IN-SITU RELIABILITY EVALUATION
OF MINE POWER SYSTEM COMPONENTS

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ABSTRACT

The reliable operation of the ground fault protection components in the mine power distribution system is an important factor in assuring the safety of personnel who operate and maintain underground mining equipment and the availability of that underground mining equipment for coal prodiction. These components (molded-case circuit breakers, undervoltage relays, ground check monitors, and ground fault relays) are responsible for protection of personnel from exposure to the hazards associated with elevated frame potential of mining equipment.

This paper outlines the effort to establish accurate reliability data for these major components of the mine power distribution system by monitoring the components in the actual mine environment. Reporting procedures, method of data analysis, failure modes, and probable mechanisms of failure observed during the evaluation period are discussed in detail.

INTRODUCTION

Reliability is defined as the probability of a device performing adequately, for the period of time intended, under the operating conditions encountered [1]. Reliability is, therefore, the probability that a given device, component, or system will perform as intended.

To develop a quantitative general expression for reliability, let the probability of failure as a function of time be defined as:

$$P(T \le t) = F(t), \quad t \ge 0 \qquad (1)$$

where T is a random variable denoting the failure time. F(t) is the probability that the system will fail by time t.

Then, if reliability is defined as the probability of not failing or the probability that the device, component, or system will perform its intended function at a certain time t, the reliability function, R(t), can be written as

$$R(t) = 1 - F(t) = P(T > t) \tag{2}$$

If the time to failure random variable, T, has a density function $f(\tau)$, then

$$R(t) = 1 - F(t) = 1 - \int_0^t f(\tau)\, d\tau = \int_t^\infty f(\tau)\, d\tau \tag{3}$$

The expected life, or the expected time during which a component will perform successfully is defined as

$$E(T) = \int_0^\infty \tau f(\tau) d\tau \tag{4}$$

Another method for determining the expected life is given by

$$E(T) = \int_0^\infty R(t)\, dt \tag{5}$$

The expected life, E(T), is also called the mean time to failure (MTTF).

The probability of failure of a device, component, or system in a given time interval $[t_1, t_2]$ can be obtained as

$$F_{t_2-t_1} = \int_{t_1}^{t_2} f(\tau) d\tau = F(t)\Big|_{t_1}^{t_2}$$

$$= F(t_2) - F(t_1) \tag{6}$$

or in terms of the reliability function as

$$F_{t_2-t_1} = (1-R(t_2)) - (1-R(t_1))$$

$$= R(t_1) - R(t_2) \tag{7}$$

The failure rate, that is the rate at which failures occur in a certain time interval $[t_1, t_2]$ is defined as the probability that a failure per unit time occurs in the interval, given that a failure has not occurred prior to t_1. Therefore, the failure rate can be defined as

$$\lambda_{t_2-t_1} = \frac{R(t_1) - R(t_2)}{(t_2-t_1)\ R(t_1)} \qquad (8)$$

If the time interval is redefined as $[t,\ t+\Delta t]$, then the equation becomes

$$\lambda_{t-t+\Delta t} = \frac{R(t) - R(t+\Delta t)}{\Delta t\ R(t)} \qquad (9)$$

The instantaneous failure rates can now be defined as

$$\lambda(t) = \mathrm{Lim}_{t \to 0} \frac{R(t) - R(t+\Delta t)}{\Delta t\ R\ (t)}$$

$$= \frac{1}{R(t)} \left[- \frac{dR(t)}{dt} \right] \qquad (10)$$

Rearrangement of equation (10) gives

$$\lambda(t)dt = - \frac{dR(t)}{R(t)} \qquad (11)$$

Integration from time 0 to time t yields

$$\int_0^t \lambda(t)dt = -\ell n\ R(t)\Big]_1^{R(t)} \qquad (12)$$

$$\ell n\ R(t) = - \int_0^t \lambda(t)dt$$

Solving for the reliability function, $R(t)$,

$$R(t) = e^{-\int_0^t \lambda(t)dt} = \exp\left[-\int_0^t \lambda(t)dt\right] \qquad (13)$$

This is a mathematical description of reliability in the most general way possible. This expression is independent of the specific failure distribution involved.

To establish a failure distribution for components of the mine power distribution system, consider Figure 1. This is an accepted representation of the failure behavior of components based on examination of failure data for several years [2]. Basically, this "bathtub curve" represents three characteristic failure regions.

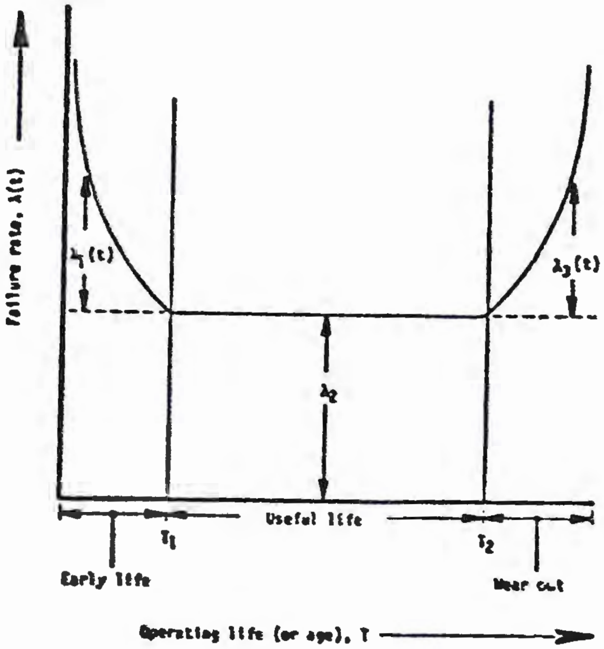


Figure 1. Mortality curve: Failure rate versus age.

Early in the lifetime of a population of components ($< T_1$), a large number of failures occur due to initial weakness or defects. The early failures, also called infant mortalities, appear as a decreasing $\lambda_1(t)$ function.

When the substandard components have all failed at age T_1, the failure rate stabilizes at an approximately constant value, λ_2. This period of operation is known as useful life since the components can be used to the greatest advantage. Failures during useful life are known as "random" or "catastrophic" since they occur randomly and unpredictably.

When the population of components reaches age T_2, the failure rate again increases when degradation failures begin to appear as a consequence of aging or wear when the components are nearing "rated life". This failure region with an increasing $\lambda_3(t)$ function is called the wearout region.

The failure region of interest for mine power system distribution components is the middle or useful life region of Figure 1. In this region, the failure rate is constant.

Therefore, for a constant failure rate, λ, the reliability function, equation (13), becomes

$$R(t) = e^{-\int_0^t \lambda(t)dt} = e^{-\int_0^t \lambda dt}$$

$$R(t) = e^{-\lambda t} \tag{14}$$

and the failure distribution is exponential.

Then to evaluate the reliability of a component at any time t where $t \geq 0$, a value for the failure rate, λ, must first be established.

The failure rate of mine power system components for given operating and environmental conditions can be estimated in one of the following ways:

1) A theoretical model based on a thorough understanding of the physics of failure mechanisms can be used to predict a failure rate. Unfortunately, few physical failure models for the mining environment are known. Prediction must be based on failure mechanisms predominate in components for other environments [3].

2) A statistical estimate of the failure rate can be made using accumulated field data on failures or information from maintenance records. This technique is widely used in other industries.

3) Suitable accelerated life tests in the laboratory can be performed. This technique is useful in obtaining a rough estimate of the failure rate in a very short duration of time. However, justification of the extrapolation of the accelerated results into real time is difficult because failure mechanisms encountered in accelerated test conditions need not be the same as those occurring during normal operating conditions.

Of the above techniques, statistical estimation using field data is by far the best and most accepted approach to obtain a realistic failure rate for a component.

Failure rates based on theoretical models, statistical estimates from maintenance records, and estimates from accelerated life test data have been developed for some mine power system components [4-8]. This paper outlines an effort to develop statistical estimates of failure rates from acquisition of field data by monitoring the life history of several components of the mine power system "in-situ", in an actual mine environment.

SELECTION OF COMPONENTS FOR RELIABILITY EVALUATION

The protection components of the mine power distribution system are typically the molded-case circuit breaker, the undervoltage relay, the ground check monitor, and the ground fault relay. See Figure 2.

These components are responsible for the disconnection of power circuits to mining equipment for abnormal system conditions, such as, short circuits, overcurrent, ground faults, system undervoltage, and open ground conductor. In order to ensure the protection of personnel and equipment, these abnormal conditions must be detected and cleared promptly. This requirement implies that these components must be extremely reliable. A high degree of reliability also assures increased productivity by minimizing the unavailability of the equipment.

To evaluate the reliability of these protection components, the following items were selected for an in-situ life test program:

7 - 600 A molded-case circuit breakers with undervoltage relays,

4 - 500 A molded-case circuit breakers with undervoltage relays,

9 - 225 A molded-case circuit breakers with undervoltage relays,

20 - ground fault relays, and

20 - ground check monitors.

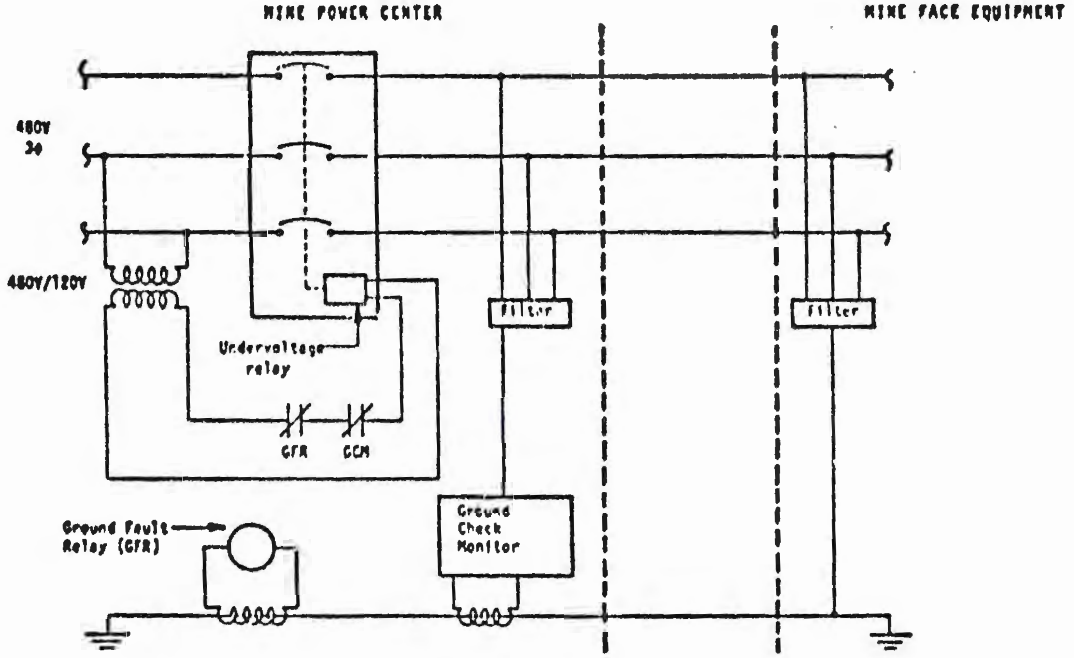


Figure 2. Ground fault protection system.

A sample size of twenty is a typical size for life tests of components of a system [1].

FIELD MONITORING AND DATA ACQUISITION TECHNIQUE

J & L Steel's Nemacolin Mine, in Nemacolin, Pa., agreed to cooperate with West Virginia University (WVU) in providing an operational mine site for the life test program to be performed. All the components identified in the previous section were tagged with unique identification stickers. Postcards were provided to the mine personnel for notification to WVU of installation and failure dates for each component. The format used for these postcards is illustrated in Figure 3.

The mine personnel began phasing the tagged components into operational service on various mine sections starting in July 1981.

As tagged components failed, they were removed from service by the mine personnel and returned to WVU for laboratory analysis to determine failure modes and possible failure mechanisms. Records of field life were maintained for each tagged component.

METHOD FOR DATA ANALYSIS

In general, once a statistical model is selected to describe the given life data, one has to estimate the parameter(s) of the selected model. A wide variety of techniques are available to find point and interval estimates of these parameters [1]. A point estimate of a parameter is a single number which is the "best" estimate of the parameter.

The techniques often used for obtaining a point estimate of the parameter(s) of lifetime distribution are:

1) least-square estimation,

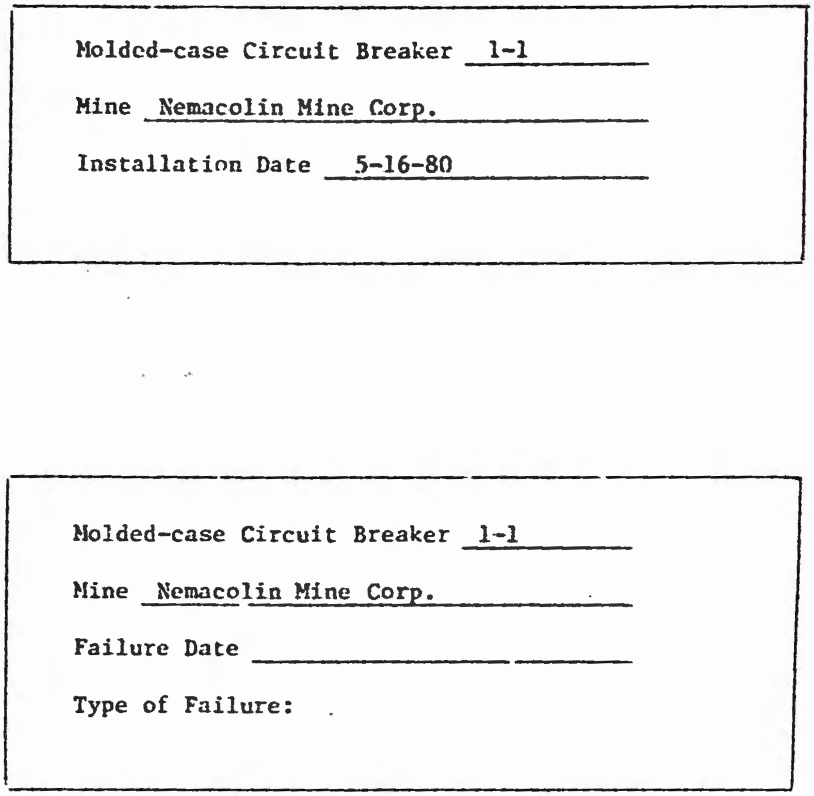
2) moment estimation, and

3) maximum likelihood estimation or MLE.

Among these three, the MLE is the most widely used in practice [1,2].

The MLE easily handles a major consideration of the in-situ life test program data: the life tests will be terminated at a specified time before all components have failed.

The mathematical procedure for computing an MLE is described here briefly. Consider a sample of size n with observed time-to-failure data $\{t_1, t_2, t_3, \ldots, t_n\}$ drawn from a population described by the probability density function $f(t,\theta)$ where θ is the parameter of the population to be estimated. The probability of one sample lying within dt_i at t_i is



Molded-case Circuit Breaker 1-1

Mine Nemacolin Mine Corp.

Installation Date 5-16-80

Molded-case Circuit Breaker 1-1

Mine Nemacolin Mine Corp.

Failure Date ________

Type of Failure:

FIGURE 3. Postcards provided for in-situ test program.

$$P[t_i < \tau < t_i + dt_i] = f(t_i,\ \theta)\ dt_i \qquad (15)$$

The combined probability of the sample values lying within the intervals dt_1, dt_2, dt_3, ..., dt_n is

$$P[t_i < \tau_1 < t_1 + dt_1,\ \ldots,\ t_n < \tau_n < \tau_n < t_n + dt_n]$$

$$= \prod_{i=1}^{n} f(t_i,\theta)\ d(t_i) \qquad (16)$$

provided that the observations are random and independent. Equation (16), with the differentials omitted, is known as the likelihood of the sample, and can be considered to be a function of the parameter θ. The value of $\hat{\theta}$, which gives a maximum likelihood of the sample is the point estimate of the parameter.

Usually the probability density function involves exponential terms, therefore, it becomes more convenient to work with the natural logarithm of the likelihood. The logarithm of a function and the function itself will assume maximum values together. By definition,

$$L(\theta) = \ln \prod_{i=1}^{n} f(t_i,\theta)$$

$$= \sum_{i=1}^{n} \ln f\ (t_i,\theta) \qquad (17)$$

Solving the equation,

$$\frac{\partial L(\theta)}{\partial \theta} = 0, \qquad (18)$$

for $\hat{\theta}$ gives the desired maximum likelihood estimate of the parameter θ.

Applying this general mathematical procedure described above to the in-situ life test data that will be obtained will produce a point estimate of the parameter λ, the failure rate, for each component type tested.

In specific, remember the statistical model chosen to represent the mine power system components' reliability function was an exponential failure distribution with a constant failure rate as described by the equations

$$R_{(t)} = e^{-\lambda t},$$

λ = constant, and

$$f(t) = \lambda\ e^{-\lambda t}. \tag{19}$$

If a sample size n is tested and an r < n number of items are allowed to fail without replacing them in the test, a case of censored life test without replacement occurs. For this truncated case, the likelihood function is the joint probability of r independent items failing and m = n - r independent items not failing. Since the probability of not failing is the reliability function $R(t_j, \theta)$, the joint probability is

$$J(\theta) = \prod_{i=1}^{r} f(t_i,\theta)\ [\sum_{j=1}^{m} R(t_j,\theta)] \tag{20}$$

The likelihood function then becomes

$$L(\theta) = \sum_{i=1}^{r} \ell n\ f(t_i,\theta) + \sum_{j=1}^{m} \ell n\ R(t_j,\theta) \tag{21}$$

Substituting for $f(t_i,\theta)$ and $R(t_j,\theta)$

$$L(\lambda) = \sum_{i=1}^{r} \ell n\ \lambda e^{-\lambda t} + \sum_{j=1}^{m} \ell n\ e^{-\lambda t}$$

$$L(\lambda) = r\ \ell n\ \lambda - \lambda \sum_{i=1}^{r} t_i - \lambda \sum_{j=1}^{m} t_j \tag{23}$$

Using equation (18), the estimate of the parameter λ is

$$\hat{\lambda} = \frac{r}{\sum_{i=1}^{r} t_i + \sum_{j=1}^{m} t_j} \tag{24}$$

If the test is terminated after a specified number of hours t*, when some number of items r have failed out of a set n, then equation (24) becomes

$$\hat{\lambda}_c = \frac{r}{\sum_{i=1}^{r} t_i + (n-r)\ t^*} \tag{25}$$

where

$\hat{\lambda}_c$ = the failure rate for the component type,

r = number of components in the test sample,

n = number of components that failed,

t_i = i^{th} ordered failure time, and

t^* = the time at which the test is terminated.

Previous work in the area of failure rate estimation for mine power system components has verified the exponential failure distribution model [4-8]. However, this exponential failure distribution can be confirmed for the life test data collected from the in-situ test program by using the Kolmogorov-Smirnov Test described in detail in reference [2].

STATUS OF IN-SITU RELIABILITY EVALUATION PROGRAM

The majority of the components involved in the in-situ test program are now in operational service. One section power center with the remainder of the tagged components should be in service by August 1982.

Failures of ground check monitors, molded-case circuit breakers, and undervoltage relays have been reported. All of the failed components have been returned to WVU where they were examined to determine failure modes and possible failure mechanisms. In some cases, the best engineering judgement of the failure mechanism is little more than conjecture. All failures reported in the in-situ test program are summarized in Tables 1 to 3.

Analysis of this time-to-failure data to determine the failure rates for the component types under test will not be valid until more failures are reported over a longer period of test time (about 2 to 5 years). At that point in time, the final results of the in-situ life test program will be published.

CONCLUSIONS

This paper outlines a general program for evaluating the reliability of mine power distribution system components by monitoring the life history of a population of these components. A method of analyzing the time to failure data accumulated to produce an estimate of the failure rate is also present.

The failure rate of a component once established can be used in determining cost effective maintenance scheduling practices for the component type [5,9]. Also, reliability improvement trade-offs can be better assessed.

Upon completion of the in-situ life test program, a better understanding of the failure modes and the failure physics experienced in the

Ground Check Monitor	Field Life	Description of Failure	Failure Mode	Probable Failure Mechanism
#1	33 days	No indication of transmitter working	Transmitter frequency drift	Vibration causing potentiometer arm movement
#2	33 days	False indication of open ground	Receiver frequency drift	Vibration causing potentiometer arm movement
#3	33 days	False indication of open ground	Receiver frequency drift	Vibration causing potentiometer arm movement
#4	57 days	No indication lights	Failure in power supply circuit (voltage regulator IC failure)	Vibration or humidity
#5	56 days	No indication lights	Failure in power supply circuit (diode bridge failure)	Overvoltage
#6	33 days	False indication of open ground	Filter element open	Overvoltage
#7	147 days	No indication lights	"On" switch contacts broken	Mechanical stress or vibration
#8	108 days	False indication of open ground	Broken solder tracing on transmitter card	Mechancial stress or vibration
#9	226 days	False indication of open ground	Receiver frequency drift	Vibration causing potentiometer arm movement
#10	226 days	False indication of open ground	Receiver frequency drift	Vibration causing potentiometer arm movement
#11	226 days	False indication of open ground	Transmitter frequency drift	Vibration causing potentiometer arm movement
#12	226 days	False indication of open ground	Transmitter frequency drift	Vibration causing potentiometer arm movement

Table 1. Failure Reports for Ground Check Monitors.

Circuit Breaker	Field Life	Description of Failure	Failure Mode	Probable Failure Mechanism
#1 (225 A)	147 days	Circuit breaker would not reset	Latch mechanism out of tolerance	Vibration or mechanical stress
#2 (500 A)	108 days	Circuit breaker would not reset	Trip mechanism jammed	Vibration or mechanical stress

Table 2. Failure Reports for Molded-Case Circuit Breakers.

Undervoltage Relay (UVR)	Field Life	Description of Failure	Failure Mode	Probable Failure Mechanism
#1 (UVR for 600 A Circuit Breaker)	31 days	UVR would not pick-up	UVR coil open	Overvoltage
#2 (UVR for 225 A Circuit Breaker)	31 days	Circuit breaker would not reset	Reset arm of UVR broken	Mechanical stress
#3 (UVR for 225 A Circuit Breaker)	37 days	Circuit breaker would not reset	UVR mechanical trip adjustment arm loose	Vibration

Table 3. Failure Reports for Undervoltage Relays.

mine environment should be achieved. A comparison of the results of this in-situ reliability evaluation with previous theoretical models and estimates [4-8] will generate more accurate future reliability predictions for untested equipment types.

ACKNOWLEDGEMENTS

contract #

The authors appreciate the funding of this research by the U. S. Bureau of Mines, in the form of Contract No. J0199119. The authors wish to acknowledge the cooperation of J & L Steel's Nemacolin Mine and especially Mr. Don Sapp of the maintenance department.

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Corp Author(s): WVU Conference on Coal Mine Electrotechnology (6th : 1982 : Morgantown, W. Va.); West Virginia University.; Dept. of Electrical Engineering. ; IEEE Industry

Applications Society.; Mining Industry Committee. ; Pittsburgh Mining and Safety Research Center. ; United States.; Mine Safety and Health Admininstration.

Publication: [Morgantown, WV] : Dept. of Electrical Engineering, West Virginia University,

Year: 1982

Description: 428 p. : ill. ; 28 cm.

Language: English

Series: Contract ;; no. JO123017; [Open file report ;; 83-163]; **Variation:** Contract (United States. Bureau of Mines) ;; JO123017.; Open file report (United States. Bureau of Mines) ;; 83-163.

SUBJECT(S)

Descriptor: Coal mines and mining -- Electric equipment -- Congresses.
Coal mines and mining -- Electronic equipment -- Congresses.
Electricity in mining -- Congresses.

Note(s): Spine title: The Sixth WVU Conference on Coal Mine Electrotechnology./ Sponsored by Department of Electrical Engineering, College of Engineering, West Virginia University; Mining Industry Committee, IEEE Industry and Applications Society; and U.S. Bureau of Mines, Pittsburgh Mining and Safety Research Center in cooperation with Mine Safety and Health Administration./ "November 1982."/ Includes bibliographical references.

Class Descriptors: **LC:** TN23

Other Titles: Sixth WVU Conference on Coal Mine Electrotechnology.; Coal mine electrotechnology.

Responsibility: [Wils L. Cooley, editor].

Material Type: Conference publication (cnp)

Document Type: Book

Entry: 19930325

Update: 20020405

Accession No: **OCLC:** 27797052

Database: WorldCat

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