 |
| 2.3 | 9 | 0.000716 | -0.00995 | 0.000931 | 0.99464 |
| 1.1 | 0 | na | na | na | na |
| 1.2 | 2 | na | na | na | na |
| 1.3 | 3 | na | na | na | na |

na = not applicable

Table 3-2c. Model Parameters Using Loglinear (First-order Polynomial) Regression for $R(t)$

| Group | Number of | $a_0$ | $a_1$ (year$^{-1}$) | $a_2$ (year$^{-2}$) | $R_c$ Value |
|---|---|---|---|---|---|

| | Distinct Failures (*k*) | | | | |
|---|---|---|---|---|---|
| 4.1 | 17 or 19 | na | na | na | na |
| 4.2 | 25 | 0 | 0.028412 | 0 | 0.81365 |
| 4.3 | 10 | 0 | 0.013923 | 0 | 0.98168 |
| 3.1 | 14 | na | na | na | na |
| 3.2 | 10 | na | na | na | na |
| 3.3 | 11 | na | na | na | na |
| 2.1 | 2 | 0 | 0.002268 | 0 | 1.00000 |
| 2.2 | 5 | na | na | na | na |
| 2.3 | 9 | na | na | na | na |
| 1.1 | 0 | 1 | 0 | 0 | 1.00000 |
| 1.2 | 2 | 0 | 0.001938 | 0 | 1.00000 |
| 1.3 | 3 | na | na | na | na |

na = not applicable

Table 3-3. Recommended Model Parameters Using Regression for *R*(*t*)

| Group | Model Type | Number of Distinct Failures (*k*) | $a_0$ | $a_1$ (year$^{-1}$) | $a_2$ (year$^{-2}$) | $R_c$ Value or Adjusted $R_c^2$ |
|---|---|---|---|---|---|---|
| 4.1 | Nonlinear (2nd-order) | 17 | -1.71776 | 0.1113 | -0.00091 | 0.98379 |
| 4.2 | Nonlinear (2nd-order) | 25 | 0.02563 | -0.01068 | 0.001028 | 0.99095 |
| 4.3 | Nonlinear (2nd-order) | 10 | -0.0472 | 0.015172 | -1.3E-05 | 0.96907 |
| 3.1 | Nonlinear (2nd-order) | 14 | 0.04129 | -0.00708 | 0.000323 | 0.96884 |
| 3.2 | Nonlinear (2nd-order) | 10 | 0.27943 | -0.03042 | 0.000895 | 0.93594 |
| 3.3 | Nonlinear (2nd-order) | 11 | 0.71266 | -0.0738 | 0.001965 | 0.95459 |
| 2.1 | Loglinear (1st-order) | 2 | 0 | 0.002268 | 0 | 1.00000 |
| 2.2 | Nonlinear (2nd-order) | 5 | -0.00049 | -0.004 | 0.00062 | 0.96568 |
| 2.3 | Nonlinear (2nd-order) | 9 | 0.000716 | -0.00995 | 0.000931 | 0.99464 |
| 1.1 | Lower limit using the exponential distribution | 0 | 0 | 0.00061124 | 0 | na |
| 1.2 | Loglinear (1st-order) | 2 | 0 | 0.001938 | 0 | 1.00000 |
| 1.3 | Loglinear (2nd-order) | 3 | 0 | -0.00062 | 0.001066 | 1.00000 |

na = not applicable

Figure 3-1. Reliability Function for Low Power Generators for POL < 1951 (Group 4.1)

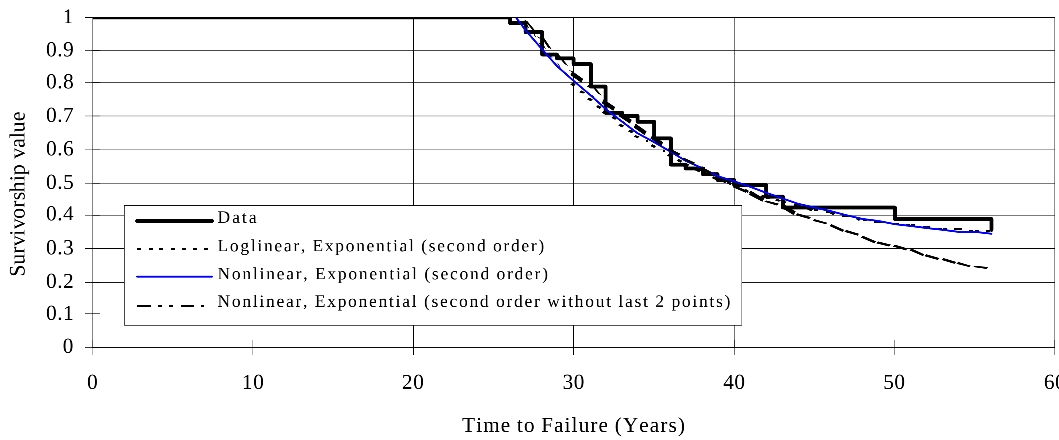



Figure 3-2. Reliability Function for Medium Power Generators for POL < 1951 (Group 4.2)

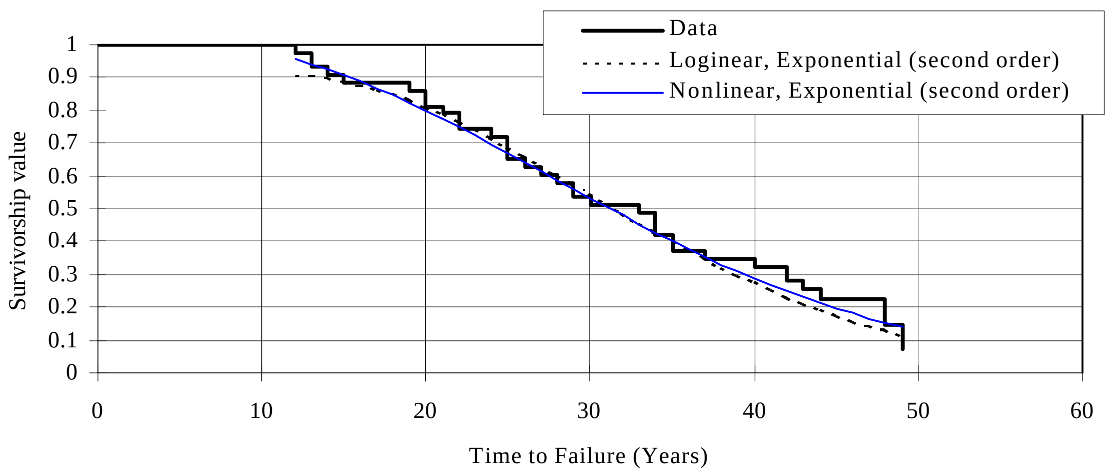



Figure 3-3. Reliability Function for High Power Generators for POL < 1951 (Group 4.3)

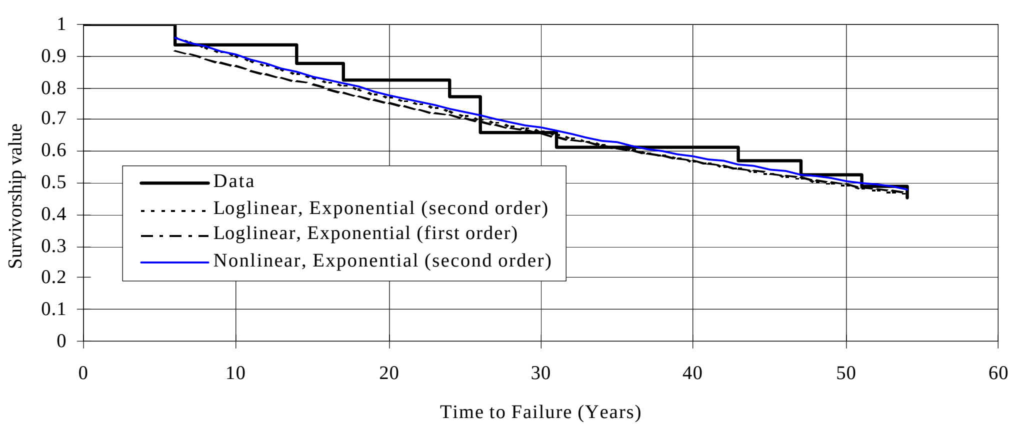


Figure 3-4. Reliability Function for Low Power Generators for 1950 < POL < 1961 (Group 3.1)

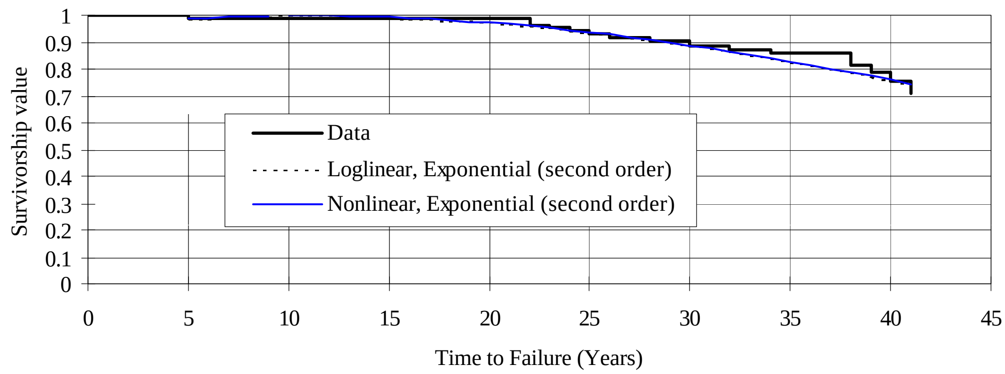



Figure 3-5. Reliability Function for Medium Power Generators for 1950 < POL < 1961 (Group 3.2)

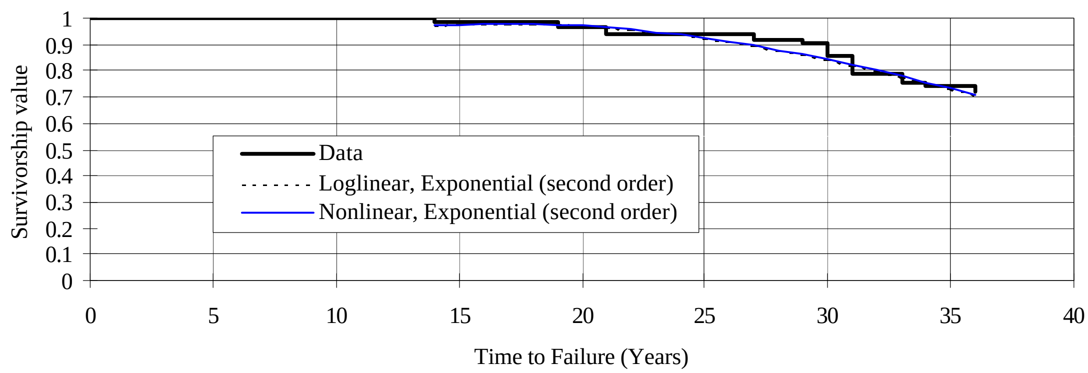



Figure 3-6. Reliability Function for High Power Generators for 1950 < POL < 1961 (Group 3.3)

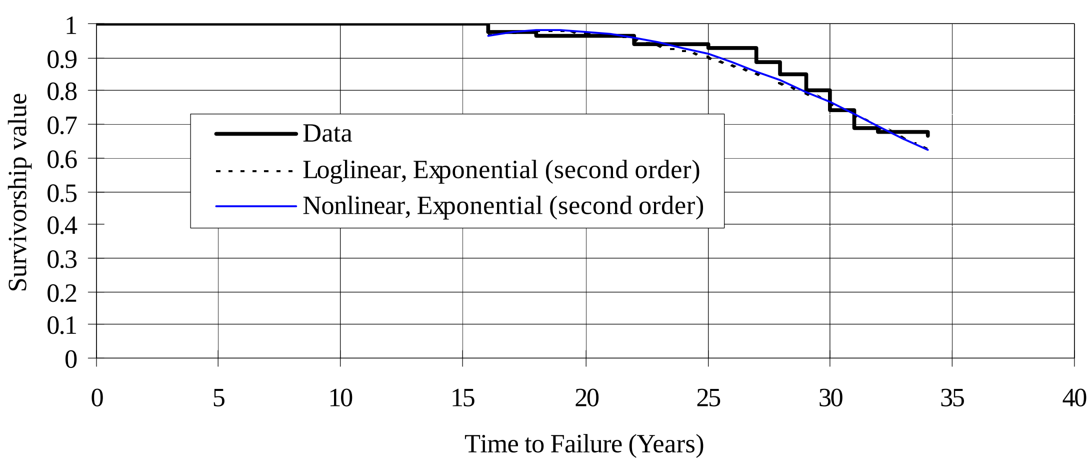


Figure 3-7. Reliability Function for Low Power Generators for 1960 < POL < 1971 (Group 2.1)

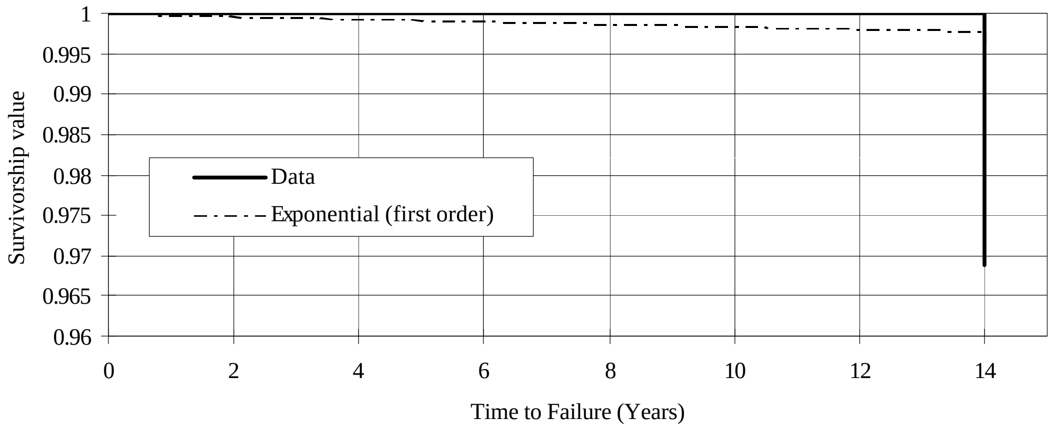



Figure 3-8. Reliability Function for Medium Power Generators for 1960 < POL < 1971 (Group 2.2)

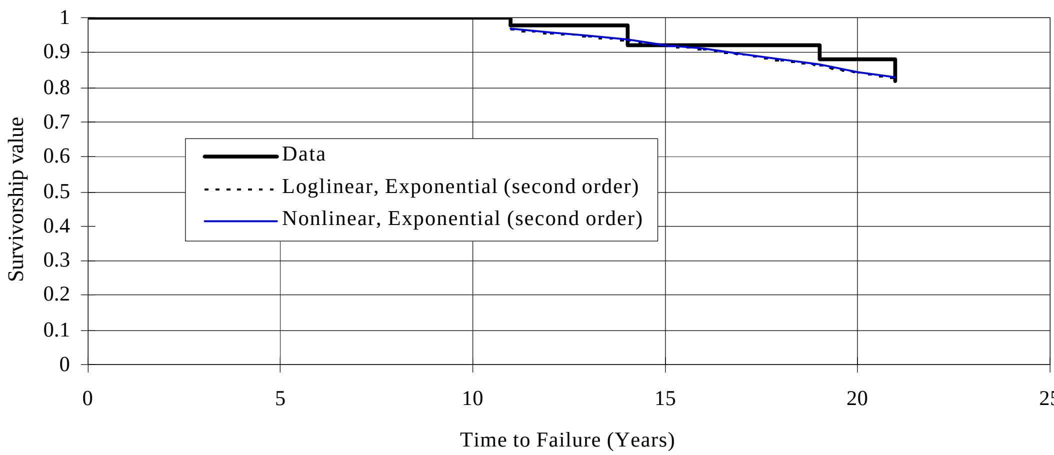



Figure 3-9. Reliability Function for High Power Generators for 1960 < POL < 1971 (Group 2.3)

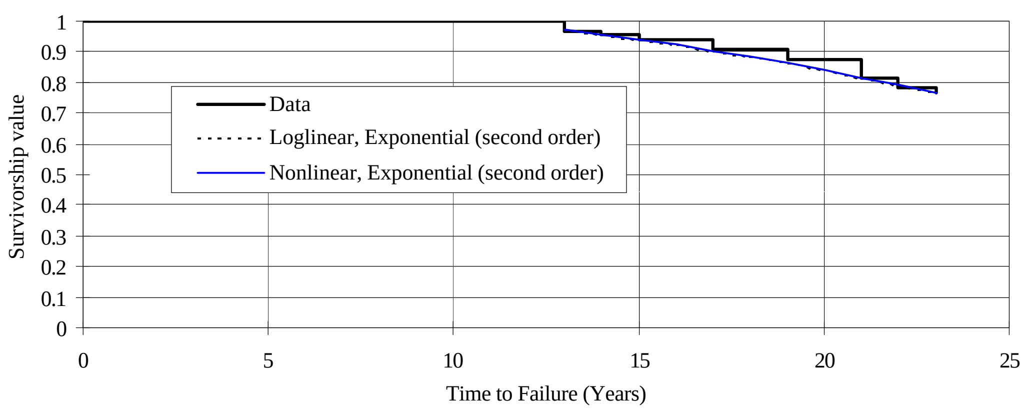


Figure 3-10. Reliability Function for Low Power Generators for POL > 1970 (Group 1.1)

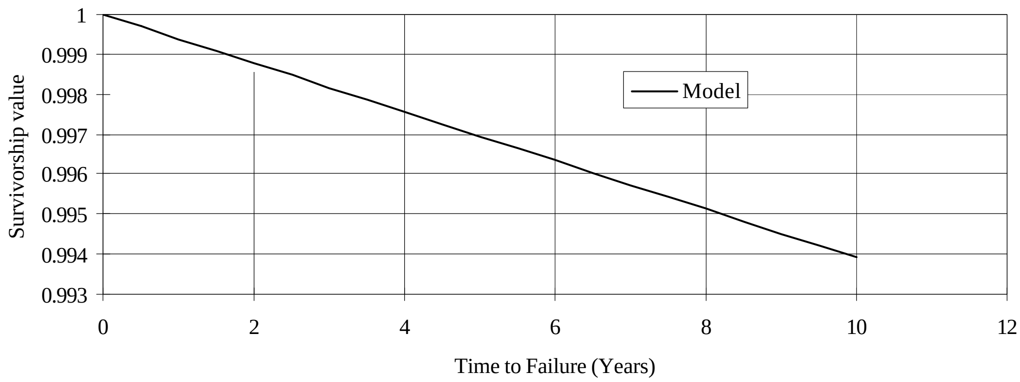



Figure 3-11. Reliability Function for Medium Power Generators for POL > 1970 (Group 1.2)

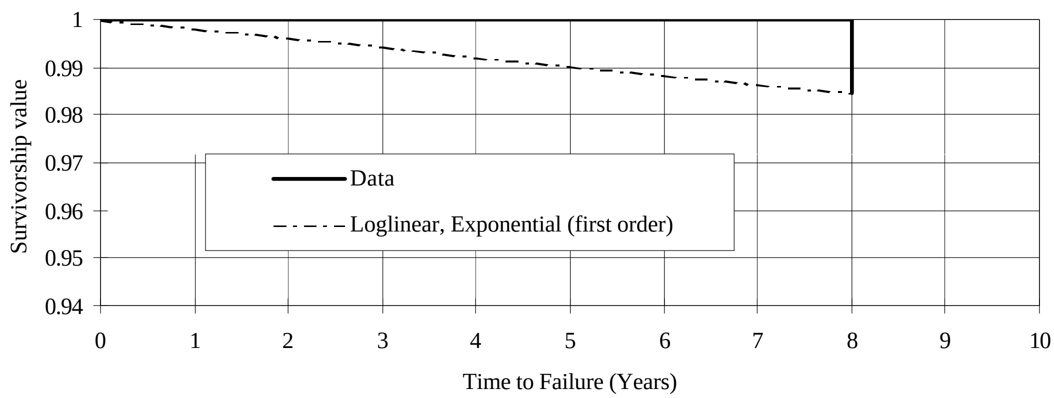



Figure 3-12. Reliability Function for High Power Generators for POL > 1970 (Group 1.3)

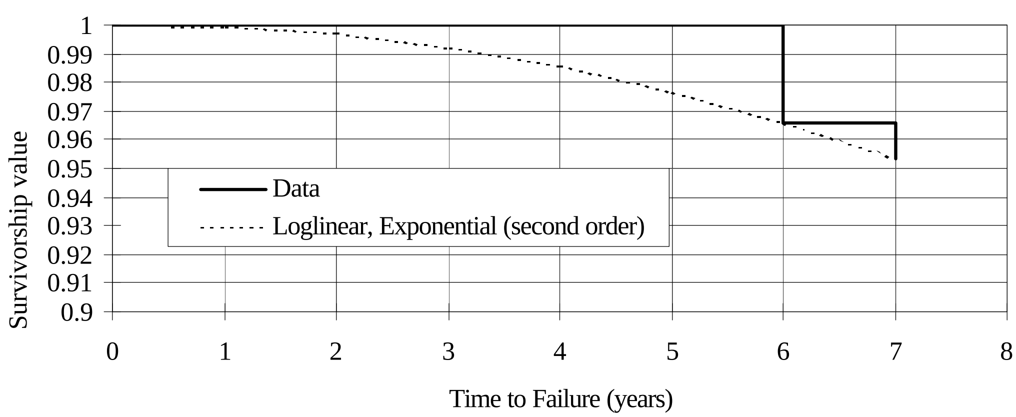
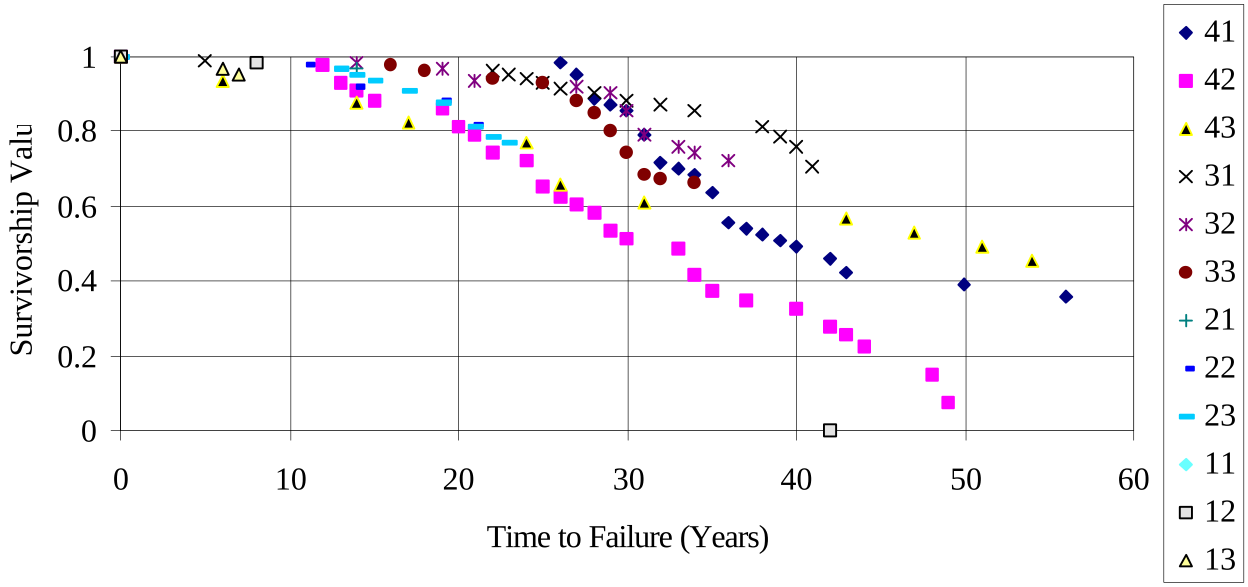


Figure 3-13. Reliability Functions for 12 Groups of Generators




## 3.3.2. Bivariate Models Using Average Plant-on-Line Dates

To study the significance of the power capacity, the following model was fitted for each of *POL* groups using respective average power (*P* in MW) values as shown in Table 3-1:

$$R(t,P) = \exp(-(a_0 + a_1 t + a_2 t^2 + b_1 P + b_2 tP)) \qquad (3\text{-}13)$$

where $b_1$ and $b_2$ are power-related model parameters using the 19 data values for Group 4.1. The significance of each factor included in Eq. 3-13 was studied using stepwise regression (Krane 1963, and Mendenhall and Sincich 1988). The estimated model parameters and adjusted $R_C^2$ for each groups are given in Table 3-4. Model parameters with zero estimated values are parameters that were determined to be not significant according to stepwise regression. The models in Table 3-4 are less accurate than the models in Table 3-3 based on their adjusted $R_C^2$. Therefore, the models in Table 3-3 are recommended.

Table 3-4. Bivariate Models Using Average Plant-on-Line Dates, *R*(*t*, *P*)

| Group | $a_0$ | $a_1$ (year$^{-1}$) | $a_2$ (year$^{-2}$) | $b_1$ (MW$^{-1}$) | $b_2$ (year$^{-1}$ MW$^{-1}$) | Adjusted $R_C^2$ |
|---|---|---|---|---|---|---|
| 4 | 0.02244285 | 0 | 0.000484044 | 0 | 0 | 0.561 |
| 3 | 0.09401995 | -0.01428786 | 0.000431951 | -0.002186 | 0.000177 | 0.878 |
| 2 | 0.00107225 | -0.00872835 | 0.000865890 | 0 | 0 | 0.975 |
| 1 | -0.00067435 | 0 | 0 | 0 | 0.00059541 | 0.981 |

### 3.3.3. Trivariate Model Using Average Power and Average Plant-on-line Dates

Using stepwise regression the following model was fitted to the entire data using average power values and average plant-on-line year in the form of two digits (i.e., the year 1963 has a *T* value of 63):

$$R(t,P,T) = \exp(-(a_0 + a_1 t + a_2 t^2 + b_1 P + b_2 T + b_3 PT + b_4 Pt + b_5 PTt)) \qquad (3\text{-}14)$$

where *T* is the average *POL* date (in years counting from 1900) for each average power capacity group (*P* in MW) for each power capacity group. The following factors were determined to be significant: *t*, $t^2$, and the interaction *Pt*. Thus, the following model was obtained using the 19 data values for Group 4.1:

$$R(t,P) = \exp(-(0.030706679 - 0.012733166t + 0.000593775t^2 + 0.000051563Pt)) \quad (3\text{-}15)$$

The adjusted $R_c^2$ value for this model is 0.765. Again, the model according to Eq. 3-15 is less accurate than the models in Table 3-3 based on their adjusted $R_c^2$. Therefore, the models in Table 3-3 are recommended.

### 3.3.4. Early Life Prediction

The reliability function for early life prediction (i.e., up to the time to the first failure) can be developed using one of the following two methods:

1. Nonparametric point estimate using the exponential distribution, or
2. Nonparametric confidence estimation.

The two methods are described and used in this section.

1. <u>Nonparametric Point Estimate Using the Exponential Distribution</u>

This method is based on the exponential distribution with a parameter that is computed to get a reliability-function value equal to the reliability-function value at first failure (Barlow and Proschan 1975). Therefore, the parameter of the exponential distribution ($a_1$) is estimated as

$$a_1 = \frac{-\ln(S_n(t_1))}{t_1} \qquad (3\text{-}16)$$

where $t_1$ = time to the first failure, and $S_n(t_1)$ = the reliability-function value at first failure. Therefore, the reliability function is given by

$$R(t) = \exp(-a_1 t) \qquad (3\text{-}17)$$

Substituting Eq. 3-16 into Eq. 3-17 produces

$$R(t) = \exp\left[\frac{\ln(S_n(t_1))}{t_1} t\right] \qquad (3\text{-}18)$$

The results of using this method for the 11 groups (group 1.1 was excluded because it does not have any failures) are shown in Table 3-5.

Table 3-5. Exponential Distribution for Early Life Prediction using Point Estimation

| Group | First Failure Time ($t_1$ from Table 3-1) | Reliability Function at $t_1$ (Table 3-1) | Parameter of Exponential Distribution ($a_1$ using Eq. 3-16) |
|---|---|---|---|
| 4.1 | 26 | 0.98413 | 0.00061528 |
| 4.2 | 12 | 0.97674 | 0.001961232 |
| 4.3 | 6 | 0.9375 | 0.01075642 |
| 3.1 | 5 | 0.9881 | 0.002394274 |
| 3.2 | 14 | 0.98387 | 0.001161536 |
| 3.3 | 16 | 0.976744 | 0.001470668 |
| 2.1 | 14 | 0.96875 | 0.002267764 |
| 2.2 | 11 | 0.98 | 0.00183661 |
| 2.3 | 13 | 0.96923 | 0.002404103 |
| 1.1 | na | na | na |
| 1.2 | 8 | 0.98462 | 0.001937437 |
| 1.3 | 6 | 0.96591 | 0.005780769 |

na = not applicable

2. Nonparametric Confidence Estimation

This method is based on a lower γ-confidence limit for a quantile of level *p* and the random variable $T(\gamma,p)$ as given by (Barlow and Proschan 1966)

$$P\left(\int_{T(\gamma,p)}^{\infty} dF \geq (1-p)\right) = \gamma \qquad (3\text{-}19)$$

where γ = confidence probability, *F* = cumulative distribution function of time to failure, and *p* = the quantile. The random variable $T(\gamma,p)$ is the time at which the reliability function exceeds (1-*p*) with a confidence probability γ.

A nonparametric estimate for $T(\gamma,p)$ is used herein, denoted $t(\gamma,1-p,r)$, and is given by

$$t(\gamma,1-p,r) = T_{s,r}\ \min\left(\frac{2}{\chi_{\gamma}^{2}(2r)}\ln(\frac{1}{1-p}),\frac{1}{n}\right) \qquad (3\text{-}20)$$

in which *n* = sample size, and $T_{s,r}$ = total failure-free time accumulated by all equipment in a sample of size *n* up to the *r*th failure and is given by

$$T_{s,r} = \sum_{i=1}^{r} t_i + (n-r)t_r \qquad (3\text{-}21)$$

Group 4.1 was used as an example based on its first failure where $S_n(t_1)$ = 0.984 (i.e., the value of Kaplan-Meier estimate for the first-failure time of 26 years). Using a confidence probability γ = 0.8, $t(\gamma,1-p,r)$ can be based on (1-*p*) = $S_n(t_1)$ = 0.984 as follows:

$$t(0.8, 0.984, 1) = 16.4 \text{ years} \quad (3\text{-}22)$$

For an assumed (1-$p$) = 0.99 and the same confidence probability, $t(\gamma, 1-p, r)$ is

$$t(0.8, 0.990, 1) = 10.2 \text{ years} \quad (3\text{-}23)$$

The γ-confidence limits on $t(\gamma, p, r)$ for the 11 groups using (1-$p$) = 0.990 and 0.995 are given in Table 3-6.

Table 3-6. Nonparametric Confidence Estimation for Early Life Prediction

| Group | Lower 80%-confidence Limit on $t(\gamma, S_n(t_r), r)$ in years | |
|---|---|---|
| | $S_n(t_1)$ = 0.99 | $S_n(t_1)$ = 0.995 |
| 4.1 | 10.2 | 5.1 |
| 4.2 | 3.2 | 1.6 |
| 4.3 | 0.6 | 0.3 |
| 3.1 | 2.6 | 1.3 |
| 3.2 | 5.4 | 2.7 |
| 3.3 | 8.6 | 4.3 |
| 2.1 | 2.8 | 1.4 |
| 2.2 | 3.4 | 1.7 |
| 2.3 | 5.3 | 2.6 |
| 1.1 | na | na |
| 1.2 | 3.7 | 1.8 |
| 1.3 | 4.6 | 2.3 |

na = not applicable

### 3.3.5. Late Life (Extrapolation) Prediction

A reliability prediction model of the type given in Eq. 3-1, 3-2 and 3-4 can be used beyond the upper range of time to failure data for late life prediction (i.e., extrapolation), if it meets the conditions of Eq. 3-3 up to a late-life time $t^*$. The main requirement of interest herein is

$$\frac{dH(t)}{dt} \geq 0 \qquad \text{for } t \geq t^* \quad (3\text{-}24a)$$

In terms of model in Eq. 3-9, this condition can be written as

$$a_2 \geq -\frac{a_1}{2t^*} \quad (3\text{-}24b)$$

All the recommended models as given in Table 3-3 satisfy the above condition up to $t^*$ = 50 years beyond the longest time to censoring or failure, which is quite sufficient for the application considered herein.

### 3.3.6. Effect of Generator Manufacturer on Reliability

The USACE generators were examined in terms of their manufacturers as shown in Table 3-7a. In this section, only generators produced by General Electric (GE) and Westinghouse (WH) were considered due to the availability of sufficient data for the analysis. Table 3-7b shows a breakdown of the GE and WH generators by the *POL* group designations as defined in Table 2-1. The reliability functions for each group per manufacturer were determined using the Kaplan-Meier procedure. Then, the resulting reliability functions were used to fit the following model based on loglinear regression:

$$R(t, P, T, M) = \exp(-(a_0 + a_1 t + a_2 t^2 + b_1 P + b_2 T + b_3 M)) \quad (3\text{-}25a)$$

where *M* = is a dummy variable for manufacturer that takes on values of 1 and 0 for GE and WH generators, respectively. The resulting regression model has an $R_c^2$ of 0.708 with all significant coefficients. The coefficients for the variables *T* and *M* have about the same significance. Hypothesis testing was then performed using the following null hypothesis for each group in Table 3-7b:

$$H_o: R(t,T) \text{ for GE} = R(t,T) \text{ for WH} \quad (3\text{-}25b)$$

The null hypothesis was accepted for groups 4, 2 and 1, but not for 3. Therefore, it can be concluded that the differences between the reliability values of the GE and WH generators are, in general, statistically insignificant.

Table 3-7a. Manufacturers of USACE Generators

| Manufacturer | Number of Records |
|---|---|
| Allis-Chalmers | 14 |
| Elliot | 12 |
| English Electric | 4 |
| General Electric (GE) | 201 |
| Siemans | 8 |
| Westinghouse (WH) | 118 |

Table 3-7b. Breakdown of General Electric and Westinghouse USACE Generators

| Group | *POL*, *T*, in Years | GE No. *n* of Equipment (No. *r* of Failures) | GE Fraction of Surviving Equipment [(*n*-*r*)/n] | GE Average Power Capacity in MW | WH No. *n* of Equipment (No. *r* of Failures) | WH Fraction of Surviving Equipment [(*n*-*r*)/n] | WH Average Power Capacity in MW |
|---|---|---|---|---|---|---|---|
| 4 | 1930<T≤1950 | 11 (5) | 0.545 | 51.22 | 7 (5) | 0.286 | 32.00 |
| 3 | 1950<T≤1960 | 57 (10) | 0.825 | 56.89 | 41 (15) | 0.634 | 45.67 |
| 2 | 1960<T≤1970 | 37 (12) | 0.676 | 101.02 | 30 (5) | 0.833 | 44.45 |
| 1 | 1970<T≤1995 | 96 (4) | 0.958 | 87.57 | 40 (0) | 1.000 | 61.32 |

# 3.4. Summary of Reliability and Hazard Functions

In this study, the following general reliability function $R(t)$ was used:

$$R(t) = \exp[-a_o - a_1 t - a_2 t^2] \qquad (3\text{-}26)$$

where the model parameters are defined in Table 3-3. The density $f(t)$ and hazard $h(t)$ functions are given respectively by

$$f(t) = \exp[a_1 t + 2a_2 t]R(t) \qquad (3\text{-}27)$$

$$h(t) = \frac{-\frac{dR(t)}{dt}}{R(t)} \qquad (3\text{-}28a)$$

$$h(t) = a_1 + 2a_2 t \qquad (3\text{-}28b)$$

The reliability and hazard function evaluations for the 12 groups are shown in Tables 3-8 to 3-11. All the models show decreasing reliability function trends, however, the hazard functions show both increasing and decreasing trends.

Table 3-8. Reliability and Hazard Function Evaluations for Groups 4.1, 4.2, and 4.3

| Time (Yrs) from POL | Group 4.1 | | Group 4.2 | | Group 4.3 | |
|---|---|---|---|---|---|---|
| | Reliability | Hazard | Reliability | Hazard | Reliability | Hazard |
| 20 | na | na | 0.7999 | 0.03044 | 0.77799 | 0.014652 |
| 25 | na | na | 0.6696 | 0.04072 | 0.72327 | 0.014522 |
| 30 | 0.8325 | 0.05497 | 0.5324 | 0.05100 | 0.67283 | 0.014392 |
| 35 | 0.6369 | 0.05217 | 0.4021 | 0.06128 | 0.62632 | 0.014262 |
| 40 | 0.4941 | 0.04937 | 0.2885 | 0.07156 | 0.58340 | 0.014132 |
| 45 | 0.3887 | 0.04657 | 0.1966 | 0.08184 | 0.54378 | 0.014002 |
| 50 | 0.3101 | 0.04377 | 0.1273 | 0.09212 | 0.50717 | 0.013872 |
| 55 | 0.2509 | 0.04097 | 0.0782 | 0.10240 | 0.47334 | 0.013742 |
| 60 | 0.2059 | 0.03817 | 0.0457 | 0.11268 | 0.44206 | 0.013612 |
| 65 | 0.1713 | 0.03537 | 0.0254 | 0.12296 | 0.41310 | 0.013482 |
| 70 | 0.1446 | 0.03257 | 0.0134 | 0.13324 | 0.38630 | 0.013352 |
| 75 | 0.1237 | 0.02977 | 0.0067 | 0.14352 | 0.36147 | 0.013222 |
| 80 | 0.1073 | 0.02697 | 0.0032 | 0.15380 | 0.33846 | 0.013092 |
| 85 | 0.0945 | 0.02417 | 0.0014 | 0.16408 | 0.31711 | 0.012962 |
| 90 | 0.0843 | 0.02137 | 0.00062 | 0.17436 | 0.29731 | 0.012832 |
| 95 | 0.0763 | 0.01857 | 0.0003 | 0.18464 | 0.27892 | 0.012702 |
| 100 | 0.0700 | 0.01577 | 9.7E-05 | 0.19492 | 0.26185 | 0.012572 |

Table 3-9. Reliability and Hazard Function Evaluations for Groups 3.1, 3.2, and 3.3

| Time (Yrs) from POL | Group 3.1 | | Group 3.2 | | Group 3.3 | |
|---|---|---|---|---|---|---|
| | Reliability | Hazard | Reliability | Hazard | Reliability | Hazard |
| 20 | 0.97152 | 0.00584 | 0.97139 | 0.00538 | 0.97759 | 0.00480 |
| 25 | 0.93598 | 0.00907 | 0.92468 | 0.01433 | 0.90866 | 0.02445 |
| 30 | 0.88728 | 0.01230 | 0.84170 | 0.02328 | 0.76555 | 0.04410 |
| 35 | 0.82765 | 0.01553 | 0.73264 | 0.03223 | 0.58462 | 0.06375 |
| 40 | 0.75966 | 0.01876 | 0.60980 | 0.04118 | 0.40468 | 0.08340 |
| 45 | 0.68607 | 0.02199 | 0.48534 | 0.05013 | 0.25391 | 0.10305 |
| 50 | 0.60970 | 0.02522 | 0.36938 | 0.05908 | 0.14440 | 0.12270 |
| 55 | 0.53314 | 0.02845 | 0.26882 | 0.06803 | 0.07444 | 0.14235 |
| 60 | 0.45873 | 0.03168 | 0.18708 | 0.07698 | 0.03478 | 0.16200 |
| 65 | 0.38838 | 0.03491 | 0.12449 | 0.08593 | 0.01473 | 0.18165 |
| 70 | 0.32355 | 0.03814 | 0.07922 | 0.09488 | 0.00566 | 0.20130 |
| 75 | 0.26523 | 0.04137 | 0.04820 | 0.10383 | 0.00197 | 0.22095 |
| 80 | 0.21393 | 0.04460 | 0.02805 | 0.11278 | 0.00062 | 0.24060 |
| 85 | 0.16979 | 0.04783 | 0.01561 | 0.12173 | 0.00018 | 0.26025 |
| 90 | 0.13260 | 0.05106 | 0.00830 | 0.13068 | 4.60E-05 | 0.27990 |

Table 3-10. Reliability and Hazard Function Evaluations for Groups 2.1, 2.2, and 2.3

| Time (Yrs) from POL | Group 2.1 | | Group 2.2 | | Group 2.3 | |
|---|---|---|---|---|---|---|
| | Reliability | Hazard | Reliability | Hazard | Reliability | Hazard |
| 10 | 0.97757 | 0.002268 | 0.97872 | 0.0084 | na | 0.00867 |
| 15 | 0.96655 | 0.002268 | 0.92403 | 0.0146 | 0.94088 | 0.01798 |
| 20 | 0.95565 | 0.002268 | 0.84577 | 0.0208 | 0.84020 | 0.02729 |
| 25 | 0.94488 | 0.002268 | 0.75050 | 0.0270 | 0.71617 | 0.03660 |
| 30 | 0.93422 | 0.002268 | 0.64564 | 0.0332 | 0.58268 | 0.04591 |
| 35 | 0.92369 | 0.002268 | 0.53848 | 0.0394 | 0.45251 | 0.05522 |
| 40 | 0.91327 | 0.002268 | 0.43539 | 0.0456 | 0.33544 | 0.06453 |
| 45 | 0.90298 | 0.002268 | 0.34129 | 0.0518 | 0.23734 | 0.07384 |
| 50 | 0.89279 | 0.002268 | 0.25937 | 0.0580 | 0.16030 | 0.08315 |
| 55 | 0.88273 | 0.002268 | 0.19109 | 0.0642 | 0.10334 | 0.09246 |
| 60 | 0.87277 | 0.002268 | 0.13649 | 0.0704 | 0.06359 | 0.10177 |
| 65 | 0.86293 | 0.002268 | 0.09451 | 0.0766 | 0.03735 | 0.11108 |
| 70 | 0.85320 | 0.002268 | 0.06345 | 0.0828 | 0.02094 | 0.12039 |
| 75 | 0.84358 | 0.002268 | 0.04129 | 0.0890 | 0.01121 | 0.12970 |
| 80 | 0.83407 | 0.002268 | 0.02606 | 0.0952 | 0.00572 | 0.13901 |

Table 3-11. Reliability and Hazard Function Evaluations for Groups 1.1, 1.2, and 1.3

| Time (Yrs) from POL | Group 1.1 | | Group 1.2 | | Group 1.3 | |
|---|---|---|---|---|---|---|
| | Reliability | Hazard | Reliability | Hazard | Reliability | Hazard |
| 10 | 0.99391 | 0.000611 | 0.98081 | 0.001938 | 0.904475 | 0.02070 |
| 15 | 0.99087 | 0.000611 | 0.97135 | 0.001938 | 0.794096 | 0.03136 |
| 20 | 0.98785 | 0.000611 | 0.96198 | 0.001938 | 0.661001 | 0.04202 |
| 25 | 0.98484 | 0.000611 | 0.95270 | 0.001938 | 0.521654 | 0.05268 |
| 30 | 0.98183 | 0.000611 | 0.94352 | 0.001938 | 0.390315 | 0.06334 |
| 35 | 0.97883 | 0.000611 | 0.93442 | 0.001938 | 0.276886 | 0.07400 |
| 40 | 0.97585 | 0.000611 | 0.92541 | 0.001938 | 0.186225 | 0.08466 |
| 45 | 0.97287 | 0.000611 | 0.91648 | 0.001938 | 0.118748 | 0.09532 |
| 50 | 0.96990 | 0.000611 | 0.90765 | 0.001938 | 0.071791 | 0.10598 |
| 55 | 0.96694 | 0.000611 | 0.89889 | 0.001938 | 0.041149 | 0.11664 |
| 60 | 0.96399 | 0.000611 | 0.89023 | 0.001938 | 0.022362 | 0.12730 |
| 65 | 0.96105 | 0.000611 | 0.88164 | 0.001938 | 0.011522 | 0.13796 |
| 70 | 0.95812 | 0.000611 | 0.87314 | 0.001938 | 0.005628 | 0.14862 |

# 4. BAYESIAN TECHNIQUES FOR RELIABILITY PREDICTION

The reliability and hazard functions of Section 3.4 can be viewed as marginal functions that do not account for the particular condition of a piece of equipment, but they provide average or generic results for a group or stratum. In the practical use of hazard functions in investment decision analysis, a generic function might not be sufficient for a particular piece of equipment. Hence, the generic function needs to be modified by conditioning on a particular piece of equipment, resulting in a modified hazard function. By conditioning on a particular piece of equipment, the physical or performance condition of the equipment is introduced as a factor for modifying the generic function. The US Army Corps of Engineers (USACE) maintains information on test results of a particular piece of equipment that are aggregated to obtain a condition index. The test results and the condition index are needed to perform this modification.

Once a generic hazard function and a condition index are obtained for a particular piece of equipment, they can be combined to obtain the modified hazard function using Bayesian techniques. Bayesian techniques require the development of a likelihood function and a computational procedure for combining the generic hazard function and the condition index with associated probabilities.

In Section 3.4, reliability functions were summarized for groups of generators that were defined by the date of having the plant on line (*POL*) and the power rating of the generators. The resulting reliability functions in Section 3.4 are called herein the group reliability functions. These reliability functions can be used as prior information in the Bayesian techniques to obtain plant-specific reliability functions by utilizing new plant information on generator failures or censoring to obtain plant reliability functions as posterior reliability functions. This case is discussed in Section 4.2.2. In Section 4.2.3, a method is presented to obtain a unit (i.e., generator) specific reliability function based on a plant (or group) reliability function based on obtaining either censoring information or the condition index of the unit.

## 4.1. Bayesian Estimation

### 4.1.1. Parameter Estimation

For an unknown parameter Q, a prior distribution for the parameters can be subjectively determined and expressed using a probability density function $f_Q(q)$. The parameter Q is assumed to be continuous with probabilities that can be computed based on its density function. Again, the distribution of Q reflects the uncertainty in this parameter including its randomness.

Now assume that new (objective) information ε was obtained. Using Bayes' theorem (Ayyub and McCuen 1996), the posterior distribution for the parameter can be obtained as

$$f_Q(q|e) = \frac{f_\Theta(q)\, P(e|q)}{\int_{-\infty}^{\infty} P(e|q)\, f_\Theta(q)\; dq} \qquad (4\text{-}1)$$

where $f_Q(q)$ = the prior density function of Q; $f_Q(q|e)$ = the posterior density function of Q; and $P(e|q)$ = the probability of obtaining the new information (e) given a certain value for the parameter (q). The probability $P(e|q)$ is called the likelihood function $L(q)$. The following notations for the posterior distribution is also common:

$$f\,'_Q(q) = \frac{f_\Theta(q)\, L(q)}{\int_{-\infty}^{\infty} L(q)\, f_\Theta(q)\; dq} \qquad (4\text{-}2)$$

where $f\,'_Q(q)$ = the conditional density function of q given e, or the posterior density function of Q.

Using the prior density function of the parameter Q, the prior expected value of the parameter can be computed as

$$\mathrm{E}(Q) = \int_{-\infty}^{\infty} q f_\Theta(q)\, dq \qquad (4\text{-}3)$$

Based on the posterior distribution, the posterior expected value of Q can be computed as

$$\mathrm{E}(Q|e) = \int_{-\infty}^{\infty} q f\,'_\Theta(q)\, dq \qquad (4\text{-}4)$$

In many engineering problems, the parameter Q can be used to define a probability distribution of a random variable *X*. The Bayesian estimation of the parameter can be used to compute Bayesian probabilities that are obtained with the gained information about the parameters. For example, the probability that *X* is less than some value $x_o$ can be computed using the prior distribution as

$$\mathrm{P}(X<x_o) \;=\; \int_{-\infty}^{\infty} P(X < x_o|q)\, f_\Theta(q)\, dq \qquad (4\text{-}6)$$

or

$$F_X(x_o) = \int_{-\infty}^{\infty} F_X(x_o|\theta) f_\Theta(\theta) d\theta \qquad (4\text{-}7)$$

where $F_X(x_o)$ = the cumulative distribution function of $X$ evaluated at $x_o$. Using the posterior distribution results in the following expression:

$$P(X<x_o) = \int_{-\infty}^{\infty} P(X < x_o|\theta) f'_\Theta(\theta) d\theta \qquad (4\text{-}8)$$

or

$$F_X(x_o) = \int_{-\infty}^{\infty} F_X(x_o|\theta) f'_\Theta(\theta) d\theta \qquad (4\text{-}9)$$

## 4.1.2. Bayesian Estimation of Normal Distribution

A random variable $X$ is considered herein to be normally distributed. The mean value of the random variable is of interest, and is unknown. The prior distribution of the unknown mean ($\mu$) is normal with a mean value and variance $\mu_o$, and $\sigma_o^2$, respectively. New (objective) information was obtained by a sample of size $n$. The mean value based on the sample is $\bar{X}$, and the variance of the sample mean is $S^2$. We are interested in determining the posterior distribution of the mean. The following expression based on Bayes' theorem can be used (Ayyub and McCuen 1996):

$$f'(\mu) = \frac{f(\mu)\, L(\mu)}{\int_{-\infty}^{\infty} L(\mu) f(\mu)\, d\mu} \qquad (4\text{-}10)$$

where $f(\mu)$ = the prior density function of $\mu$, which is normal with mean and variance of $\mu_o$, and $\sigma_o^2$, respectively, (i.e., $N(\mu_o, \sigma_o^2)$); $f'(\mu)$ = the posterior density function of the unknown mean $\mu$; and $L(\mu)$ = the likelihood function for the sample of size $n$. The likelihood function can be computed as the product of $n$ values of the density function of the normal distribution with a mean $\mu$ and standard deviation $S/\sqrt{n}$, each evaluated at a sampled value $x_i$. It can be shown that this $L(\mu)$ results in $f'(\mu)$ which is normally distributed with the following posterior mean value and variance, respectively:

$$\mu' = \frac{\mu_o S^2 + \bar{X}\sigma_o^2}{S^2 + \sigma_o^2} \qquad (4\text{-}11)$$

and

$$\sigma'^2 = \frac{\sigma_o^2 S^2}{\sigma_o^2 + S^2} \qquad (4\text{-}12)$$

The resulting $\mu'$, and $\sigma'$ are the posterior mean and standard deviation of the unknown mean value $\mu$, respectively. Using the normal posterior distribution, any Bayesian probabilities of interest for the random variable $X$ can be computed.

The prior and posterior mean values and variances can also be used in other aspects of statistical analysis such as confidence intervals and hypothesis testing. For example, they can be used to establish the following prior confidence interval on the mean:

$$\mu_o - z_{\alpha/2}\sigma \le \mu \le \mu_o + z_{\alpha/2}\sigma \qquad (4\text{-}13)$$

Also, they can be used to establish the following posterior confidence interval:

$$\mu' - z_{\alpha/2}\sigma' \le \mu \le \mu' + z_{\alpha/2}\sigma' \qquad (4\text{-}14)$$

where (1-$\alpha$) is the confidence level, and $z_\alpha$ is the standard normal quantile of level $\alpha$.. In a similar approach, prior hypothesis testing and posterior hypothesis testing can be performed.

### 4.1.3. Bayesian Updating of Binomial Distribution Parameters

The binomial distribution plays an important role in reliability. Suppose that $n$ identical units have been placed on test (without replacement of the failed units) for a specified time, $t$, and that the test yields $r$ failures, and $s = n - r$ surviving units. The number of surviving units, $q$, can be considered as a discrete random variable having the binomial distribution with parameters $n$ and $p(t)$, where $p(t)$ is the probability of survival (i.e., reliability) of a single unit during time $t$. In other words, $p(t)$ is the probability of success in a binomial trial.

The maximum likelihood estimate of the parameter $p$ is the ratio $s/n$, which is widely used as a classical estimate. To get a Bayesian estimation procedure for the reliability function, let us consider $p$ as the reliability, i.e., survivor probability in a single Bernoulli trial. If the number of units placed on test, $n$, is fixed in advance, the probability distribution of the number, $x$, of surviving units during the test (i.e., the number of "successes") is given by the binomial distribution probability mass function $P_X(x)$ with the parameters $n$ and $p$ as follows:

$$P_X(x) = \frac{n!}{(n-x)!\,x!}\, p^x (1-p)^{n-x} \qquad (4\text{-}15)$$

The beta probability distribution is a conjugate distribution for the parameter $p$, which means that in this case the posterior distribution is also beta distribution. Therefore, the following prior parameter moments can be used (Ang and Tang 1975):

$$\bar{p} = \frac{s}{n} \qquad (4\text{-}16a)$$

$$S_p = \sqrt{\frac{sr}{(n+1)n^2}} \qquad (4\text{-}16b)$$

where $s + r = n$. The posterior estimates of $s$ and $r$ based on $x$ surviving units as the new, i.e., gained, information, from $n_o$ tested units are denoted $s'$ and $r'$, respectively, and are given by

$$s' = s + x \tag{4-17a}$$

$$r' = r + n_o - x \tag{4-17b}$$

Therefore, the posterior parameters $p'$ and $n'$ are, respectively, given by

$$\bar{p}' = \frac{s'}{s + r + n_o} \tag{4-18a}$$

$$n' = n + n_o \tag{4-18b}$$

The standard error of the estimate, $p$, is calculated using the following expression:

$$S_p' = \sqrt{\frac{s'r'}{(n'+1)n'^2}} \tag{4-19}$$

The prior and posterior mean values and variances can also be used in other aspects of statistical analysis such as confidence intervals and hypothesis testing. For example, they can be used to establish the following 100(1-α) % prior confidence interval on the parameter $p$:

$$p_L \le p \le p_U \tag{4-20a}$$

where $p_L$ and $p_U$ are solutions of the following equations:

$$P(p < p_L) = I_{p_L}(s, n - s) = \alpha / 2 \tag{4-20b}$$

$$P(p > p_U) = I_{p_U}(s, n - s) = 1 - \alpha / 2 \tag{4-20c}$$

where $I_p$ = is, the so-called, incomplete beta function given

$$I_p(a,b) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \int_0^p x^{a-1}(1-x)^{b-1} dx \tag{4-21}$$

which could be calculated using, for example, the MS Excel's BETAINV function.

The respective 100(1-α)% posterior two-sided interval for $p$ is given by:

$$p_L' \le p \le p_U' \tag{4-22a}$$

where $p_L'$ and $p_U'$ are solutions of the following equations:

$$P(p < p_L') = I_{p_L'}(s', n' - s') = \alpha / 2 \tag{4-22b}$$

$$P(p > p_U') = I_{p_U'}(s', n' - s') = 1 - \alpha / 2 \tag{4-22c}$$

Note that as *n* approaches infinity, the Bayes estimate (4-18a) approaches the classical maximum likelihood estimate, $x/n_0$. In other words, the classical inference tends to dominate the Bayes inference as the amount of data increases.

## 4.1.4. Bayesian Updating of the Exponential and Poisson Distribution Parameter

### *4.1.4.1. Poisson Distribution*

The exponential or Poisson distribution can be used to deal with reliability problems. For a failure rate λ, the probability mass function for the Poisson distribution, that model the number of failures *x* in any fixed time period, $t_o$, is given by

$$P_X(x) = \frac{(\lambda t_o)^x}{x!} \exp(-\lambda t_o) \qquad (4\text{-}23)$$

### *4.1.4.2. Exponential Distribution*

The time between successive failures or the time to failure, *t*, follows an exponential distribution with the following density function:

$$f_T(t) = \lambda \exp(-\lambda t) \qquad (4\text{-}24)$$

The parameter λ is the same in both Eqs. 4-23 and 4-24.

### *4.1.4.3. Bayesiam Estimation*

The gamma distribution with parameters $\delta$ and $\rho$ is used as the prior distribution of the parameter $\lambda$. The mean value and the standard deviation of the of the parameters λ based on its prior distribution are (Ang and Tang 1975), respectively, given by

$$\bar{\lambda} = \frac{\delta}{\rho} \qquad (4\text{-}25a)$$

$$S_\lambda = \frac{\sqrt{\delta}}{\rho} \qquad (4\text{-}25b)$$

The gamma distribution is the conjugate distribution in Bayesian parameter estimation for both the Poisson and exponential distributions.

For a sample of *n* units with *r* distinct times to failure $t_1<t_2<\ldots<t_r$ and *n-r* times to censoring $t_{c1}$, $t_{c2}$, ... , $t_{c(n-r)}$, the total time on test (or in service), *T*, is

$$T = \sum_{i=1}^{r} t_i + \sum_{j=1}^{n-r} t_{cj} \qquad (4\text{-}26)$$

For the exponential distribution, the posterior estimates of these parameters are

$$\delta' = \delta + r \qquad \text{(4-27a)}$$

$$\rho' = \rho + T \qquad \text{(4-27b)}$$

Equations 4-25a and b results into the following posterior moments:

$$\bar{\lambda}' = \frac{\delta + r}{\rho + T} \qquad \text{(4-28a)}$$

$$S_{\lambda}' = \frac{\sqrt{\delta + r}}{\rho + T} \qquad \text{(4-28b)}$$

Note that as *n* approaches infinity, the Bayes estimate (4-28) approaches the classical maximum likelihood estimate, *r/T*.

The prior and posterior mean values and variances can also be used in other aspects of statistical analysis such as confidence intervals and hypothesis testing. For example, they can be used to establish the following 100(1-α)% prior confidence interval on the parameter *p*:

$$\frac{\delta}{\rho}\chi^2_{\alpha} < \lambda < \frac{\delta}{\rho}\chi^2_{1-\alpha} \qquad \text{(4-29)}$$

where $\chi^2_{\alpha}$ = is the chi-square variate at a cumulative value of α using 2δ degrees of freedom, which might be non-integer. Also, they can be used to establish the following posterior confidence interval:

$$\frac{\delta + r}{\rho + T}\chi^2_{\alpha} < \lambda < \frac{\delta + r}{\rho + T}\chi^2_{1-\alpha} \qquad \text{(4-30)}$$

where $\chi^2_{\alpha}$ has 2(δ+*r*) degrees of freedom. In a similar approach, prior hypothesis testing and posterior hypothesis testing can be performed.

## 4.2. Prior Reliability Information

The prior reliability information is a group reliability function as given in Table 3-3. This prior information can be updated when new reliability data are available. For example, the reliability data used for developing the group reliability functions are based on the 1993 inventory. When the data for later years are available, the group reliability functions should be updated. This additional (new) information can include the following information types: (1) time to new censoring (or non-failure) of a generator, (2) time to a new failure. These two types were described in detail throughout this report.

## 4.2.1. Additional (or New) Reliability Information

In this section, the new data are based on the condition index evaluation that can be used to predict (or forecast) the time to failure for units. The condition index (CI) (or rating) is used by the USACE (1993b), and is based on several tests that are performed and aggregated on a hydropower unit. The currently used aggregation method of test results is based on taking the minimum values of all test scores that are provided on a scale of 0 (failed) to 100 (excellent). Therefore, the condition index, as the minimum of test scores, is in the range of 0 to 100. This aggregation procedure has the advantage of simplicity, but it assumes a weakest link behavior for a piece of equipment treated as a system with fully uncorrelated test results. The aggregation method for the condition index needs to be examined in future work. The underlying tests can have weight factors that reflect the importance of the test in reflecting the reliability of the equipment. Also, the aggregation method needs to maximize information retention from test results without undermining any associated uncertainties.

For example, the Dalles plant is used herein to develop a plant reliability function as prior information in Bayesian analysis. Table 4-1 lists the units of the Dalles plant. Units 1 to 14 have power capacity of 78,000 kW (including the rewound units 12a and 13a); whereas units 15 to 20 have power capacity of 85,975 kW, and units F1 and F2 have power capacity of 13500 kW. Thus, taking into account the POL date for each generator, and according to the definitions given in Table 2-1, units F1 and F2 belong to Group 3.1, units 12a to 22 belong to Group 3.1, and units 1 to 14 belong to Group 3.3. Therefore, only units 1 to 14 are used herein to develop a plant reliability function for generators that are within Group 3.3 in order to facilitate the comparative development of Bayesian methods for the Dalles plant and a most related group (i.e., Group 3.3).

Table 4-2 shows test results and computed condition indices for hydropower generation units 3, 7, 8, 9, 10, and 14 of the Dalles plant. Condition indices are not available for other units. Linear regression analysis was used to develop a relationship between the condition index (CI) as given in Table 4-2 and the corresponding age of surviving units. In the regression model, CI was assumed to be 100 at an age equals zero. The resulting linear regression model is given by

$$\mathrm{CI} = 100.9 - 1.295\, t \tag{4-31}$$

Table 4-1. Generator Units of the Dalles Plant

| Unit number | Power (kW) | Group Designation | POL date | Time to Failure or Time to Censoring (on 12-31-1993) in years | Time to failure (TTF) or Time to censoring (TTC) |
|---|---|---|---|---|---|
| F1 | 13500 | 3.1 | 05/13/57 | 36 | TTC |
| F2 | 13500 | 3.1 | 06/03/57 | 36 | TTC |
| 1 | 78500 | 3.3 | 09/25/57 | 36 | TTC |
| 2 | 78500 | 3.3 | 10/31/57 | 36 | TTC |
| 3 | 78500 | 3.3 | 01/17/58 | 35 | TTC |
| 4 | 78500 | 3.3 | 04/24/58 | 35 | TTC |
| 5 | 78500 | 3.3 | 09/11/58 | 35 | TTC |
| 6 | 78500 | 3.3 | 10/24/58 | 35 | TTC |
| 7 | 78500 | 3.3 | 01/16/59 | 34 | TTC |
| 8 | 78500 | 3.3 | 04/16/59 | 34 | TTC |
| 9 | 78500 | 3.3 | 08/28/59 | 34 | TTC |
| 10 | 78500 | 3.3 | 10/10/59 | 34 | TTC |
| 11 | 78500 | 3.3 | 01/26/60 | 33 | TTC |
| 12 | 78500 | 3.3 | 04/05/60 | 22 | TTF |
| 13 | 78500 | 3.3 | 07/22/60 | 27 | TTF |
| 14 | 78500 | 3.3 | 10/28/60 | 33 | TTC |
| 12a | 78500 | 1.3 | 01/01/82 | 11 | TTC |
| 13a | 78500 | 1.3 | 01/01/88 | 5 | TTC |
| 15 | 85975 | 1.3 | 12/11/72 | 21 | TTC |
| 16 | 85975 | 1.3 | 12/17/72 | 20 | TTC |
| 17 | 85975 | 1.3 | 02/05/73 | 20 | TTC |
| 18 | 85975 | 1.3 | 02/27/73 | 20 | TTC |
| 19 | 85975 | 1.3 | 04/14/73 | 20 | TTC |
| 20 | 85975 | 1.3 | 05/15/73 | 20 | TTC |
| 21 | 85975 | 1.3 | 10/12/73 | 20 | TTC |
| 22 | 85975 | 1.3 | 11/13/73 | 20 | TTC |

The CI model and data are shown in Figure 4-1. The adjusted $R_c$ square is 0.312, and the regression standard error of estimate is 22.82. The fit of the model to the data is of moderate to poor quality. As additional condition index values become available, the model coefficients should be re-estimated to improve the fit. Assuming that a unit fails once its CI index reaches 9, a predicted time to failure (TTF) for the unit can be made using the following model which is based on Eq. 4-31:

$$\text{TTF}_{\text{CI}} = (\text{Unit age at CI}) + \frac{(9 - 100.9) - (\text{CI for unit - } 100.9)}{1.295} \qquad (4\text{-}32)$$

where $\text{TTF}_{\text{CI}}$ = predicted time to failure based on CI. The results of using Eq. 4-32 are shown in the last row of Table 4-2. The additional (new) data for Bayesian analysis are given in Table 4-3.

Table 4-2. Tests and Condition Indices for Hydropower Generators of the Dalles Units

| Test or CI | Unit 3 | Unit 7 | Unit 8 | Unit 9 | Unit 10 | Unit 11 | Unit 14 |
|---|---|---|---|---|---|---|---|
| Age at CI inspection (years) | 36.2 | 35.2 | 34.9 | 35.0 | 35.5 | 34.2 | 33.1 |
| Blackout test | | | | | | | |
| Corona probe test | | | | | | | |
| DC high potential test | 70 | 10 | 60 | 9 | 15 | 65 | 70 |
| Insulation resistance test | 99 | 10 | 99 | 9 | 99 | 99 | 90 |
| Ozone detection test | | | | | | | |
| Partial discharge analysis | | | | | | | |
| Circuit ring insulation | | 90 | | 100 | | | |
| Core inspection | | 39 | | 99 | | | |
| Endturn inspection | | 60 | | 96 | | | |
| Lead inspection | | 60 | | 100 | | | |
| Slot inspection | | 45 | | | | | |
| Wedge system inspection | | 80 | | 49 | | | |
| Reduced rating | | 10 | | 16 | | | |
| CI as the minimum value of tests | 70 | 10 | 60 | 9 | 15 | 65 | 70 |
| Classification of unit | survival | failure | survival | failure | survival | survival | survival |
| Predicted time to failure $TTF_{CI}$ (or actual time to failure) in years | 83.3 | (35.2) | 74.3 | (34) | 40.1 | 77.4 | 80.2 |

Figure 4-1. Condition Index (CI) Data and Model


Based on the additional (new) data, and keeping in mind its small size of 7 TTF values, the two-parameter Weibull distribution was therefore fitted. The following reliability model, based on the these data, was obtained:

$$R_{new}(t) = \exp\left(-(0.001763 \;\; t^{1.582291})\right) \qquad (4\text{-}33)$$

Example evaluation of this model (Eq. 4-33) are shown in Table 4-4.

Table 4-3. Additional (or New) Information for the Dalles Units based on Eq. 4-32

| Unit | Unit age at failure or censoring (years) | Condition (Information source) |
|---|---|---|
| 3 | 83.3 | Predicted failure ($TTF_{CI}$) |
| 7 | 35.2 | Failure (TTF) |
| 8 | 74.3 | Predicted failure ($TTF_{CI}$) |
| 9 | 34.0 | Failure (TTF) |
| 10 | 40.1 | Predicted failure ($TTF_{CI}$) |
| 11 | 77.4 | Predicted failure ($TTF_{CI}$) |
| 14 | 80.2 | Predicted failure ($TTF_{CI}$) |

Table 4-4. Reliability Function based on Additional Information for the Dalles Units

| Time to failure (*t*) in years | *R*(*t*) using Eq. 4-33 |
|---|---|
| 34.0 | 0.626758 |
| 35.2 | 0.610454 |
| 40.1 | 0.545208 |
| 74.3 | 0.199980 |
| 77.4 | 0.179590 |
| 80.2 | 0.162611 |
| 83.3 | 0.145333 |

## 4.2.2. Posterior Reliability for a Set of Hydropower Units

The objective of this section is to update the group reliability functions, *R(t)*, given in Table 3-3, using the CI data analysis results and Bayesian techniques. The approach considered below is based on Bayesian updating of the binomial distribution parameter given in Section 4.1.3. The approach is illustrated by the updating of Group 3.3 for which the CI data were available.

***Prior Distribution for a Given Group***

For each group reliability function, *R(t)*, given in Table 3-3, and for a specified time of interest, $t_o$, the beta distribution is the prior distribution for the binomial parameter with the following prior mean and variance as was given by Eqs. 4-16:

$$\overline{p} = R(t_0) \qquad (4\text{-}34a)$$

$$S_e(R(t_0)) = S_p = \sqrt{\frac{R(t_0)(1-R(t_0))}{(n+1)n^2}} \qquad (4\text{-}34b)$$

where $n$ is the size of the sample that was used for fitting $R(t)$. For Group 3.3 generators, $n$ = 86 as shown in Table 2-1.

***Additional (New) Reliability Information***

The additional reliability information was obtained using the CI data, based on a failure-time sample of size $n_0$. A Weibull model was fitted to the new data as shown in Eq. 4-33 for the 7 Dalles units number 3, 7, 8, 9,10, and 14 as described in Section 4.2.1.

***Posterior Estimation of Reliability Function***

The point posterior estimate (the posterior distribution mean) of the reliability function $R'(t_0)$ for the specified time, $t_0$, is calculated using Eqs. 4-18 and 4-19 in as follows:

$$R'(t) = \frac{nR(t_0) + n_0 R_{new}(t_0)}{n + n_o} \tag{4-35a}$$

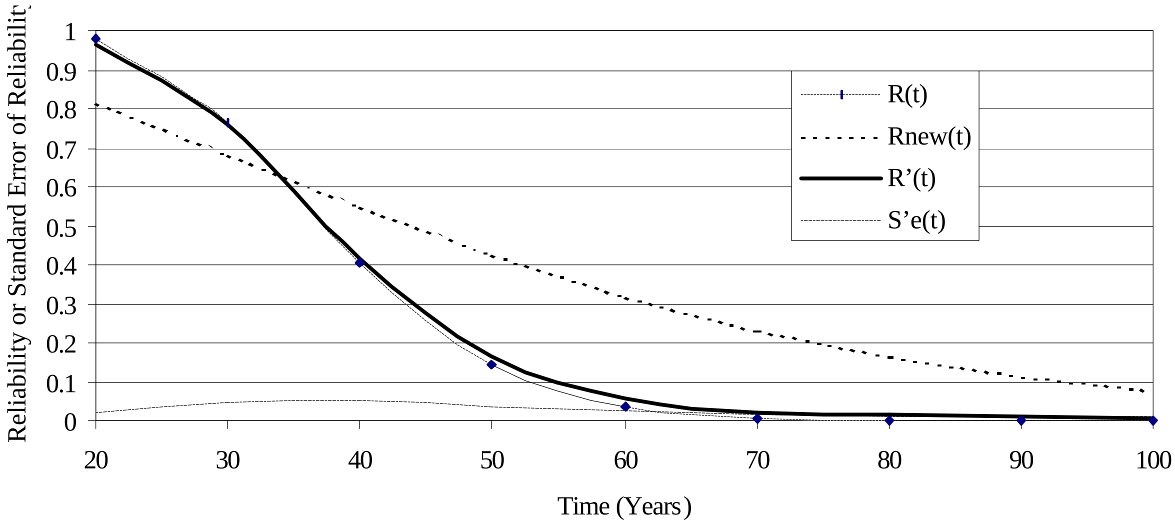
$$S_e^{'}(R'(t_0)) = \sqrt{\frac{\left(nR(t_0) + n_0 R_{new}(t_0)\right)\left(n_0 + n - nR(t_0) - n_0 R_{new}(t_0)\right)}{(n + n_0 + 1)(n + n_0)^2}} \tag{4-35b}$$

The results of $R'(t_0)$ and $S'_e(t_0)$ calculations are given in Table 4-5 and plotted in Figure 4-2.

Table 4-5. Bayesian Estimation of Reliability for Group 3.3 to Dalles Plant Units Updating

| $t$, years | $R(t)$ | $R_{new}(t)$ | $R'(t)$ | $S'_e(t)$ |
|---|---|---|---|---|
| 20 | 0.977590 | 0.817281 | 0.965528 | 0.018817 |
| 30 | 0.765551 | 0.681639 | 0.759235 | 0.044098 |
| 40 | 0.404679 | 0.546514 | 0.415355 | 0.050827 |
| 50 | 0.144401 | 0.423146 | 0.165382 | 0.038320 |
| 60 | 0.034782 | 0.317385 | 0.056053 | 0.023725 |
| 70 | 0.005655 | 0.231159 | 0.022629 | 0.015339 |
| 80 | 0.000621 | 0.163780 | 0.012901 | 0.011640 |
| 90 | 0.000046 | 0.113055 | 0.008552 | 0.009497 |
| 100 | 0.000002 | 0.076128 | 0.005732 | 0.007787 |

Figure 4-2. Bayesian Estimation of Reliability for Group 3.3 to Dalles Plant Units Updating




## 4.2.3. Posterior Reliability for a Specific Hydropower Unit in a Plant

The objective of this section is to obtain a unit-specific reliability function, using Bayesian techniques, based on respective group reliability data (i.e., the prior information) and the CI data for the given unit (i.e., the additional reliability information). Two models are used in this section, binomial distribution of Section 4.1.3 and exponential distribution of Section 4.1.4.

### *4.2.3.1. Binomial Model*

The prior reliability information is the respective group reliability function, $R(t)$, as given in Table 3-3. Units 3, 7, 8, 9, 10, 11, and 14 of the Dalles plant belong to Group 3.3, therefore they are considered to have the same prior reliability function of Group 3.3.

For each unit (3, 7, 8, 9, 10, 11, and 14) of the Dalles plant, the additional reliability information is its predicted age to failure based on Eq. 4-32 using the CI test results. The predicted times to failure are shown in Table 4-3. For each unit, this information is used in conjunction of the binomial model (Section 4.1.3) to estimate a reliability function with a sample size, $n$, of 1 as follows:

$$R_{new}(t) = \begin{cases} 1 & \text{for } t < t_1 \\ 0 & \text{for } t > t_1 \end{cases} \tag{4-36}$$

where $t_1$ is a predicted unit's age at failure from Table 4-3.

The point posterior estimate of the reliability function $R'(t_0)$ for a specified time, $t_0$, is calculated using Eqs. 4-18 and 4-19 with $n_0 = 1$. The Bayesian updating of the reliability function is similar to the group updating case considered in Section 4.2.2. The posterior reliability and its standard error estimates for the unit are given by

$$R'(t) = \frac{nR(t_0) + R_{new}(t_0)}{n+1} \tag{4-37a}$$

$$S_e^{'}(R'(t_0)) = \sqrt{\frac{\left(nR(t_0) + R_{new}(t_0)\right)\left(n+1-nR(t_0) - R_{new}(t_0)\right)}{(n+2)(n+1)^2}} \tag{4-37b}$$

The computed $R'(t_0)$ and $S'_e(t_0)$ for units 3, 7, 8, 9, 10, 11, and 14 are given in Tables 4-6a to 6g. The hazard function can be evaluated numerically using Eq. 3-28a.

Table 4-6a. Reliability Predictions for the Dalles Unit 3

| *t*, years | $R(t)$ | $R_{new}(t)$ | $R'(t)$ | $S'_e(t)$ |
|---|---|---|---|---|
| 20 | 0.977590 | 1 | 0.977848 | 0.015872 |
| 30 | 0.765551 | 1 | 0.768246 | 0.045503 |
| 40 | 0.404679 | 1 | 0.411522 | 0.053069 |
| 50 | 0.144401 | 1 | 0.154235 | 0.038949 |
| 60 | 0.034782 | 1 | 0.045876 | 0.022562 |
| 70 | 0.005655 | 1 | 0.017084 | 0.013974 |
| 80 | 0.000621 | 1 | 0.012108 | 0.011794 |
| 90 | 0.000046 | 0 | 4.55E-05 | 0.000727 |
| 100 | 0.000002 | 0 | 1.98E-06 | 0.000152 |

Table 4-6b. Reliability Predictions for the Dalles Unit 7

| *t*, years | $R(t)$ | $R_{new}(t)$ | $R'(t)$ | $S'_e(t)$ |
|---|---|---|---|---|
| 20 | 0.977590 | 1 | 0.977848 | 0.015872 |
| 30 | 0.765551 | 1 | 0.768246 | 0.045503 |
| 40 | 0.404679 | 0 | 0.400028 | 0.052831 |
| 50 | 0.144401 | 0 | 0.142741 | 0.037723 |
| 60 | 0.034782 | 0 | 0.034382 | 0.019649 |
| 70 | 0.005655 | 0 | 0.005590 | 0.008040 |
| 80 | 0.000621 | 0 | 0.000614 | 0.002671 |
| 90 | 0.000046 | 0 | 4.55E-05 | 0.000727 |
| 100 | 0.000002 | 0 | 1.98E-06 | 0.000152 |

Table4-6c. Reliability Predictions for the Dalles Unit 8

| $t$, years | $R(t)$ | $R_{new}(t)$ | $R'(t)$ | $S'_e(t)$ |
|---|---|---|---|---|
| 20 | 0.977590 | 1 | 0.977848 | 0.015872 |
| 30 | 0.765551 | 1 | 0.768246 | 0.045503 |
| 40 | 0.404679 | 1 | 0.411522 | 0.053069 |
| 50 | 0.144401 | 1 | 0.154235 | 0.038949 |
| 60 | 0.034782 | 1 | 0.045876 | 0.022562 |
| 70 | 0.005655 | 1 | 0.017084 | 0.013974 |
| 80 | 0.000621 | 0 | 0.000614 | 0.002671 |
| 90 | 0.000046 | 0 | 4.55E-05 | 0.000727 |
| 100 | 0.000002 | 0 | 1.98E-06 | 0.000152 |

Table 4-6d. Reliability Predictions for the Dalles Unit 9

| $t$, years | $R(t)$ | $R_{new}(t)$ | $R'(t)$ | $S'_e(t)$ |
|---|---|---|---|---|
| 20 | 0.977590 | 1 | 0.977848 | 0.015872 |
| 30 | 0.765551 | 1 | 0.768246 | 0.045503 |
| 40 | 0.404679 | 0 | 0.400028 | 0.052831 |
| 50 | 0.144401 | 0 | 0.142741 | 0.037723 |
| 60 | 0.034782 | 0 | 0.034382 | 0.019649 |
| 70 | 0.005655 | 0 | 0.005590 | 0.008040 |
| 80 | 0.000621 | 0 | 0.000614 | 0.002671 |
| 90 | 0.000046 | 0 | 4.55E-05 | 0.000727 |
| 100 | 0.000002 | 0 | 1.98E-06 | 0.000152 |

Table 4-6e. Reliability Predictions for the Dalles Unit 10

| $t$, years | $R(t)$ | $R_{new}(t)$ | $R'(t)$ | $S'_e(t)$ |
|---|---|---|---|---|
| 20 | 0.977590 | 1 | 0.977848 | 0.015872 |
| 30 | 0.765551 | 1 | 0.768246 | 0.045503 |
| 40 | 0.404679 | 1 | 0.411522 | 0.053069 |
| 50 | 0.144401 | 0 | 0.142741 | 0.037723 |
| 60 | 0.034782 | 0 | 0.034382 | 0.019649 |
| 70 | 0.005655 | 0 | 0.005590 | 0.008040 |
| 80 | 0.000621 | 0 | 0.000614 | 0.002671 |
| 90 | 0.000046 | 0 | 4.55E-05 | 0.000727 |
| 100 | 0.000002 | 0 | 1.98E-06 | 0.000152 |

Table 4-6f. Reliability Predictions for the Dalles Unit 11

| $t$, years | $R(t)$ | $R_{new}(t)$ | $R'(t)$ | $S'_e(t)$ |
|---|---|---|---|---|
| 20 | 0.977590 | 1 | 0.977848 | 0.015872 |
| 30 | 0.765551 | 1 | 0.768246 | 0.045503 |
| 40 | 0.404679 | 1 | 0.411522 | 0.053069 |
| 50 | 0.144401 | 1 | 0.154235 | 0.038949 |
| 60 | 0.034782 | 1 | 0.045876 | 0.022562 |
| 70 | 0.005655 | 1 | 0.017084 | 0.013974 |
| 80 | 0.000621 | 0 | 0.000614 | 0.002671 |
| 90 | 0.000046 | 0 | 4.55E-05 | 0.000727 |
| 100 | 0.000002 | 0 | 1.98E-06 | 0.000152 |

Table 4-6g. Reliability Predictions for the Dalles Unit 14

| $t$, years | $R(t)$ | $R_{new}(t)$ | $R'(t)$ | $S'_e(t)$ |
|---|---|---|---|---|
| 20 | 0.977590 | 1 | 0.977848 | 0.015872 |
| 30 | 0.765551 | 1 | 0.768246 | 0.045503 |
| 40 | 0.404679 | 1 | 0.411522 | 0.053069 |
| 50 | 0.144401 | 1 | 0.154235 | 0.038949 |
| 60 | 0.034782 | 1 | 0.045876 | 0.022562 |
| 70 | 0.005655 | 1 | 0.017084 | 0.013974 |
| 80 | 0.000621 | 1 | 0.012108 | 0.011794 |
| 90 | 0.000046 | 0 | 4.55E-05 | 0.000727 |
| 100 | 0.000002 | 0 | 1.98E-06 | 0.000152 |

#### *4.2.3.2. Exponential Model*

The prior reliability information is the respective group reliability function, $R(t)$, as given in Table 3-3. Units 3, 7, 8, 9, 10, 11, and 14 of the Dalles plant belong to Group 3.3, therefore they are considered to have the same prior reliability function of Group 3.3. The reliability function of Group 3.3 is not the exponential reliability function. Nevertheless, for a tutorial purpose, the exponential distribution case is considered herein.

The prior distribution is selected using the respective group data. For each unit (3, 7, 8, 9, 10, 11, and 14) of the Dalles plant, the parameters d and r of the prior distribution are calculated as follows:

d = the number of failures in Group 3.3 according to the 1993 inventory data (Appendix A)
= 29 (4-38a)

r = $T_0 - t_c$ (4-38b)

where $T_0$ = 2861 years as calculated by Eq. 4-26 based on all units of Group 3.3, and $t_c$ is the time to censoring (age) for a given unit.

For each unit (3, 7, 8, 9, 10, 11, and 14) of the Dalles plant, the additional reliability information is its predicted age to failure based on Eq. 4-32 using the CI test results. The predicted times to failure are shown in Table 4-3.

The point posterior estimate of parameter λ of the exponential distribution is calculated using Eqs. 4-28 with $r$ = 1, and $T$ = the age at failure of a specified unit predicted using Eq. 4-32. Therefore, Eqs. 4-28 are used as follows:

$$\bar{\lambda}' = \frac{\delta + 1}{\rho + T} \qquad \text{(4-39a)}$$

$$S_{\lambda}' = \frac{\sqrt{\delta + 1}}{\rho + T} \qquad \text{(4-39b)}$$

The results of the posterior estimation of λ for the Dalles plant units are given in Table 4-7. The hazard function can be evaluated numerically using Eq. 3-28a, which is in this case λ'.

Table 4-7. Bayesian Updating of the Exponential Distribution Parameter and Its Standard Error for the Dalles Units

| Unit | $T$ (year) | λ' (year$^{-1}$) | $S'_e(\lambda)$ (year$^{-1}$) |
|---|---|---|---|
| 3 | 83.3 | 0.01031 | 0.00188 |
| 7 | 35.2 | 0.01048 | 0.00191 |
| 8 | 74.3 | 0.01034 | 0.00189 |
| 9 | 34.0 | 0.01049 | 0.00191 |
| 10 | 40.1 | 0.01046 | 0.00191 |
| 11 | 77.4 | 0.01033 | 0.00189 |
| 14 | 80.2 | 0.01032 | 0.00188 |

# 5. CONCLUSIONS

In this study, assessment methods of the time-dependent reliability and hazard functions of hydropower equipment were developed. For hydropower equipment, complete data or right censored data are commonly encountered. The 1993 inventory of generators as provided by the USACE include also records of failure and replacement. The following are conclusions and observations based on the study:

1. A preliminary examination of the records provided by the USACE revealed that the average age at failure is 28 years. Also, the average age of equipment based on this 1993 inventory is 24 years.
2. The generators were grouped by plant-on-line date and power to produce 12 groups. The life data of generators within each group were analyzed. Reliability functions were developed, and models based on nonlinear numerical curve fitting using an exponential function with a second-order polynomial tail were proposed.
3. Early-life special models and late-life prediction (extrapolation) models were also developed.
4. The effect of manufacturer on generator reliability was investigated. It can be concluded that the differences between the reliability values of the General Electric USACE and Westinghouse USACE generators are, in general, statistically insignificant.
5. In the practical use of hazard functions in investment decision analysis, a generic function might not be sufficient for a particular piece of equipment. Hence, the generic function needs to be modified by conditioning on a set of equipment (i.e., units) or a particular piece of equipment (i.e., a unit), resulting in a modified (posterior) reliability and hazard functions. The US Army Corps of Engineers (USACE) maintains information on test results of equipment that are aggregated to obtain a condition index for each unit. Once a generic hazard function and condition indices are obtained for pieces of equipment, they can be combined to obtain the modified reliability and hazard functions using Bayesian techniques.
6. The suggested methods were demonstrated using hydropower generators. Other similar hydropower equipment types can be treated using similar methods.

# 6. FUTURE WORK

The results of the above tasks constitute a basis for attaining the general objective of this study, that is to develop an assessment method of the time-dependent reliability and hazard functions of on a set of hydropower equipment (i.e., units) or a particular piece of equipment (i.e., a unit). The following additional tasks are needed to achieve the general objective of the study:

1. Verification and validation, if possible. Verification of validation of the suggested methods require appropriate real data. The availability of the needed data will significantly affect the level of success in this task.
2. Other reliability factors. Several factors and their effect on generator reliability were considered in this study such as time, power level, plant-on-line date, and manufacturer. Other factors can investigated such as a more detailed investigation of manufacturer, condition-index test results, generator types, insulation, turbine type, pressure, trip speed, power factor, and exciter information.
3. Software. Computer software can be developed to assist engineers with these calculations. Visual basic can be used to develop the software. The result will be a user-friendly software in a PC-Windows environment that can be linked to a database of generators' information. The investigators have developed reliability software using this environment for the USACE. Selected software in this area can be demonstrated by the investigators.
4. Other hydropower equipment. The suggested methods were demonstrated using hydropower generators. Other similar hydropower equipment types can be treated using similar methods.

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# Appendix A.
# USACE Life Database for Generators

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| Alexander GS | 1 | 01/01/30 | 12750 | | | | 0 | 63 |
| Smokey Falls GS | 1 | 01/01/30 | 13200 | | | | 0 | 63 |
| Alexander GS | 2 | 12/01/30 | 12750 | | | | 0 | 62 |
| Alexander GS | 3 | 03/01/31 | 12750 | | | | 0 | 62 |
| Blue Ridge | 1 | 07/01/31 | 20000 | 12/01/87 | 22000 | Degradation | 56 | 56 |
| Chats Falls GS | 3 | 10/01/31 | 22325 | | | | 0 | 61 |
| Chats Falls GS | 5 | 10/01/31 | 22325 | | | | 0 | 61 |
| Chats Falls GS | 2 | 10/01/31 | 22325 | 01/01/74 | 22325 | Other - Fire | 42 | 42 |
| Chats Falls GS | 6 | 10/01/32 | 19975 | | | | 0 | 60 |
| Chats Falls GS | 7 | 10/01/32 | 19975 | | | | 0 | 60 |
| Chats Falls GS | 8 | 10/01/32 | 19975 | | | | 0 | 60 |
| Chats Falls GS | 9 | 10/01/32 | 19975 | | | | 0 | 60 |
| Abitibi Canyon GS | 1 | 01/05/33 | 41255 | 01/01/75 | 41255 | Degradation | 42 | 42 |
| Abitibi Canyon GS | 2 | 12/01/33 | 63000 | 05/01/77 | 63000 | Other - Unit Replace | 43 | 43 |
| Abitibi Canyon GS | 5 | 01/01/36 | 43200 | 02/01/80 | 43200 | Uprate | 44 | 44 |
| Abitibi Canyon GS | 4 | 01/01/36 | 43200 | 03/01/79 | 43200 | Degradation | 43 | 43 |
| Norris | 2 | 07/01/36 | 50400 | | | | 0 | 57 |
| Norris | 1 | 09/01/36 | 50400 | 11/01/90 | 55620 | Coil Failure | 54 | 54 |
| Wheeler | 1 | 11/01/36 | 32400 | 09/01/84 | 35100 | Degradation | 48 | 48 |
| Wheeler | 2 | 04/01/37 | 32400 | 06/01/86 | 35100 | Degradation | 49 | 49 |
| Ontario Power GS | 9 | 01/01/38 | 8776 | | | | 0 | 55 |
| Pickwick | 2 | 06/01/38 | 36000 | 12/01/86 | 40400 | Degradation | 49 | 49 |
| BONNEVILLE | 2 | 06/06/38 | 43200 | 01/01/75 | 54200 | | 37 | 37 |
| BONNEVILLE | 1 | 07/18/38 | 43200 | | | | 0 | 55 |
| Pickwick | 1 | 08/01/38 | 36000 | 05/01/86 | 40400 | Coil Failure | 48 | 48 |
| Guntersville | 1 | 08/01/39 | 24300 | 10/01/78 | 28800 | Coil Failure | 39 | 39 |
| Guntersville | 2 | 10/01/39 | 24300 | 07/01/79 | 28800 | Coil Failure | 40 | 40 |
| Ear Falls GS | 3 | 01/01/40 | 5400 | 01/01/90 | 5400 | Degradation | 50 | 50 |
| Guntersville | 3 | 01/01/40 | 24300 | 10/01/74 | 28800 | Coil Failure | 35 | 35 |
| Chickamauga | 3 | 03/01/40 | 27000 | 12/01/75 | 30000 | Coil Failure | 36 | 36 |
| Hiwassee | 1 | 05/01/40 | 57600 | 11/01/90 | 70650 | Coil Failure | 51 | 51 |
| Chickamauga | 2 | 05/01/40 | 27000 | 10/01/76 | 30000 | Coil Failure | 36 | 36 |
| Chickamauga | 1 | 07/01/40 | 27000 | 04/01/76 | 30000 | Coil Failure | 36 | 36 |
| BONNEVILLE | 4 | 12/23/40 | 54000 | | | | 0 | 52 |
| Wheeler | 3 | 01/01/41 | 32400 | 10/01/82 | 35100 | Degradation | 42 | 42 |
| BONNEVILLE | 3 | 01/09/41 | 54000 | | | | 0 | 52 |
| Wheeler | 4 | 03/01/41 | 32400 | 06/01/81 | 35100 | Coil Failure | 40 | 40 |
| BONNEVILLE | 5 | 09/05/41 | 54000 | | | | 0 | 52 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| Watts Bar | 3 | 02/01/42 | 30000 | 12/01/78 | 33300 | Coil Failure | 37 | 37 |
| Wilson | 12 | 03/01/42 | 25200 | 06/01/69 | 25200 | Degradation | 27 | 27 |
| Cherokee | 1 | 04/01/42 | 30000 | 04/01/76 | 33480 | Coil Failure | 34 | 34 |
| Watts Bar | 2 | 04/01/42 | 30000 | 10/01/73 | 33300 | Coil Failure | 32 | 32 |
| Wilson | 11 | 05/01/42 | 25200 | 10/01/77 | 25200 | Coil Failure | 35 | 35 |
| BONNEVILLE | 6 | 05/18/42 | 54000 | | | | 0 | 51 |
| Cherokee | 3 | 06/01/42 | 30000 | 10/01/74 | 34650 | Coil Failure | 32 | 32 |
| Pickwick | 4 | 06/01/42 | 36000 | 10/01/54 | 40400 | Degradation | 12 | 12 |
| Watts Bar | 1 | 07/01/42 | 30000 | 06/01/78 | 33300 | Coil Failure | 36 | 36 |
| Wilson | 10 | 07/01/42 | 25200 | 11/01/68 | 25200 | Degradation | 26 | 26 |
| Pickwick | 3 | 08/01/42 | 36000 | 10/01/71 | 40400 | Degradation | 29 | 29 |
| Wilson | 9 | 08/01/42 | 25200 | 09/01/69 | 25200 | Degradation | 27 | 27 |
| Barrett Chute GS | 1 | 08/06/42 | 20400 | 01/01/71 | 20400 | Other - Replaced | 28 | 28 |
| Barrett Chute GS | 2 | 08/25/42 | 20400 | 01/01/73 | 20400 | Other - Replaced | 30 | 30 |
| Wilson | 16 | 04/01/43 | 25200 | 10/01/80 | 25200 | Coil Failure | 38 | 38 |
| Ocoee 3 | 1 | 04/01/43 | 24000 | 05/01/75 | 28800 | Coil Failure | 32 | 32 |
| BONNEVILLE | 7 | 04/01/43 | 54000 | 01/01/69 | 54000 | | 26 | 26 |
| Douglas | 3 | 05/01/43 | 30000 | 04/01/71 | 31500 | Degradation | 28 | 28 |
| BONNEVILLE | 8 | 06/16/43 | 54000 | 01/01/60 | 54000 | | 17 | 17 |
| FORT PECK-PLANT#1 | 1 | 07/23/43 | 35000 | 05/29/78 | 43500 | | 35 | 35 |
| Apalachia | 2 | 09/01/43 | 37500 | 04/01/73 | 41400 | Degradation | 30 | 30 |
| BONNEVILLE | 9 | 09/15/43 | 54000 | 01/01/70 | 54000 | | 26 | 26 |
| DeCew Falls 2 GS | 1 | 10/01/43 | 57600 | | | | 0 | 49 |
| Wilson | 15 | 11/01/43 | 25200 | 11/01/79 | 25200 | Coil Failure | 36 | 36 |
| Apalachia | 1 | 11/01/43 | 37500 | 04/01/77 | 41400 | Coil Failures | 33 | 33 |
| Fort Loudoun | 2 | 11/01/43 | 32000 | 09/01/58 | 32000 | Degradation | 15 | 15 |
| BONNEVILLE | 10 | 12/15/43 | 54000 | 01/01/58 | 54000 | | 14 | 14 |
| Douglas | 1 | 01/01/44 | 30000 | 03/01/72 | 31500 | Degradation | 28 | 28 |
| Fort Loudoun | 1 | 01/01/44 | 32000 | 10/01/56 | 32000 | Degradation | 13 | 13 |
| Watts Bar | 5 | 03/01/44 | 30000 | 04/01/77 | 33300 | Coil Failure | 33 | 33 |
| Watts Bar | 4 | 04/01/44 | 30000 | 05/01/79 | 33300 | Coil Failure | 35 | 35 |
| DENISON | 1 | 06/10/44 | 35000 | | | | 0 | 49 |
| NORFORK | 2 | 06/18/44 | 35000 | 07/07/79 | 40275 | | 35 | 35 |
| Kentucky | 3 | 09/01/44 | 32000 | 09/01/63 | 32000 | Degradation | 19 | 19 |
| Kentucky | 2 | 11/01/44 | 32000 | 10/01/57 | 32000 | Degradation | 13 | 13 |
| Alexander GS | 4 | 01/01/45 | 13500 | | | | 0 | 48 |
| Fontana | 2 | 01/01/45 | 81000 | 12/01/91 | 81000 | Coil Failure | 47 | 47 |
| Fontana | 1 | 01/01/45 | 67500 | 12/01/75 | 81000 | Coil Failure | 31 | 31 |
| Fontana | 3 | 03/01/45 | 67500 | 05/01/69 | 76500 | Degradation | 24 | 24 |
| Kentucky | 1 | 04/01/45 | 32000 | 05/01/70 | 37000 | Degradation | 25 | 25 |
| Kentucky | 4 | 12/01/45 | 32000 | 10/01/70 | 37000 | Degradation | 25 | 25 |
| Aguasabon GS | 2 | 01/01/48 | 20250 | | | | 0 | 45 |
| Aguasabon GS | 1 | 01/01/48 | 20250 | 04/01/90 | 20250 | Degradation | 42 | 42 |
| Kentucky | 5 | 01/01/48 | 32000 | 09/01/69 | 37000 | Degradation | 22 | 22 |
| DeCew Falls 2 GS | 2 | 01/01/48 | 57600 | 01/01/54 | 57600 | Other - Converted to | 6 | 6 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| FORT PECK-PLANT#1 | 2 | 02/01/48 | 15000 | 12/01/78 | 18250 | | 31 | 31 |
| Ear Falls GS | 4 | 06/01/48 | 5400 | 01/01/91 | 5400 | Degradation | 43 | 43 |
| Stewartville GS | 1 | 09/21/48 | 20400 | | | | 0 | 44 |
| Stewartville GS | 2 | 09/28/48 | 20400 | | | | 0 | 44 |
| Wheeler | 5 | 10/01/48 | 32400 | 06/01/82 | 35100 | Coil Failure | 34 | 34 |
| Fort Loudoun | 3 | 10/01/48 | 32000 | 09/01/62 | 32000 | Degradation | 14 | 14 |
| Stewartville GS | 3 | 10/28/48 | 20400 | | | | 0 | 44 |
| DALE HOLLOW | 1 | 12/18/48 | 18000 | | | | 0 | 44 |
| Fort Loudoun | 4 | 01/01/49 | 32000 | 09/01/68 | 35190 | Degradation | 20 | 20 |
| DALE HOLLOW | 2 | 01/26/49 | 18000 | | | | 0 | 44 |
| Wheeler | 6 | 02/01/49 | 32400 | 05/01/77 | 35100 | Coil Failure | 28 | 28 |
| Douglas | 2 | 05/01/49 | 26000 | 04/01/77 | 28800 | Coil Failure | 28 | 28 |
| Watauga | 2 | 08/01/49 | 25000 | 05/01/80 | 28800 | Coil Failure | 31 | 31 |
| Watauga | 1 | 09/01/49 | 25000 | 10/01/78 | 28800 | Coil Failure | 29 | 29 |
| DENISON | 2 | 09/15/49 | 35000 | | | | 0 | 44 |
| Wheeler | 7 | 10/01/49 | 32400 | 11/01/83 | 35100 | Coil Failure | 34 | 34 |
| Wilson | 13 | 12/01/49 | 25200 | 06/01/80 | 25200 | Degradation | 31 | 31 |
| Chenaux GS | 2 | 01/01/50 | 15300 | 03/01/93 | 15300 | Degradation | 43 | 43 |
| Chenaux GS | 1 | 01/01/50 | 15300 | | | | 0 | 43 |
| Wilson | 14 | 01/01/50 | 25200 | 06/01/82 | 25200 | Coil Failure | 32 | 32 |
| ALLATOONA | 1 | 01/31/50 | 36000 | | | | 0 | 43 |
| Wilson | 17 | 02/01/50 | 25200 | 10/01/81 | 25200 | Degradation | 32 | 32 |
| NORFORK | 1 | 02/07/50 | 35000 | 02/08/79 | 36250 | | 29 | 29 |
| Wheeler | 8 | 03/01/50 | 32400 | 06/01/84 | 35100 | Coil Failure | 34 | 34 |
| Wilson | 18 | 03/01/50 | 25200 | 06/01/81 | 25200 | Degradation | 31 | 31 |
| ALLATOONA | 2 | 05/25/50 | 36000 | | | | 0 | 43 |
| Pine Portage GS | 1 | 06/17/50 | 29700 | | | | 0 | 43 |
| NARROWS | 2 | 06/22/50 | 8500 | | | | 0 | 43 |
| Wilbur | 4 | 07/01/50 | 7000 | | | | 0 | 42 |
| G.W. Rayner GS | 1 | 07/04/50 | 21150 | | | | 0 | 42 |
| Des Joachims GS | 1 | 07/06/50 | 45000 | 01/01/77 | 45000 | Degradation | 27 | 27 |
| Des Joachims GS | 2 | 07/06/50 | 45000 | 01/01/75 | 45000 | Degradation | 25 | 25 |
| G.W. Rayner GS | 2 | 07/28/50 | 21150 | | | | 0 | 42 |
| Des Joachims GS | 3 | 08/12/50 | 45000 | 01/01/77 | 45000 | Degradation | 26 | 26 |
| Des Joachims GS | 4 | 08/27/50 | 45000 | 01/01/71 | 45000 | Degradation | 20 | 20 |
| NARROWS | 1 | 09/22/50 | 8500 | | | | 0 | 43 |
| Des Joachims GS | 5 | 10/01/50 | 45000 | 01/01/73 | 45000 | Degradation | 22 | 22 |
| Des Joachims GS | 6 | 11/05/50 | 45000 | 01/01/75 | 45000 | Degradation | 24 | 24 |
| CENTER HILL | 1 | 12/11/50 | 45000 | | | | 0 | 43 |
| Des Joachims GS | 7 | 12/13/50 | 45000 | 01/01/72 | 45000 | Degradation | 21 | 21 |
| Chenaux GS | 5 | 01/01/51 | 15300 | | | | 0 | 42 |
| Chenaux GS | 8 | 01/01/51 | 15300 | | | | 0 | 42 |
| Chenaux GS | 7 | 01/01/51 | 15300 | 12/01/91 | 15300 | Degradation | 41 | 41 |
| Chenaux GS | 4 | 01/01/51 | 15300 | 11/01/90 | 15300 | Degradation | 40 | 40 |
| Chenaux GS | 6 | 01/01/51 | 15300 | 12/01/89 | 15300 | Degradation | 39 | 39 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| Chenaux GS | 3 | 01/01/51 | 15300 | 12/01/88 | 15300 | Degradation | 38 | 38 |
| CENTER HILL | 2 | 01/17/51 | 45000 | | | | 0 | 42 |
| Des Joachims GS | 8 | 02/01/51 | 45000 | 01/01/87 | 45000 | Degradation | 36 | 36 |
| South Holston | 1 | 02/01/51 | 35000 | 06/01/85 | 38500 | Coil Failure | 34 | 34 |
| CENTER HILL | 3 | 04/11/51 | 45000 | | | | 0 | 42 |
| WOLF CREEK | 6 | 10/06/51 | 50000 | | | | 0 | 42 |
| ST. MARYS | 1 | 10/12/51 | 5000 | | | | 0 | 42 |
| WOLF CREEK | 5 | 10/31/51 | 50000 | | | | 0 | 42 |
| ST. MARYS | 2 | 11/29/51 | 5000 | | | | 0 | 42 |
| WOLF CREEK | 4 | 12/16/51 | 50000 | | | | 0 | 42 |
| FORT PECK-PLANT#1 | 3 | 12/19/51 | 35000 | 07/22/78 | 43500 | | 27 | 27 |
| Otto Holden GS | 1 | 01/01/52 | 25650 | | | | 0 | 41 |
| Otto Holden GS | 2 | 01/01/52 | 25650 | | | | 0 | 41 |
| Otto Holden GS | 3 | 01/01/52 | 25650 | | | | 0 | 41 |
| Otto Holden GS | 4 | 01/01/52 | 25650 | | | | 0 | 41 |
| Otto Holden GS | 5 | 01/01/52 | 25650 | | | | 0 | 41 |
| Otto Holden GS | 6 | 01/01/52 | 25650 | | | | 0 | 41 |
| Otto Holden GS | 7 | 01/01/52 | 25650 | | | | 0 | 41 |
| Otto Holden GS | 8 | 01/01/52 | 25650 | | | | 0 | 41 |
| ST. MARYS | 3 | 02/04/52 | 5000 | | | | 0 | 41 |
| Chickamauga | 4 | 03/01/52 | 27000 | 11/01/79 | 30000 | Coil Failure | 28 | 28 |
| Guntersville | 4 | 03/01/52 | 24300 | 06/01/78 | 28800 | Coil Failure | 26 | 26 |
| WOLF CREEK | 3 | 03/17/52 | 50000 | | | | 0 | 41 |
| Nickajack | 1 | 07/01/52 | 24300 | 11/01/75 | 27450 | Coil Failure | 23 | 23 |
| WOLF CREEK | 2 | 07/24/52 | 50000 | | | | 0 | 41 |
| WOLF CREEK | 1 | 08/22/52 | 50000 | | | | 0 | 41 |
| BULL SHOALS | 1 | 09/18/52 | 40000 | 04/06/83 | 45000 | | 31 | 31 |
| BULL SHOALS | 2 | 09/29/52 | 40000 | 05/04/83 | 45000 | | 31 | 31 |
| Pickwick | 5 | 10/01/52 | 36000 | 10/01/85 | 40400 | Degradation | 33 | 33 |
| JOHN H. KERR | 2 | 11/18/52 | 32000 | | | | 0 | 41 |
| Pickwick | 6 | 12/01/52 | 36000 | 10/01/82 | 40400 | Coil Failure | 30 | 30 |
| BULL SHOALS | 3 | 12/01/52 | 40000 | 07/01/81 | 45000 | | 29 | 29 |
| JOHN H. KERR | 1 | 12/15/52 | 12000 | | | | 0 | 41 |
| Ocoee 2 | 1 | 01/01/53 | 10500 | 01/01/91 | 11548 | Uprate | 38 | 38 |
| Cherokee | 2 | 01/01/53 | 30000 | 04/01/75 | 34650 | Coil Failure | 22 | 22 |
| J. STROM THURMOND | 1 | 01/05/53 | 40000 | | | | 0 | 40 |
| JOHN H. KERR | 3 | 01/20/53 | 32000 | | | | 0 | 40 |
| J. STROM THURMOND | 2 | 02/23/53 | 40000 | | | | 0 | 40 |
| Boone | 3 | 03/01/53 | 25000 | | | | 0 | 40 |
| JOHN H. KERR | 4 | 03/21/53 | 32000 | | | | 0 | 40 |
| FORT GIBSON | 1 | 03/30/53 | 11250 | | | | 0 | 40 |
| FORT GIBSON | 2 | 03/31/53 | 11250 | | | | 0 | 40 |
| FORT GIBSON | 3 | 05/29/53 | 11250 | | | | 0 | 40 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| J. STROM THURMOND | 3 | 05/29/53 | 40000 | | | | 0 | 40 |
| Boone | 2 | 06/01/53 | 25000 | | | | 0 | 40 |
| BULL SHOALS | 4 | 06/12/53 | 40000 | 01/09/83 | 45000 | | 30 | 30 |
| WHITTNEY | 1 | 06/25/53 | 15000 | | | | 0 | 40 |
| WHITTNEY | 2 | 06/25/53 | 15000 | | | | 0 | 40 |
| DETROIT | 1 | 07/01/53 | 50000 | | | | 0 | 40 |
| Boone | 1 | 09/01/53 | 25000 | 06/01/83 | 26400 | Degradation | 30 | 30 |
| FORT GIBSON | 4 | 09/02/53 | 11250 | | | | 0 | 40 |
| JOHN H. KERR | 5 | 09/06/53 | 32000 | | | | 0 | 40 |
| PHILPOTT | 2 | 09/07/53 | 6750 | | | | 0 | 40 |
| PHILPOTT | 1 | 09/14/53 | 6750 | | | | 0 | 40 |
| Cherokee | 4 | 10/01/53 | 30000 | 10/01/77 | 33400 | Coil Failure | 24 | 24 |
| J. STROM THURMOND | 4 | 10/06/53 | 40000 | | | | 0 | 40 |
| DETROIT | 2 | 10/19/53 | 50000 | | | | 0 | 40 |
| JOHN H. KERR | 6 | 10/27/53 | 32000 | | | | 0 | 40 |
| TENKILLER FERRY | 1 | 10/28/53 | 17895 | 05/20/83 | 19550 | | 30 | 30 |
| TENKILLER FERRY | 2 | 10/29/53 | 17895 | 06/23/78 | 19550 | | 25 | 25 |
| MCNARY | 1 | 11/06/53 | 70000 | | | | 0 | 40 |
| DALE HOLLOW | 3 | 11/17/53 | 18000 | | | | 0 | 40 |
| Fort Patrick Henry | 2 | 12/01/53 | 18000 | | | | 0 | 39 |
| JOHN H. KERR | 7 | 12/05/53 | 32000 | | | | 0 | 40 |
| MCNARY | 2 | 12/28/53 | 70000 | | | | 0 | 39 |
| DeCew Falls 2 GS | 2 | 01/01/54 | 57600 | | | | 0 | 39 |
| Sir Adam Beck 2 GS | 11 | 01/01/54 | 76475 | | | | 0 | 39 |
| Sir Adam Beck 2 GS | 12 | 01/01/54 | 76475 | | | | 0 | 39 |
| Sir Adam Beck 2 GS | 13 | 01/01/54 | 76475 | | | | 0 | 39 |
| Sir Adam Beck 2 GS | 14 | 01/01/54 | 76475 | | | | 0 | 39 |
| Sir Adam Beck 2 GS | 15 | 01/01/54 | 76475 | | | | 0 | 39 |
| Sir Adam Beck 2 GS | 16 | 01/01/54 | 76475 | | | | 0 | 39 |
| Sir Adam Beck 2 GS | 17 | 01/01/54 | 76475 | | | | 0 | 39 |
| J. STROM THURMOND | 5 | 01/26/54 | 40000 | | | | 0 | 39 |
| Fort Patrick Henry | 1 | 02/01/54 | 18000 | | | | 0 | 39 |
| Fontana | 4 | 02/01/54 | 67500 | 05/01/70 | 81000 | Degradation | 16 | 16 |
| FORT RANDALL | 1 | 03/15/54 | 40000 | | | | 0 | 39 |
| MCNARY | 3 | 04/10/54 | 70000 | | | | 0 | 39 |
| FORT RANDALL | 2 | 05/18/54 | 40000 | | | | 0 | 39 |
| J. STROM THURMOND | 6 | 05/24/54 | 40000 | | | | 0 | 39 |
| BIG CLIFF | 1 | 06/12/54 | 18000 | | | | 0 | 39 |
| MCNARY | 4 | 06/16/54 | 70000 | | | | 0 | 39 |
| J. STROM THURMOND | 7 | 07/28/54 | 40000 | | | | 0 | 39 |
| Douglas | 4 | 08/01/54 | 26000 | 10/01/76 | 28800 | Coil Failure | 22 | 22 |
| Pine Portage GS | 2 | 09/15/54 | 29700 | | | | 0 | 38 |

| **Plant Name** | **Unit Number** | **POL Date** | **Power (kW)** | **Rewind Date** | **Rewind Rating (KW)** | **Rewind Reason** | **Age at Failure (Years)** | **Age (Years)** |
|---|---|---|---|---|---|---|---|---|
| MCNARY | 5 | 09/23/54 | 70000 | | | | 0 | 39 |
| Pine Portage GS | 3 | 09/30/54 | 34650 | 01/01/76 | 34650 | Degradation | 21 | 21 |
| Pickwick | 4 | 10/01/54 | 40400 | | | | 0 | 38 |
| FORT RANDALL | 3 | 10/30/54 | 40000 | | | | 0 | 39 |
| FORT RANDALL | 4 | 10/30/54 | 40000 | | | | 0 | 39 |
| Chatuge | 1 | 12/01/54 | 10000 | | | | 0 | 38 |
| LOOKOUT POINT | 3 | 12/16/54 | 40000 | | | | 0 | 39 |
| MCNARY | 6 | 12/30/54 | 70000 | | | | 0 | 38 |
| Pine Portage GS | 4 | 12/30/54 | 34650 | 01/01/88 | 34650 | Degradation | 33 | 33 |
| Sir Adam Beck 2 GS | 9 | 01/01/55 | 46750 | | | | 0 | 38 |
| Sir Adam Beck 2 GS | 10 | 01/01/55 | 46750 | | | | 0 | 38 |
| Sir Adam Beck 2 GS | 18 | 01/01/55 | 76475 | | | | 0 | 38 |
| Sir Adam Beck 2 GS | 19 | 01/01/55 | 76475 | | | | 0 | 38 |
| Sir Adam Beck 2 GS | 20 | 01/01/55 | 76475 | | | | 0 | 38 |
| Sir Adam Beck 2 GS | 21 | 01/01/55 | 76475 | | | | 0 | 38 |
| Sir Adam Beck 2 GS | 22 | 01/01/55 | 76475 | | | | 0 | 38 |
| FORT RANDALL | 5 | 02/04/55 | 40000 | | | | 0 | 38 |
| LOOKOUT POINT | 2 | 02/16/55 | 40000 | | | | 0 | 38 |
| MCNARY | 7 | 02/28/55 | 70000 | | | | 0 | 38 |
| ALBENI FALLS | 1 | 04/01/55 | 14200 | | | | 0 | 38 |
| LOOKOUT POINT | 1 | 04/25/55 | 40000 | | | | 0 | 38 |
| ALBENI FALLS | 2 | 05/16/55 | 14200 | | | | 0 | 38 |
| DEXTER | 1 | 05/19/55 | 15000 | | | | 0 | 38 |
| FORT RANDALL | 6 | 06/02/55 | 40000 | | | | 0 | 38 |
| MCNARY | 8 | 06/15/55 | 70000 | | | | 0 | 38 |
| ALBENI FALLS | 3 | 08/06/55 | 14200 | | | | 0 | 38 |
| MCNARY | 9 | 08/14/55 | 73700 | | | | 0 | 38 |
| CHIEF JOSEPH | 1 | 08/20/55 | 64000 | 01/01/87 | 88270 | | 31 | 31 |
| CHIEF JOSEPH | 2 | 08/20/55 | 64000 | 01/01/87 | 88270 | | 31 | 31 |
| CHIEF JOSEPH | 3 | 08/20/55 | 64000 | 01/01/87 | 88270 | | 31 | 31 |
| BLAKELY MT. | 1 | 09/15/55 | 37500 | | | | 0 | 38 |
| FORT RANDALL | 7 | 09/23/55 | 40000 | | | | 0 | 38 |
| BLAKELY MT. | 2 | 10/01/55 | 37500 | | | | 0 | 38 |
| MCNARY | 10 | 10/28/55 | 70000 | | | | 0 | 38 |
| CHIEF JOSEPH | 4 | 11/16/55 | 64000 | 01/01/87 | 88270 | | 31 | 31 |
| Nottely | 1 | 01/01/56 | 15000 | | | | 0 | 37 |
| FORT RANDALL | 8 | 01/10/56 | 40000 | | | | 0 | 37 |
| GARRISON | 1 | 01/28/56 | 80000 | 11/23/85 | 109250 | | 30 | 30 |
| GARRISON | 2 | 03/13/56 | 80000 | 12/05/86 | 109250 | | 31 | 31 |
| Manitou Falls GS | 1 | 03/29/56 | 14400 | | | | 0 | 37 |
| Manitou Falls GS | 2 | 04/04/56 | 14400 | | | | 0 | 37 |
| MCNARY | 11 | 04/08/56 | 70000 | | | | 0 | 37 |
| MCNARY | 12 | 04/22/56 | 70000 | | | | 0 | 37 |
| Hiwassee | 2 | 05/01/56 | 59500 | | | | 0 | 37 |
| Manitou Falls GS | 3 | 05/03/56 | 14400 | | | | 0 | 37 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| Manitou Falls GS | 4 | 07/15/56 | 14400 | | | | 0 | 36 |
| CHIEF JOSEPH | 5 | 08/09/56 | 64000 | 01/01/82 | 88270 | | 25 | 25 |
| GARRISON | 3 | 08/20/56 | 80000 | 06/14/85 | 109250 | | 29 | 29 |
| GAVINS POINT | 1 | 09/20/56 | 33345 | 03/01/88 | 44100 | | 31 | 31 |
| Fort Loudoun | 1 | 10/01/56 | 32000 | 10/01/77 | 35550 | Degradation | 21 | 21 |
| CHIEF JOSEPH | 6 | 10/03/56 | 64000 | 01/01/87 | 88270 | | 30 | 30 |
| GAVINS POINT | 2 | 10/15/56 | 33345 | 03/18/88 | 44100 | | 31 | 31 |
| CHIEF JOSEPH | 7 | 11/22/56 | 64000 | 01/01/87 | 88270 | | 30 | 30 |
| Sir Adam Beck 2 GS | 23 | 01/01/57 | 76475 | | | | 0 | 36 |
| Sir Adam Beck 2 GS | 24 | 01/01/57 | 76475 | | | | 0 | 36 |
| GAVINS POINT | 3 | 01/05/57 | 33345 | 03/07/87 | 44100 | | 30 | 30 |
| CHIEF JOSEPH | 8 | 01/11/57 | 64000 | 01/01/79 | 88270 | | 22 | 22 |
| JIM WOODRUFF | 1 | 02/01/57 | 10000 | | | | 0 | 36 |
| MCNARY | 14 | 02/08/57 | 70000 | 01/01/87 | 84700 | | 30 | 30 |
| MCNARY | 13 | 02/08/57 | 70000 | 01/01/73 | 73700 | | 16 | 16 |
| JIM WOODRUFF | 2 | 03/01/57 | 10000 | | | | 0 | 36 |
| OLD HICKORY | 1 | 04/05/57 | 25000 | | | | 0 | 36 |
| CHIEF JOSEPH | 9 | 04/13/57 | 64000 | 01/01/86 | 88270 | | 29 | 29 |
| JIM WOODRUFF | 3 | 04/26/57 | 10000 | | | | 0 | 36 |
| THE DALLES | F1 | 05/13/57 | 13500 | | | | 0 | 36 |
| THE DALLES | F2 | 06/03/57 | 13500 | | | | 0 | 36 |
| CHIEF JOSEPH | 10 | 06/06/57 | 64000 | 01/01/86 | 88270 | | 29 | 29 |
| BUFORD | 1 | 06/20/57 | 44444 | | | | 0 | 36 |
| Sir Adam Beck PGS | 1 | 06/27/57 | 29450 | | | | 0 | 36 |
| OLD HICKORY | 2 | 07/02/57 | 25000 | | | | 0 | 36 |
| BUFORD | 2 | 07/26/57 | 44444 | | | | 0 | 36 |
| CHIEF JOSEPH | 11 | 08/10/57 | 64000 | 01/01/85 | 88270 | | 27 | 27 |
| OLD HICKORY | 3 | 09/21/57 | 25000 | | | | 0 | 36 |
| THE DALLES | 1 | 09/25/57 | 78000 | | | | 0 | 36 |
| Kentucky | 2 | 10/01/57 | 32000 | | | | 0 | 35 |
| BUFORD | 3 | 10/10/57 | 6667 | | | | 0 | 36 |
| CHIEF JOSEPH | 12 | 10/12/57 | 64000 | 01/01/85 | 88270 | | 27 | 27 |
| Sir Adam Beck PGS | 2 | 10/21/57 | 29450 | | | | 0 | 35 |
| THE DALLES | 2 | 10/31/57 | 78000 | | | | 0 | 36 |
| Sir Adam Beck PGS | 3 | 12/09/57 | 29450 | 01/01/90 | 29450 | Degradation | 32 | 32 |
| OLD HICKORY | 4 | 12/19/57 | 25000 | | | | 0 | 35 |
| BONNEVILLE | 10 | 01/01/58 | 54000 | | | | 0 | 35 |
| Ontario Power GS | 6 | 01/01/58 | 8770 | | | | 0 | 35 |
| Sir Adam Beck 2 GS | 25 | 01/01/58 | 76475 | | | | 0 | 35 |
| Sir Adam Beck 2 GS | 26 | 01/01/58 | 76475 | | | | 0 | 35 |
| CHIEF JOSEPH | 13 | 01/16/58 | 64000 | 01/01/86 | 88270 | | 28 | 28 |
| THE DALLES | 3 | 01/17/58 | 78000 | | | | 0 | 35 |
| Whitedog GS | 1 | 02/17/58 | 21600 | | | | 0 | 35 |
| Sir Adam Beck PGS | 4 | 03/03/58 | 29450 | | | | 0 | 35 |
| Manitou Falls GS | 5 | 03/17/58 | 14400 | | | | 0 | 35 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| Whitedog GS | 2 | 03/25/58 | 21600 | | | | 0 | 35 |
| Alexander GS | 5 | 04/01/58 | 13500 | | | | 0 | 35 |
| R.H. Saunders GS | 1 | 04/08/58 | 57000 | 01/01/92 | 57000 | Degradation | 34 | 34 |
| Sir Adam Beck PGS | 5 | 04/11/58 | 29450 | | | | 0 | 35 |
| CHIEF JOSEPH | 14 | 04/21/58 | 64000 | 01/01/86 | 88270 | | 28 | 28 |
| THE DALLES | 4 | 04/24/58 | 78000 | | | | 0 | 35 |
| CHEATHAM | 1 | 05/13/58 | 12000 | | | | 0 | 35 |
| Sir Adam Beck PGS | 6 | 06/09/58 | 29450 | 01/01/92 | 29450 | Degradation | 34 | 34 |
| CHIEF JOSEPH | 15 | 06/13/58 | 64000 | 01/01/86 | 88270 | | 28 | 28 |
| Whitedog GS | 3 | 06/16/58 | 21600 | | | | 0 | 35 |
| R.H. Saunders GS | 2 | 07/05/58 | 57000 | | | | 0 | 34 |
| CHEATHAM | 2 | 07/17/58 | 12000 | | | | 0 | 35 |
| Caribou Falls GS | 1 | 07/27/58 | 25650 | | | | 0 | 34 |
| R.H. Saunders GS | 4 | 07/28/58 | 57000 | | | | 0 | 34 |
| R.H. Saunders GS | 3 | 08/22/58 | 57000 | | | | 0 | 34 |
| Fort Loudoun | 2 | 09/01/58 | 32000 | 04/01/72 | 34200 | Degradation | 14 | 14 |
| Cameron Falls GS | 7 | 09/09/58 | 19000 | | | | 0 | 34 |
| THE DALLES | 5 | 09/11/58 | 78000 | | | | 0 | 35 |
| Caribou Falls GS | 2 | 09/11/58 | 25650 | | | | 0 | 34 |
| R.H. Saunders GS | 5 | 09/12/58 | 57000 | | | | 0 | 34 |
| CHIEF JOSEPH | 16 | 09/27/58 | 64000 | 01/01/86 | 88270 | | 27 | 27 |
| R.H. Saunders GS | 7 | 10/07/58 | 57000 | | | | 0 | 34 |
| Caribou Falls GS | 3 | 10/11/58 | 25650 | 01/01/64 | 25650 | Other - Fire | 5 | 5 |
| THE DALLES | 6 | 10/24/58 | 78000 | | | | 0 | 35 |
| CHEATHAM | 3 | 11/05/58 | 12000 | | | | 0 | 35 |
| R.H. Saunders GS | 6 | 11/12/58 | 57000 | | | | 0 | 34 |
| Abitibi Canyon GS | 3 | 01/01/59 | 43200 | 04/01/78 | 43200 | Degradation | 19 | 19 |
| THE DALLES | 7 | 01/16/59 | 78000 | | | | 0 | 34 |
| R.H. Saunders GS | 9 | 01/19/59 | 57000 | | | | 0 | 34 |
| R.H. Saunders GS | 8 | 01/21/59 | 57000 | | | | 0 | 34 |
| R.H. Saunders GS | 10 | 03/19/59 | 57000 | 01/01/91 | 57000 | Degradation | 32 | 32 |
| R.H. Saunders GS | 11 | 03/25/59 | 57000 | | | | 0 | 34 |
| THE DALLES | 8 | 04/16/59 | 78000 | | | | 0 | 34 |
| TABLE ROCK | 2 | 05/21/59 | 50000 | | | | 0 | 34 |
| R.H. Saunders GS | 12 | 05/29/59 | 57000 | | | | 0 | 34 |
| R.H. Saunders GS | 13 | 06/08/59 | 57000 | | | | 0 | 34 |
| TABLE ROCK | 1 | 06/22/59 | 50000 | | | | 0 | 34 |
| R.H. Saunders GS | 15 | 08/13/59 | 57000 | | | | 0 | 33 |
| R.H. Saunders GS | 14 | 08/14/59 | 57000 | | | | 0 | 33 |
| THE DALLES | 9 | 08/28/59 | 78000 | | | | 0 | 34 |
| Silver Falls GS | 1 | 09/01/59 | 45000 | | | | 0 | 33 |
| THE DALLES | 10 | 10/10/59 | 78000 | | | | 0 | 34 |
| R.H. Saunders GS | 16 | 12/18/59 | 57000 | 01/01/90 | 57000 | Degradation | 30 | 30 |
| BONNEVILLE | 8 | 01/01/60 | 54000 | | | | 0 | 33 |
| Ontario Power GS | 12 | 01/01/60 | 8776 | | | | 0 | 33 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| THE DALLES | 11 | 01/26/60 | 78000 | | | | 0 | 33 |
| GARRISON | 4 | 03/21/60 | 80000 | 11/24/77 | 95000 | | 18 | 18 |
| THE DALLES | 12 | 04/05/60 | 78000 | 01/01/82 | 78000 | | 22 | 22 |
| GARRISON | 5 | 05/04/60 | 80000 | 03/01/89 | 95000 | | 29 | 29 |
| THE DALLES | 13 | 07/22/60 | 78000 | 01/01/88 | 78000 | | 27 | 27 |
| THE DALLES | 14 | 10/28/60 | 78000 | | | | 0 | 33 |
| Red Rock Falls GS | 1 | 11/05/60 | 20250 | | | | 0 | 32 |
| Red Rock Falls GS | 2 | 01/13/61 | 20250 | | | | 0 | 32 |
| TABLE ROCK | 3 | 04/21/61 | 50000 | | | | 0 | 32 |
| TABLE ROCK | 4 | 06/16/61 | 50000 | | | | 0 | 32 |
| FORT PECK-PLANT#2 | 4 | 06/28/61 | 40000 | | | | 0 | 32 |
| FORT PECK-PLANT#2 | 5 | 06/28/61 | 40000 | | | | 0 | 32 |
| Otter Rapids GS | 1 | 09/26/61 | 43700 | | | | 0 | 31 |
| Otter Rapids GS | 2 | 10/24/61 | 43700 | | | | 0 | 31 |
| Wilson | 19 | 12/01/61 | 54000 | | | | 0 | 31 |
| ICE HARBOR | 1 | 12/18/61 | 94737 | | | | 0 | 31 |
| Wilson | 21 | 01/01/62 | 54000 | | | | 0 | 31 |
| BULL SHOALS | 5 | 01/16/62 | 45000 | 01/01/83 | 50000 | | 21 | 21 |
| ICE HARBOR | 3 | 02/08/62 | 94737 | | | | 0 | 31 |
| BULL SHOALS | 6 | 02/08/62 | 45000 | 01/01/83 | 50000 | | 21 | 21 |
| ICE HARBOR | 2 | 02/27/62 | 94737 | | | | 0 | 31 |
| Wilson | 20 | 04/01/62 | 54000 | | | | 0 | 31 |
| OAHE | 1 | 04/09/62 | 85000 | | | | 0 | 31 |
| HARTWELL | 1 | 04/24/62 | 66000 | | | | 0 | 31 |
| HILLS CREEK | 1 | 05/02/62 | 15000 | | | | 0 | 31 |
| HILLS CREEK | 2 | 05/02/62 | 15000 | | | | 0 | 31 |
| HARTWELL | 2 | 06/07/62 | 66000 | | | | 0 | 31 |
| OAHE | 3 | 07/27/62 | 85000 | 05/01/85 | 112290 | | 23 | 23 |
| Fort Loudoun | 3 | 09/01/62 | 32000 | 04/01/73 | 34200 | Degradation | 11 | 11 |
| HARTWELL | 3 | 09/17/62 | 66000 | | | | 0 | 31 |
| OAHE | 4 | 11/08/62 | 85000 | 11/03/84 | 112290 | | 22 | 22 |
| Wheeler | 9 | 12/01/62 | 32400 | 07/01/83 | 35100 | Coil Failure | 21 | 21 |
| HARTWELL | 4 | 12/11/62 | 66000 | | | | 0 | 31 |
| OAHE | 2 | 12/20/62 | 85000 | | | | 0 | 30 |
| WALTER GEORGE | 1 | 03/13/63 | 32500 | | | | 0 | 30 |
| OAHE | 5 | 03/28/63 | 85000 | 12/30/83 | 112290 | | 21 | 21 |
| WALTER GEORGE | 2 | 05/10/63 | 32500 | | | | 0 | 30 |
| OAHE | 6 | 05/23/63 | 85000 | | | | 0 | 30 |
| Wheeler | 10 | 06/01/63 | 32400 | | | | 0 | 30 |
| OAHE | 7 | 06/27/63 | 85000 | 05/30/84 | 112290 | | 21 | 21 |
| Otter Rapids GS | 3 | 07/30/63 | 43700 | | | | 0 | 29 |
| BULL SHOALS | 7 | 08/01/63 | 45000 | 01/01/83 | 50000 | | 19 | 19 |
| Kentucky | 3 | 09/01/63 | 32000 | | | | 0 | 29 |
| WALTER GEORGE | 3 | 09/16/63 | 32500 | | | | 0 | 30 |
| BULL SHOALS | 8 | 09/17/63 | 45000 | 01/01/83 | 50000 | | 19 | 19 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| Otter Rapids GS | 4 | 10/01/63 | 43700 | | | | 0 | 29 |
| WALTER GEORGE | 4 | 11/02/63 | 32500 | | | | 0 | 30 |
| Little Long GS | 1 | 11/28/63 | 60800 | | | | 0 | 29 |
| Little Long GS | 2 | 11/28/63 | 60800 | | | | 0 | 29 |
| Wheeler | 11 | 12/01/63 | 32400 | | | | 0 | 29 |
| Kakabeka Falls GS | 1 | 01/01/64 | 5398 | | | | 0 | 29 |
| Kakabeka Falls GS | 3 | 01/01/64 | 5398 | | | | 0 | 29 |
| Caribou Falls GS | 3 | 01/01/64 | 25650 | | | | 0 | 29 |
| COUGAR | 2 | 02/04/64 | 12500 | | | | 0 | 29 |
| GREERS FERRY | 1 | 03/17/64 | 48000 | | | | 0 | 29 |
| COUGAR | 1 | 03/23/64 | 12500 | | | | 0 | 29 |
| GREERS FERRY | 2 | 05/06/64 | 48000 | | | | 0 | 29 |
| Melton Hill | 1 | 07/01/64 | 36000 | | | | 0 | 28 |
| EUFAULA | 1 | 07/27/64 | 30000 | | | | 0 | 29 |
| EUFAULA | 3 | 08/21/64 | 30000 | | | | 0 | 29 |
| EUFAULA | 2 | 09/03/64 | 30000 | | | | 0 | 29 |
| BIG BEND | 1 | 10/01/64 | 58500 | | | | 0 | 29 |
| Melton Hill | 2 | 11/01/64 | 36000 | | | | 0 | 28 |
| BIG BEND | 2 | 11/24/64 | 58500 | | | | 0 | 29 |
| Kakabeka Falls GS | 2 | 01/01/65 | 5398 | | | | 0 | 28 |
| BIG BEND | 3 | 02/24/65 | 58500 | | | | 0 | 28 |
| DARDANELLE | 1 | 04/05/65 | 31000 | | | | 0 | 28 |
| DARDANELLE | 2 | 05/06/65 | 31000 | | | | 0 | 28 |
| BEAVER | 1 | 05/14/65 | 56000 | | | | 0 | 28 |
| BEAVER | 2 | 05/14/65 | 56000 | | | | 0 | 28 |
| BIG BEND | 4 | 05/19/65 | 58500 | | | | 0 | 28 |
| Harmon GS | 1 | 06/01/65 | 64600 | 01/01/87 | 64600 | Other - Replacement | 22 | 22 |
| Harmon GS | 2 | 06/01/65 | 64600 | 01/01/78 | 64600 | Degradation | 13 | 13 |
| SAM RAYBURN | 1 | 09/23/65 | 26000 | | | | 0 | 28 |
| SAM RAYBURN | 2 | 09/23/65 | 26000 | | | | 0 | 28 |
| DARDANELLE | 3 | 09/24/65 | 31000 | | | | 0 | 28 |
| BIG BEND | 5 | 10/04/65 | 58500 | | | | 0 | 28 |
| BIG BEND | 6 | 01/01/66 | 58500 | | | | 0 | 27 |
| Kakabeka Falls GS | 4 | 01/01/66 | 5398 | | | | 0 | 27 |
| DARDANELLE | 4 | 01/14/66 | 31000 | | | | 0 | 27 |
| BARKLEY | 1 | 01/20/66 | 32500 | | | | 0 | 27 |
| BARKLEY | 2 | 02/04/66 | 32500 | | | | 0 | 27 |
| BARKLEY | 3 | 03/07/66 | 32500 | | | | 0 | 27 |
| BARKLEY | 4 | 03/30/66 | 32500 | | | | 0 | 27 |
| BIG BEND | 7 | 05/13/66 | 58500 | | | | 0 | 27 |
| Kipling GS | 1 | 06/29/66 | 62700 | | | | 0 | 26 |
| Kipling GS | 2 | 07/05/66 | 62700 | 01/01/87 | 62700 | Other - Replacement | 21 | 21 |
| BIG BEND | 8 | 07/19/66 | 58500 | | | | 0 | 27 |
| Wilson | 4 | 10/01/66 | 23000 | | | | 0 | 26 |
| Wilson | 3 | 05/01/67 | 23000 | | | | 0 | 26 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| Wilson | 8 | 05/01/67 | 30960 | | | | 0 | 26 |
| GREEN PETER | 1 | 06/09/67 | 40000 | | | | 0 | 26 |
| GREEN PETER | 2 | 06/28/67 | 40000 | | | | 0 | 26 |
| Wilson | 1 | 07/01/67 | 23000 | | | | 0 | 25 |
| Wilson | 7 | 08/01/67 | 30960 | | | | 0 | 25 |
| Wilson | 2 | 11/01/67 | 23000 | | | | 0 | 25 |
| Mountain Chute GS | 1 | 11/11/67 | 71250 | | | | 0 | 25 |
| Nickajack | 4 | 12/01/67 | 24300 | | | | 0 | 25 |
| Mountain Chute GS | 2 | 12/09/67 | 71250 | | | | 0 | 25 |
| Nickajack | 3 | 01/01/68 | 24300 | | | | 0 | 25 |
| Wilson | 6 | 02/01/68 | 30960 | | | | 0 | 25 |
| Nickajack | 2 | 04/01/68 | 24300 | 10/01/81 | 27900 | Coil Failure | 14 | 14 |
| Wilson | 5 | 05/01/68 | 30960 | | | | 0 | 25 |
| KEYSTONE | 2 | 05/02/68 | 35000 | | | | 0 | 25 |
| KEYSTONE | 1 | 05/21/68 | 35000 | | | | 0 | 25 |
| JOHN DAY | 1 | 07/16/68 | 135000 | 01/01/86 | 135000 | | 17 | 17 |
| FOSTER | 1 | 08/22/68 | 10000 | | | | 0 | 25 |
| JOHN DAY | 2 | 08/29/68 | 135000 | 01/01/86 | 135000 | | 17 | 17 |
| Fort Loudoun | 4 | 09/01/68 | 35190 | | | | 0 | 24 |
| FOSTER | 2 | 09/06/68 | 10000 | | | | 0 | 25 |
| Barrett Chute GS | 3 | 09/22/68 | 55800 | | | | 0 | 24 |
| Barrett Chute GS | 4 | 10/10/68 | 55800 | | | | 0 | 24 |
| JOHN DAY | 3 | 10/15/68 | 135000 | | | | 0 | 25 |
| Wilson | 10 | 11/01/68 | 25200 | | | | 0 | 24 |
| JOHN DAY | 4 | 11/16/68 | 135000 | | | | 0 | 25 |
| BONNEVILLE | 7 | 01/01/69 | 54000 | | | | 0 | 24 |
| Aubrey Fall GS | 1 | 01/11/69 | 65075 | | | | 0 | 24 |
| Aubrey Fall GS | 2 | 01/11/69 | 65075 | | | | 0 | 24 |
| JOHN DAY | 5 | 01/22/69 | 135000 | | | | 0 | 24 |
| JOHN DAY | 6 | 02/19/69 | 135000 | 01/01/88 | 135000 | | 19 | 19 |
| JOHN DAY | 7 | 03/26/69 | 135000 | | | | 0 | 24 |
| Fontana | 3 | 05/01/69 | 76500 | | | | 0 | 24 |
| JOHN DAY | 8 | 05/12/69 | 135000 | 01/01/90 | 135000 | | 21 | 21 |
| LOWER MONUMENTAL | 1 | 05/28/69 | 135000 | | | | 0 | 24 |
| Wilson | 12 | 06/01/69 | 25200 | | | | 0 | 24 |
| Stewartville GS | 4 | 07/01/69 | 45900 | | | | 0 | 23 |
| JOHN DAY | 9 | 07/02/69 | 135000 | 01/01/84 | 135000 | | 15 | 15 |
| Stewartville GS | 5 | 08/01/69 | 45900 | | | | 0 | 23 |
| JOHN DAY | 10 | 08/26/69 | 135000 | 01/01/84 | 135000 | | 14 | 14 |
| Wilson | 9 | 09/01/69 | 25200 | | | | 0 | 23 |
| Kentucky | 5 | 09/01/69 | 37000 | | | | 0 | 23 |
| LOWER MONUMENTAL | 2 | 09/08/69 | 135000 | 01/01/89 | 135000 | | 19 | 19 |
| NARROWS | 3 | 09/11/69 | 8500 | | | | 0 | 24 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| BONNEVILLE | 9 | 01/01/70 | 54000 | | | | 0 | 23 |
| Sir Adam Beck 1 GS | 3 | 01/01/70 | 46750 | | | | 0 | 23 |
| LOWER MONUMENTAL | 3 | 01/06/70 | 135000 | | | | 0 | 23 |
| BROKEN BOW | 1 | 01/27/70 | 50000 | 01/01/84 | 50000 | | 14 | 14 |
| J.PERCY PRIEST | 1 | 02/03/70 | 28000 | | | | 0 | 23 |
| JOHN DAY | 11 | 02/04/70 | 135000 | | | | 0 | 23 |
| LITTLE GOOSE | 1 | 03/26/70 | 135000 | | | | 0 | 23 |
| MILLERS FERRY | 1 | 04/15/70 | 25000 | | | | 0 | 23 |
| MILLERS FERRY | 2 | 04/20/70 | 25000 | | | | 0 | 23 |
| JOHN DAY | 12 | 04/22/70 | 135000 | | | | 0 | 23 |
| Fontana | 4 | 05/01/70 | 81000 | | | | 0 | 23 |
| Kentucky | 1 | 05/01/70 | 37000 | 11/01/83 | 37000 | Coil Failure | 14 | 14 |
| MILLERS FERRY | 3 | 05/27/70 | 25000 | | | | 0 | 23 |
| BROKEN BOW | 2 | 06/03/70 | 50000 | 09/30/84 | 50000 | | 14 | 14 |
| Kentucky | 4 | 10/01/70 | 37000 | | | | 0 | 22 |
| LITTLE GOOSE | 2 | 10/30/70 | 135000 | | | | 0 | 23 |
| Wells GS | 1 | 11/01/70 | 101650 | | | | 0 | 22 |
| Wells GS | 2 | 11/01/70 | 101650 | | | | 0 | 22 |
| JOHN DAY | 13 | 11/03/70 | 135000 | 01/01/84 | 135000 | | 13 | 13 |
| LITTLE GOOSE | 3 | 12/08/70 | 135000 | | | | 0 | 23 |
| JOHN DAY | 14 | 12/17/70 | 135000 | | | | 0 | 22 |
| Barrett Chute GS | 1 | 01/01/71 | 20400 | | | | 0 | 22 |
| Des Joachims GS | 4 | 01/01/71 | 45000 | | | | 0 | 22 |
| Lower Notch GS | 1 | 01/01/71 | 114000 | | | | 0 | 22 |
| Lower Notch GS | 2 | 01/01/71 | 114000 | | | | 0 | 22 |
| Douglas | 3 | 04/01/71 | 31500 | | | | 0 | 22 |
| ROBERT S. KERR | 2 | 07/27/71 | 27500 | | | | 0 | 22 |
| ROBERT S. KERR | 3 | 09/01/71 | 27500 | | | | 0 | 22 |
| JOHN DAY | 15 | 09/30/71 | 135000 | | | | 0 | 22 |
| Pickwick | 3 | 10/01/71 | 40400 | | | | 0 | 21 |
| ROBERT S. KERR | 1 | 10/05/71 | 27500 | | | | 0 | 22 |
| ROBERT S. KERR | 4 | 11/02/71 | 27500 | | | | 0 | 22 |
| JOHN DAY | 16 | 11/03/71 | 135000 | | | | 0 | 22 |
| DEGRAY | 1 | 11/29/71 | 40000 | | | | 0 | 22 |
| DEGRAY | 2 | 12/01/71 | 28000 | | | | 0 | 22 |
| Des Joachims GS | 7 | 01/01/72 | 45000 | | | | 0 | 21 |
| Tims Ford | 1 | 02/01/72 | 45000 | | | | 0 | 21 |
| Douglas | 1 | 03/01/72 | 31500 | | | | 0 | 21 |
| Fort Loudoun | 2 | 04/01/72 | 34200 | | | | 0 | 21 |
| OZARK | 1 | 11/17/72 | 20000 | | | | 0 | 21 |
| THE DALLES | 15 | 12/11/72 | 85975 | | | | 0 | 21 |
| THE DALLES | 16 | 12/17/72 | 85975 | | | | 0 | 20 |
| MCNARY | 13 | 01/01/73 | 73700 | | | | 0 | 20 |
| Barrett Chute GS | 2 | 01/01/73 | 20400 | | | | 0 | 20 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| Des Joachims GS | 5 | 01/01/73 | 45000 | | | | 0 | 20 |
| THE DALLES | 17 | 02/05/73 | 85975 | | | | 0 | 20 |
| THE DALLES | 18 | 02/27/73 | 85975 | | | | 0 | 20 |
| DWORSHAK | 1 | 03/01/73 | 90000 | | | | 0 | 20 |
| STOCKTON | 1 | 03/23/73 | 47579 | | | | 0 | 20 |
| Fort Loudoun | 3 | 04/01/73 | 34200 | | | | 0 | 20 |
| Apalachia | 2 | 04/01/73 | 41400 | 12/01/80 | 41400 | Coil Failure | 8 | 8 |
| DWORSHAK | 2 | 04/06/73 | 90000 | | | | 0 | 20 |
| THE DALLES | 19 | 04/14/73 | 85975 | | | | 0 | 20 |
| DWORSHAK | 3 | 04/20/73 | 222000 | | | | 0 | 20 |
| THE DALLES | 20 | 05/15/73 | 85975 | | | | 0 | 20 |
| Great Falls | 1 | 08/01/73 | 15360 | | | | 0 | 19 |
| WEBBERS FALLS | 1 | 08/06/73 | 20000 | | | | 0 | 20 |
| CORDELL HULL | 1 | 08/09/73 | 33333 | | | | 0 | 20 |
| OZARK | 2 | 09/10/73 | 20000 | | | | 0 | 20 |
| WEBBERS FALLS | 2 | 09/13/73 | 20000 | | | | 0 | 20 |
| Watts Bar | 2 | 10/01/73 | 33300 | | | | 0 | 19 |
| THE DALLES | 21 | 10/12/73 | 85975 | | | | 0 | 20 |
| CORDELL HULL | 2 | 10/19/73 | 33333 | | | | 0 | 20 |
| OZARK | 3 | 10/31/73 | 20000 | | | | 0 | 20 |
| THE DALLES | 22 | 11/13/73 | 85975 | | | | 0 | 20 |
| WEBBERS FALLS | 3 | 12/13/73 | 20000 | | | | 0 | 19 |
| OZARK | 4 | 12/17/73 | 20000 | | | | 0 | 19 |
| DeCew Falls 1 GS | 6 | 01/01/74 | 5300 | | | | 0 | 19 |
| Chats Falls GS | 2 | 01/01/74 | 22325 | | | | 0 | 19 |
| CORDELL HULL | 3 | 02/20/74 | 33333 | | | | 0 | 19 |
| OZARK | 5 | 05/14/74 | 20000 | | | | 0 | 19 |
| Guntersville | 3 | 10/01/74 | 28800 | | | | 0 | 18 |
| Cherokee | 3 | 10/01/74 | 34650 | | | | 0 | 18 |
| Abitibi Canyon GS | 1 | 01/01/75 | 41255 | | | | 42 | 42 |
| BONNEVILLE | 2 | 01/01/75 | 54200 | | | | 0 | 18 |
| DeCew Falls 1 GS | 5 | 01/01/75 | 5000 | | | | 0 | 18 |
| Ontario Power GS | 3 | 01/01/75 | 7500 | | | | 0 | 18 |
| Des Joachims GS | 2 | 01/01/75 | 45000 | | | | 0 | 18 |
| Des Joachims GS | 6 | 01/01/75 | 45000 | | | | 0 | 18 |
| WEST POINT | 3 | 03/17/75 | 35000 | | | | 0 | 18 |
| LIBBY | 4 | 03/17/75 | 105000 | | | | 0 | 18 |
| Cherokee | 2 | 04/01/75 | 34650 | | | | 0 | 18 |
| LOWER GRANITE | 1 | 04/03/75 | 135000 | 01/01/81 | 135000 | | 6 | 6 |
| WEST POINT | 2 | 04/10/75 | 35000 | | | | 0 | 18 |
| Ocoee 3 | 1 | 05/01/75 | 28800 | | | | 0 | 18 |
| LOWER GRANITE | 2 | 05/12/75 | 135000 | 01/01/81 | 135000 | | 6 | 6 |
| LOWER GRANITE | 3 | 06/24/75 | 135000 | 01/01/82 | 135000 | | 7 | 7 |
| JONES BLUFF | 1 | 06/27/75 | 17000 | | | | 0 | 18 |
| JONES BLUFF | 2 | 07/15/75 | 17000 | | | | 0 | 18 |

| **Plant Name** | **Unit Number** | **POL Date** | **Power (kW)** | **Rewind Date** | **Rewind Rating (KW)** | **Rewind Reason** | **Age at Failure (Years)** | **Age (Years)** |
|---|---|---|---|---|---|---|---|---|
| CARTERS | 2 | 07/23/75 | 125000 | | | | 0 | 18 |
| LIBBY | 1 | 08/13/75 | 105000 | 01/01/82 | 105000 | | 6 | 6 |
| JONES BLUFF | 3 | 09/05/75 | 17000 | | | | 0 | 18 |
| LIBBY | 2 | 10/10/75 | 105000 | | | | 0 | 18 |
| JONES BLUFF | 4 | 10/24/75 | 17000 | | | | 0 | 18 |
| Nickajack | 1 | 11/01/75 | 27450 | | | | 0 | 17 |
| CARTERS | 1 | 11/17/75 | 125000 | | | | 0 | 18 |
| ICE HARBOR | 5 | 11/18/75 | 116800 | | | | 0 | 18 |
| ICE HARBOR | 4 | 11/26/75 | 116800 | | | | 0 | 18 |
| Chickamauga | 3 | 12/01/75 | 30000 | | | | 0 | 17 |
| Fontana | 1 | 12/01/75 | 81000 | | | | 0 | 17 |
| Pine Portage GS | 3 | 01/01/76 | 34650 | | | | 0 | 17 |
| Arnprior GS | 1 | 01/01/76 | 37050 | | | | 0 | 17 |
| ICE HARBOR | 6 | 01/07/76 | 116800 | | | | 0 | 17 |
| LIBBY | 3 | 01/21/76 | 105000 | | | | 0 | 17 |
| Chickamauga | 1 | 04/01/76 | 30000 | | | | 0 | 17 |
| Cherokee | 1 | 04/01/76 | 33480 | | | | 0 | 17 |
| Douglas | 4 | 10/01/76 | 28800 | | | | 0 | 16 |
| Chickamauga | 2 | 10/01/76 | 30000 | | | | 0 | 16 |
| Ontario Power GS | 8 | 01/01/77 | 8776 | | | | 0 | 16 |
| Des Joachims GS | 1 | 01/01/77 | 45000 | | | | 0 | 16 |
| Des Joachims GS | 3 | 01/01/77 | 45000 | | | | 0 | 16 |
| DeCew Falls 1 GS | 7 | 01/01/77 | 5900 | | | | 0 | 16 |
| Arnprior GS | 2 | 01/01/77 | 37050 | | | | 0 | 16 |
| Douglas | 2 | 04/01/77 | 28800 | | | | 0 | 16 |
| Watts Bar | 5 | 04/01/77 | 33300 | | | | 0 | 16 |
| Apalachia | 1 | 04/01/77 | 41400 | | | | 0 | 16 |
| CARTERS | 3 | 04/17/77 | 125000 | | | | 0 | 16 |
| Wheeler | 6 | 05/01/77 | 35100 | | | | 0 | 16 |
| Abitibi Canyon GS | 2 | 05/01/77 | 63000 | | | | 0 | 16 |
| CHIEF JOSEPH | 17 | 05/27/77 | 95000 | | | | 0 | 16 |
| CARTERS | 4 | 06/01/77 | 125000 | | | | 0 | 16 |
| LOST CREEK | 1 | 07/06/77 | 24500 | | | | 0 | 16 |
| CHIEF JOSEPH | 18 | 07/13/77 | 95000 | | | | 0 | 16 |
| LOST CREEK | 2 | 07/15/77 | 24500 | | | | 0 | 16 |
| Wilson | 11 | 10/01/77 | 25200 | | | | 0 | 15 |
| Cherokee | 4 | 10/01/77 | 33400 | | | | 0 | 15 |
| Fort Loudoun | 1 | 10/01/77 | 35550 | | | | 0 | 15 |
| LAUREL | 1 | 10/13/77 | 61000 | | | | 0 | 16 |
| CHIEF JOSEPH | 19 | 11/03/77 | 95000 | | | | 0 | 16 |
| GARRISON | 4 | 11/24/77 | 95000 | | | | 0 | 16 |
| CHIEF JOSEPH | 20 | 12/15/77 | 95000 | | | | 0 | 15 |
| DeCew Falls 1 GS | 8 | 01/01/78 | 5600 | | | | 0 | 15 |
| Ontario Power GS | 10 | 01/01/78 | 8776 | | | | 0 | 15 |
| Harmon GS | 2 | 01/01/78 | 64600 | | | | 0 | 15 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| LITTLE GOOSE | 4 | 01/25/78 | 135000 | | | | 0 | 15 |
| LOWER GRANITE | 4 | 02/15/78 | 135000 | | | | 0 | 15 |
| Abitibi Canyon GS | 3 | 04/01/78 | 43200 | | | | 0 | 15 |
| LOWER GRANITE | 5 | 04/06/78 | 135000 | | | | 0 | 15 |
| LOWER GRANITE | 6 | 04/17/78 | 135000 | | | | 0 | 15 |
| LITTLE GOOSE | 5 | 05/19/78 | 135000 | | | | 0 | 15 |
| FORT PECK-PLANT#1 | 1 | 05/29/78 | 43500 | | | | 0 | 15 |
| Guntersville | 4 | 06/01/78 | 28800 | | | | 0 | 15 |
| Watts Bar | 1 | 06/01/78 | 33300 | | | | 0 | 15 |
| CHIEF JOSEPH | 21 | 06/05/78 | 95000 | | | | 0 | 15 |
| CHIEF JOSEPH | 22 | 06/08/78 | 95000 | | | | 0 | 15 |
| TENKILLER FERRY | 2 | 06/23/78 | 19550 | | | | 0 | 15 |
| LITTLE GOOSE | 6 | 07/05/78 | 135000 | | | | 0 | 15 |
| FORT PECK-PLANT#1 | 3 | 07/22/78 | 43500 | | | | 0 | 15 |
| CHIEF JOSEPH | 23 | 08/04/78 | 95000 | | | | 0 | 15 |
| Guntersville | 1 | 10/01/78 | 28800 | | | | 0 | 14 |
| Watauga | 1 | 10/01/78 | 28800 | | | | 0 | 14 |
| FORT PECK-PLANT#1 | 2 | 12/01/78 | 18250 | | | | 0 | 15 |
| Watts Bar | 3 | 12/01/78 | 33300 | | | | 0 | 14 |
| Raccoon Mountain | 2 | 12/01/78 | 382500 | | | | 0 | 14 |
| CHIEF JOSEPH | 8 | 01/01/79 | 88270 | | | | 0 | 14 |
| Raccoon Mountain | 1 | 01/01/79 | 382500 | | | | 0 | 14 |
| Ontario Power GS | 2 | 01/01/79 | 7500 | | | | 0 | 14 |
| Ontario Power GS | 4 | 01/01/79 | 8770 | | | | 0 | 14 |
| CHIEF JOSEPH | 25 | 01/10/79 | 95000 | | | | 0 | 14 |
| LOWER MONUMENTAL | 4 | 01/18/79 | 135000 | | | | 0 | 14 |
| CHIEF JOSEPH | 24 | 01/22/79 | 95000 | | | | 0 | 14 |
| Raccoon Mountain | 3 | 02/01/79 | 382500 | | | | 0 | 14 |
| NORFORK | 1 | 02/08/79 | 36250 | | | | 0 | 14 |
| LOWER MONUMENTAL | 5 | 02/28/79 | 135000 | | | | 0 | 14 |
| Abitibi Canyon GS | 4 | 03/01/79 | 43200 | | | | 0 | 14 |
| LOWER MONUMENTAL | 6 | 04/23/79 | 135000 | | | | 0 | 14 |
| Watts Bar | 4 | 05/01/79 | 33300 | | | | 0 | 14 |
| CHIEF JOSEPH | 27 | 05/14/79 | 95000 | | | | 0 | 14 |
| CHIEF JOSEPH | 26 | 05/21/79 | 95000 | | | | 0 | 14 |
| Guntersville | 2 | 07/01/79 | 28800 | | | | 0 | 13 |
| NORFORK | 2 | 07/07/79 | 40275 | | | | 0 | 14 |
| Raccoon Mountain | 4 | 08/01/79 | 382500 | | | | 0 | 13 |
| Wilson | 15 | 11/01/79 | 25200 | | | | 0 | 13 |
| Chickamauga | 4 | 11/01/79 | 30000 | | | | 0 | 13 |
| HARRY S. TRUMAN | 6 | 12/22/79 | 28386 | | | | 0 | 13 |
| Abitibi Canyon GS | 5 | 02/01/80 | 43200 | | | | 0 | 13 |
| Watauga | 2 | 05/01/80 | 28800 | | | | 0 | 13 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| Wilson | 13 | 06/01/80 | 25200 | | | | 0 | 13 |
| Wilson | 16 | 10/01/80 | 25200 | | | | 0 | 12 |
| Apalachia | 2 | 12/01/80 | 41400 | | | | 0 | 12 |
| LOWER GRANITE | 1 | 01/01/81 | 135000 | | | | 0 | 12 |
| LOWER GRANITE | 2 | 01/01/81 | 135000 | | | | 0 | 12 |
| BONNEVILLE 2 | 18 | 05/19/81 | 66500 | | | | 0 | 12 |
| Wilson | 18 | 06/01/81 | 25200 | | | | 0 | 12 |
| Wheeler | 4 | 06/01/81 | 35100 | | | | 0 | 12 |
| BULL SHOALS | 3 | 07/01/81 | 45000 | | | | 0 | 12 |
| BONNEVILLE 2 | 17 | 09/18/81 | 66500 | | | | 0 | 12 |
| Wilson | 17 | 10/01/81 | 25200 | | | | 0 | 11 |
| Nickajack | 2 | 10/01/81 | 27900 | | | | 0 | 11 |
| BONNEVILLE 2 | F2 | 11/18/81 | 13110 | | | | 0 | 12 |
| HARRY S. TRUMAN | 5 | 12/09/81 | 28386 | | | | 0 | 12 |
| BONNEVILLE 2 | 16 | 12/24/81 | 66500 | | | | 0 | 11 |
| BONNEVILLE 2 | F1 | 12/29/81 | 13110 | | | | 0 | 11 |
| THE DALLES | 12 | 01/01/82 | 78000 | | | | 0 | 11 |
| CHIEF JOSEPH | 5 | 01/01/82 | 88270 | | | | 0 | 11 |
| LIBBY | 1 | 01/01/82 | 105000 | | | | 0 | 11 |
| LOWER GRANITE | 3 | 01/01/82 | 135000 | | | | 0 | 11 |
| HARRY S. TRUMAN | 4 | 02/02/82 | 28386 | | | | 0 | 11 |
| BONNEVILLE 2 | 15 | 03/31/82 | 66500 | | | | 0 | 11 |
| BONNEVILLE 2 | 14 | 04/30/82 | 66500 | | | | 0 | 11 |
| HARRY S. TRUMAN | 1 | 05/19/82 | 28386 | | | | 0 | 11 |
| Wilson | 14 | 06/01/82 | 25200 | | | | 0 | 11 |
| Wheeler | 5 | 06/01/82 | 35100 | | | | 0 | 11 |
| BONNEVILLE 2 | 13 | 06/25/82 | 66500 | | | | 0 | 11 |
| HARRY S. TRUMAN | 3 | 07/11/82 | 28386 | | | | 0 | 11 |
| HARRY S. TRUMAN | 2 | 08/24/82 | 28386 | | | | 0 | 11 |
| BONNEVILLE 2 | 12 | 09/02/82 | 66500 | | | | 0 | 11 |
| BONNEVILLE 2 | 11 | 09/29/82 | 66500 | | | | 0 | 11 |
| Wheeler | 3 | 10/01/82 | 35100 | | | | 0 | 10 |
| Pickwick | 6 | 10/01/82 | 40400 | | | | 0 | 10 |
| BULL SHOALS | 5 | 01/01/83 | 50000 | | | | 0 | 10 |
| BULL SHOALS | 6 | 01/01/83 | 50000 | | | | 0 | 10 |
| BULL SHOALS | 7 | 01/01/83 | 50000 | | | | 0 | 10 |
| BULL SHOALS | 8 | 01/01/83 | 50000 | | | | 0 | 10 |
| BULL SHOALS | 4 | 01/09/83 | 45000 | | | | 0 | 10 |
| BULL SHOALS | 1 | 04/06/83 | 45000 | | | | 0 | 10 |
| BULL SHOALS | 2 | 05/04/83 | 45000 | | | | 0 | 10 |
| TENKILLER FERRY | 1 | 05/20/83 | 19550 | | | | 0 | 10 |
| Boone | 1 | 06/01/83 | 26400 | | | | 0 | 10 |
| Wheeler | 9 | 07/01/83 | 35100 | | | | 0 | 9 |
| Wheeler | 7 | 11/01/83 | 35100 | | | | 0 | 9 |
| Kentucky | 1 | 11/01/83 | 37000 | | | | 0 | 9 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| HARTWELL | 5 | 11/10/83 | 80000 | | | | 0 | 10 |
| OAHE | 5 | 12/30/83 | 112290 | | | | 0 | 9 |
| JOHN DAY | 10 | 01/01/84 | 135000 | | | | 0 | 9 |
| JOHN DAY | 13 | 01/01/84 | 135000 | | | | 0 | 9 |
| BROKEN BOW | 1 | 01/01/84 | 50000 | | | | 0 | 9 |
| JOHN DAY | 9 | 01/01/84 | 135000 | | | | 0 | 9 |
| Sir Adam Beck 1 GS | 4 | 01/01/84 | 50800 | | | | 0 | 9 |
| CLARENCE CANNON | 2 | 01/25/84 | 27000 | | | | 0 | 9 |
| ST. STEPHEN | 1 | 03/06/84 | 28000 | | | | 0 | 9 |
| ST. STEPHEN | 2 | 03/07/84 | 28000 | | | | 0 | 9 |
| ST. STEPHEN | 3 | 03/07/84 | 28000 | | | | 0 | 9 |
| CLARENCE CANNON | 1 | 03/08/84 | 27000 | | | | 0 | 9 |
| OAHE | 7 | 05/30/84 | 112290 | | | | 0 | 9 |
| Wheeler | 8 | 06/01/84 | 35100 | | | | 0 | 9 |
| Wheeler | 1 | 09/01/84 | 35100 | | | | 0 | 8 |
| LIBBY | 5 | 09/26/84 | 105000 | | | | 0 | 9 |
| BROKEN BOW | 2 | 09/30/84 | 50000 | | | | 0 | 9 |
| OAHE | 4 | 11/03/84 | 112290 | | | | 0 | 9 |
| RICHARD B. RUSSELL | 1 | 12/20/84 | 75000 | | | | 0 | 8 |
| CHIEF JOSEPH | 11 | 01/01/85 | 88270 | | | | 0 | 8 |
| CHIEF JOSEPH | 12 | 01/01/85 | 88270 | | | | 0 | 8 |
| Sir Adam Beck 1 GS | 5 | 01/01/85 | 50800 | | | | 0 | 8 |
| RICHARD B. RUSSELL | 2 | 01/29/85 | 75000 | | | | 0 | 8 |
| RICHARD B. RUSSELL | 3 | 04/26/85 | 75000 | | | | 0 | 8 |
| OAHE | 3 | 05/01/85 | 112290 | | | | 0 | 8 |
| South Holston | 1 | 06/01/85 | 38500 | | | | 0 | 8 |
| GARRISON | 3 | 06/14/85 | 109250 | | | | 0 | 8 |
| Pickwick | 5 | 10/01/85 | 40400 | | | | 0 | 7 |
| RICHARD B. RUSSELL | 4 | 11/22/85 | 75000 | | | | 0 | 8 |
| GARRISON | 1 | 11/23/85 | 109250 | | | | 0 | 8 |
| CHIEF JOSEPH | 9 | 01/01/86 | 88270 | | | | 0 | 7 |
| CHIEF JOSEPH | 10 | 01/01/86 | 88270 | | | | 0 | 7 |
| CHIEF JOSEPH | 13 | 01/01/86 | 88270 | | | | 0 | 7 |
| CHIEF JOSEPH | 14 | 01/01/86 | 88270 | | | | 0 | 7 |
| CHIEF JOSEPH | 15 | 01/01/86 | 88270 | | | | 0 | 7 |
| CHIEF JOSEPH | 16 | 01/01/86 | 88270 | | | | 0 | 7 |
| JOHN DAY | 1 | 01/01/86 | 135000 | | | | 0 | 7 |
| JOHN DAY | 2 | 01/01/86 | 135000 | | | | 0 | 7 |
| Pickwick | 1 | 05/01/86 | 40400 | | | | 0 | 7 |
| Wheeler | 2 | 06/01/86 | 35100 | | | | 0 | 7 |
| Pickwick | 2 | 12/01/86 | 40400 | | | | 0 | 6 |
| GARRISON | 2 | 12/05/86 | 109250 | | | | 0 | 7 |

| Plant Name | Unit Number | POL Date | Power (kW) | Rewind Date | Rewind Rating (KW) | Rewind Reason | Age at Failure (Years) | Age (Years) |
|---|---|---|---|---|---|---|---|---|
| MCNARY | 14 | 01/01/87 | 84700 | | | | 0 | 6 |
| CHIEF JOSEPH | 1 | 01/01/87 | 88270 | | | | 0 | 6 |
| CHIEF JOSEPH | 2 | 01/01/87 | 88270 | | | | 0 | 6 |
| CHIEF JOSEPH | 3 | 01/01/87 | 88270 | | | | 0 | 6 |
| CHIEF JOSEPH | 4 | 01/01/87 | 88270 | | | | 0 | 6 |
| CHIEF JOSEPH | 6 | 01/01/87 | 88270 | | | | 0 | 6 |
| CHIEF JOSEPH | 7 | 01/01/87 | 88270 | | | | 0 | 6 |
| Des Joachims GS | 8 | 01/01/87 | 45000 | | | | 0 | 6 |
| Kipling GS | 2 | 01/01/87 | 62700 | | | | 0 | 6 |
| Harmon GS | 1 | 01/01/87 | 64600 | | | | 0 | 6 |
| GAVINS POINT | 3 | 03/07/87 | 44100 | | | | 0 | 6 |
| Blue Ridge | 1 | 12/01/87 | 22000 | | | | 0 | 5 |
| THE DALLES | 13 | 01/01/88 | 78000 | | | | 0 | 5 |
| JOHN DAY | 6 | 01/01/88 | 135000 | | | | 0 | 5 |
| Pine Portage GS | 4 | 01/01/88 | 34650 | | | | 0 | 5 |
| GAVINS POINT | 1 | 03/01/88 | 44100 | | | | 0 | 5 |
| GAVINS POINT | 2 | 03/18/88 | 44100 | | | | 0 | 5 |
| Chenaux GS | 3 | 12/01/88 | 15300 | | | | 0 | 4 |
| LOWER MONUMENTAL | 2 | 01/01/89 | 135000 | | | | 0 | 4 |
| Great Falls | 2 | 01/01/89 | 18400 | | | | 0 | 4 |
| GARRISON | 5 | 03/01/89 | 95000 | | | | 0 | 4 |
| Chenaux GS | 6 | 12/01/89 | 15300 | | | | 0 | 3 |
| JOHN DAY | 8 | 01/01/90 | 135000 | | | | 0 | 3 |
| Ear Falls GS | 3 | 01/01/90 | 5400 | | | | 0 | 3 |
| Sir Adam Beck PGS | 3 | 01/01/90 | 29450 | | | | 0 | 3 |
| R.H. Saunders GS | 16 | 01/01/90 | 57000 | | | | 0 | 3 |
| Aguasabon GS | 1 | 04/01/90 | 20250 | | | | 0 | 3 |
| Norris | 1 | 11/01/90 | 55620 | | | | 0 | 2 |
| Hiwassee | 1 | 11/01/90 | 70650 | | | | 0 | 2 |
| Chenaux GS | 4 | 11/01/90 | 15300 | | | | 0 | 2 |
| Ocoee 2 | 1 | 01/01/91 | 11548 | | | | 0 | 2 |
| Ear Falls GS | 4 | 01/01/91 | 5400 | | | | 0 | 2 |
| Sir Adam Beck 1 GS | 8 | 01/01/91 | 50800 | | | | 0 | 2 |
| R.H. Saunders GS | 10 | 01/01/91 | 57000 | | | | 0 | 2 |
| Ocoee 2 | 2 | 04/01/91 | 11548 | | | | 0 | 2 |
| Fontana | 2 | 12/01/91 | 81000 | | | | 0 | 1 |
| Chenaux GS | 7 | 12/01/91 | 15300 | | | | 0 | 1 |
| Sir Adam Beck PGS | 6 | 01/01/92 | 29450 | | | | 0 | 1 |
| R.H. Saunders GS | 1 | 01/01/92 | 57000 | | | | 0 | 1 |
| Chenaux GS | 2 | 03/01/93 | 15300 | | | | 0 | 0 |