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# A Reliability Study on the AC Power Distribution System of HANARO

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## Abstract

Electric power is essential for all industrial plant. All who use electric power desire a perfect frequency, voltage stability, and reliability all the time. But this cannot be realized in practice because of the many causes of a power supply disturbance that are beyond the control of the utility. Since the first criticality of the HANARO research reactor, the major reasons for reactor trips were system malfunctions and inexperienced operators in the initial stage of its operation. As HANARO is stabilizing, the power supply outage becomes the major reason for a reactor trip. This paper describes the status of power supply outages. The Electric power system of HANARO is classified into four groups, Class 4, 3, 2, and 1, according to the safety related extent of the load. This paper deals with the reliability of not only HANARO class 4 power but also Class 3 power.

## 1. Introduction

The Electric power system of HANARO is classified into four groups, Class 4, 3, 2, and 1, according to the safety related extent of the load. The Class 4 power is a commercial power which supplies the load centers and the large motors such as primary cooling pumps and secondary cooling pumps. The Class 3 power is an emergency ac power backed up by an emergency diesel generator and provides power for important reactor system such as emergency water supply system, emergency ventilation system, etc. The Class 2 power is an uninterruptible ac power backed up by UPS and a battery. Finally, Class 1 power is an uninterruptible dc power backed up by a battery.

The HANARO has been stabilizing its operation since 1995. As HANARO is stabilizing, the power supply outage becomes the major reason for a reactor trip. The HANARO Class 4 power system is described and the historical information on the design and operational changes is also provided. The outages are classified into a sustained power outage and a momentary power outage according to the duration, and a scheduled outage and a forced outage according to the existence of the schedule.

This paper describes the reliability of the diesel generator for the HANARO research reactor. Detailed data was collected for this study, including failures, start attempts for testing or for actual demands. Data from 1995 to 2002 has been collected, and taken from the diesel start and failure records, diesel maintenance and test records, and the reactor control room logs.

## 2. Class 4 Power System

### 2.1. Class 4 Power System Description

The simplified single line diagram of the Class 4 power system at the KAERI site is shown in Figure 1. There are two on-site substations, SS1 and SS2, each of which is connected to the Deokjin substation, KEPCO. SS1 is supplied by 154kV of feeder and designated as a preferre d source. SS2 has an automatic transfer switch normally connected to SS1 and has an alternat e feeder for an emergency. Power disturbances in the Deokjin substation affect the power syst em of KAERI. There were two major design changes in the Class 4 power system. The primary feeder was changed from the Sintanjin substation to the Deokjin substation on June 3, 1990. The 154kV onsite substation was built and the primary feeder was changed to the 154kv Deokjin line on June 11, 1999.

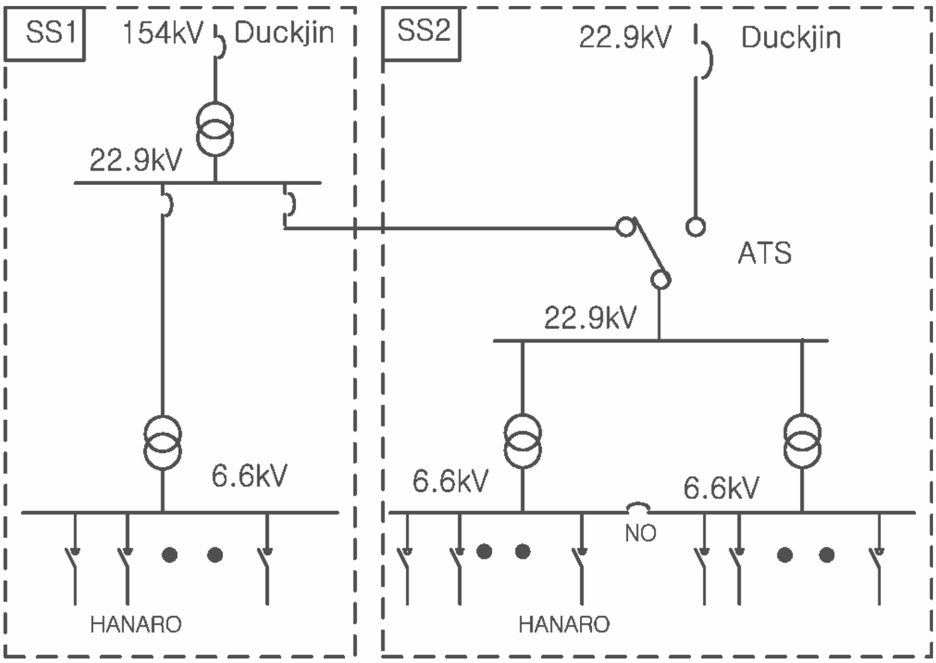

Figure 1 Simplified Single Line Diagram of HANARO Class 4 Power

### 2.2. Class 4 Power Outages

As mentioned above, the outage is classified by the duration and the existence of the schedule. First, when used to quantify the duration of a voltage interruption, a sustained power outage refers to the time frame associated with a long variation duration which is greater than 1 min. Momentary power interruption is the complete loss of the voltage(<0.1pu) on one or more of the phase conductors for a time less than 1 min. The scheduled power outage is an outage that occurs when a component is deliberately taken out of service at a selected time, usually for the purpose of construction, maintenance, or repair. The forced outage is an outage that cannot be deferred. Some equipment could be stopped by a momentary voltage drop or swell. HANARO has no monitoring system for the momentary abnormal phenomena, so this paper deals with the outages only according to the existence of the schedule.

The data for the class 4 power outages at the KAERI site was collected from 1988 to 2001 and provided by a person in charge of the electric safety of KAERI and HANARO. We classify the outages as follows. Site-Wide outages are due to KEPCO and/or the KAERI substation and the Local HANARO outages are a summation of the site-wide outages and the outages at HANARO only. 113 outages have occurred from 1988 to 2001, which consist of 71 scheduled outages and 42 forced outages. The scheduled outages are not included in this analysis.

### 2.3. Reliability study of Class 4 Power

Annual average number of outages is 3 and 40.5% of the total are sustained power outages. The exponentially weighted moving average (EWMA) is a statistic for monitoring the process that averages the data in a way that gives less and less weight to the data as it is further removed in time from the current measurement. The EWMA statistics are weighted averages, and thus their standard deviations are smaller than the standard deviations of the raw data and the corresponding control limits are narrower than the control limits for the Shewhart individual observation charts. The EWMA charts are more sensitive than regularly used control charts for detecting small shifts in a process. The advantage of using EWMA is that it picks up trends more quickly than the simple moving averages. The disadvantage of EWMA is that more false signals are likely to be generated. The EWMA is calculated, to provide a more accurate assessment of the long-term trend rather than the five-year moving average method. The annual outage frequency and EWMA annual outage frequency of the site-wide Class 4 power for the last 14 years are shown in Fig. 2. The standard deviation of the EWMA number of outages is 0.4 while that of the number of outages is 2.1. The EWMA number of outages stays around the average of 3.18. The current best-estimate site-wide outage rate, based on the last EWMA, is 2.36 per year. Fig. 3 shows the average outage time per outage and the EWMA outage time. The EWMA outage time indicates an increasing trend over the last 14 years. The average EWMA outage time of the last 5 years is 39.4% higher than that of the previous 5 years.

The outage durations are arranged according to the duration range in Table 1. The outage duration is, in other words, the time to repair. The cumulative percent restoration probability (or the outage time probability), in Table 1, is the probability that the outage will be repaired within time t (or will last for a time t), given that the outage occurred at time 0. Hence, 90% of the total outages have been restored within 90 minutes. Or 10% of the total outages lasted for more than 90 minutes.

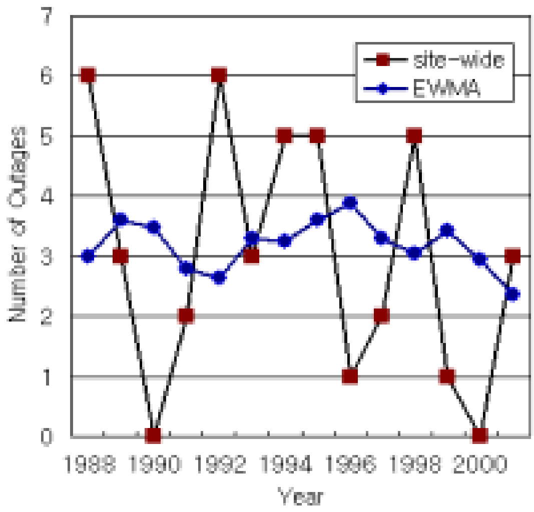


Figure 2 Site-wide Class 4 Power Outage

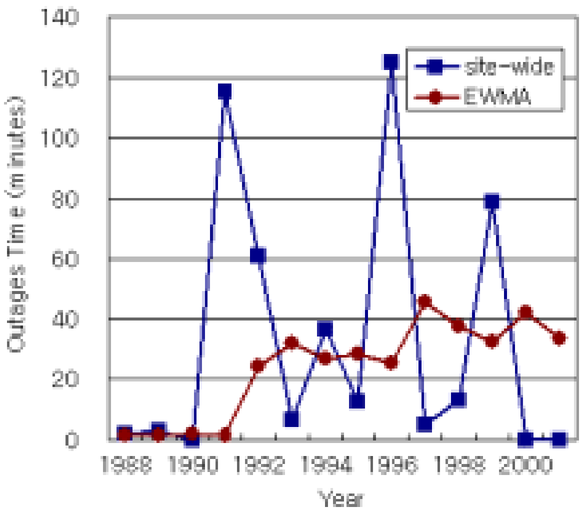


Figure 3 Site-wide Class 4 Power Outage Time

Table 1 Class 4 Power Outage Durations for Site-wide

| Outage duration (TTR) (minutes) | | Site-wide | |
|---|---|---|---|
| Range | Bin | Number of outages | Cumulative % restoration probability |
| <=.75 | 0.5 | 21 | 50 |
| >.75 – 1.5 | 1 | 3 | 57 |
| >1.5 – 2.5 | 2 | 1 | 60 |
| >2.5 – 3.5 | 3 | 0 | 60 |
| >3.5 – 5 | 4 | 1 | 62 |
| >5 – 8 | 6 | 2 | 67 |
| >8 – 15 | 10 | 3 | 74 |
| >15 – 30 | 20 | 4 | 83 |
| >30 – 50 | 40 | 2 | 88 |
| >50 – 70 | 60 | 0 | 88 |
| >70 – 90 | 80 | 1 | 90 |
| >90 | 100 | 4 | 100 |
| Totals | | 42 | |

The Class 4 power reliability R(t) can be represented by the standard reliability expression $R(t)= \exp(-\lambda t)$. R(t) is defined as the probability that there will be no Class 4 power failure during the time zero to time t, given that the power was last restored for time zero. The Class 4 reliability is 0.8043 at 10 days of time to failure using the latest EWMA of 2.36 failures per year for $\lambda$.

## 3. Class 3 Power System

This paper describes the reliability of the diesel generator for the HANARO research reactor. Detailed data was collected for this study, including failures, start attempts for testing or for actual demands. Data from 1995 to 2002 has been collected, and taken from the diesel start and failure records, diesel maintenance and test records, and the reactor control room logs. This study shows the failure-to-start probabilities and the failure-to-run probabilities of diesel generator within the 90% confidence bounds. A comparison with the NUREG and AECL studies is shown in this paper. Table 2 shows the summary of the diesel start demands and failures. The outputs from this reliability analysis are the failure to start probabilities (per demand) and the failure to run probabilities (per hour). Also this paper shows the standby failure rate and total failure rate of the diesel generator.

The technical data of the diesel generator for HANARO is as follows.

Installation: 1994
Engine Type: Cummins KTA-38G2
Rating: 1200Hp, 1800RPM
Generator Type: Bokuk BLA-725
Generator Rating: 906kVA, 725kW, 460V, 3Phase, 60Hz

### 3.1. Failure to Start

Annual count for the start demand failures and failure to run are listed in table 2. This section is concerned with the quantification of the probability of a failure to start. Failure to start means failure of a system to start when it receives a start signal. In this paper, this includes a failure of the breaker to automatically close, failure to reach a rated engine speed and output voltage and a frequency.

#### 3.1.1. Time dependent Failure to Start

There are three parameters which influence the failure to start probability. One is the time independent stress induced by a start attempt. Another is the failure rate for the diesel entering the loss of the capability to start while in standby, and the other is time since the last start attempt. General model that approximates the probability of a failure to start that accounts for all three parameters is

$$P_{FTS} = q + \lambda t \tag{1}$$

where $P_{FTS}$ is the probability of a failure to start, q is the time independent probability caused by stresses of the test itself, $\lambda$ is the standby failure rate which is time dependent, and t is time since the last start attempt. If the test interval is T, the average probability of a failure to start from a loss of offsite power is

$$P_{FTS} = q + \lambda \frac{T}{2} \tag{2}$$

To calculate the time dependent failure rate $\lambda$, we use the EWMA(exponentially weighted moving average). Table 3 summarizes the EWMA number of failure to start, and the current best-estimate start failure, based on the last EWMA, is 0.748 per year. The test interval T of the HANARO diesel generator is 1 month, standby failure rate is $8.54 \times 10^{-5}$ /h. The time independent probability q is $1.65 \times 10^{-2}$ using a binomial distribution with a 90% confidence limit. In Eq. (2), the probability of the time dependent failure to start is $3.18 \times 10^{-2}$.

Table 2 Diesel Start Demand and Failure Summary

| Year | Total Demands | Failure to start | Failure to Run | Run Time (Hour) |
|---|---|---|---|---|
| 1995 | 10 | 2 | 3 | 65.1 |
| 1996 | 24 | 0 | 4 | 44.9 |
| 1997 | 19 | 2 | 0 | 38.8 |
| 1998 | 18 | 0 | 0 | 28.3 |
| 1999 | 20 | 0 | 2 | 82.4 |
| 2000 | 13 | 0 | 0 | 14.2 |
| 2001 | 17 | 1 | 1 | 18.1 |
| 2002 | 15 | 0 | 0 | 19.3 |
| Total | 136 | 5 | 10 | 311.1 |

### 3.1.2. Time independent Failure to Start

The time independent probability of a failure to start is taken from the relationship between the F distribution and the binomial distribution. The binomial distribution is used when there are two mutually exclusive outcomes which are a successful start and a failure to start. The binomial probability distribution function P(s) is

Table 3 EWMA Number of Failure to Start

| Year | Number of Failure to Start | EWMA Number of Failure to Start (per year) |
|---|---|---|
| 1995 | 2 | 1.333 |
| 1996 | 0 | 1.467 |
| 1997 | 2 | 1.173 |
| 1998 | 0 | 1.339 |
| 1999 | 0 | 1.071 |
| 2000 | 0 | 0.857 |
| 2001 | 1 | 0.685 |
| 2002 | 0 | 0.748 |
| Average | 0.625 | 1.084 |
| Stnd dev | 0.916 | 0.294 |

$$P(s) = \frac{n!}{s!(n-s)!} p^s (1-p)^{(n-s)}, \text{ for s=0, 1, 2, … , n} \qquad (3)$$

where n is the number of start demands, s is the number of failures to start, and p is proportion number for the failure to start. The confidence interval of the F distribution is expressed in Eq. (4), (5).

$$F_L = F_{\frac{\alpha}{2}} = F\left[\frac{\alpha}{2}, 2(n-s+1), 2s\right] \qquad (4)$$

$$F_U = F_{1-\frac{\alpha}{2}} = F\left[1-\frac{\alpha}{2}, 2(n-s), 2(s+1)\right] \qquad (5)$$

$F_L$ and $F_U$ are the lower and upper confidence limit, and $\alpha$ is the significant level. If the confidence bound is 90%, $\alpha$ is 0.05. From Eq. (3), (4) and (5), the time independent probabilities of a failure to start are

$$P_L = \frac{1}{1 + \frac{n-s+1}{s} \times F_L} \qquad (6)$$

$$P_U = \frac{1}{1 + \frac{n-s}{s+1} \times F_U} \qquad (7)$$

where $P_L$ and $P_U$ are the probability at the lower and upper confidence limit.

Table 4 summarizes the failure to start of the diesel generator. The probability of failure to start is calculated at 90% confidence limits. The failures per DG year is 0.625/year, mean of a failure to start is $3.68 \times 10^{-2}$/demand. The probability of failure to start is $1.46 \times 10^{-2}$/demand at a lower confidence limit and $7.57 \times 10^{-2}$/demand at an upper confidence limit. This represents the maximum likelihood estimate of the failure to start with the 90% confidence bounds. A comparison with the AECL and NUREG studies is shown in Fig. 4. The failure probability of the NUREG study shows that the industry average is $2.50 \times 10^{-2}$/demand and the range is $8.0 \times 10^{-3}$ to $1.0 \times 10^{-1}$. NRX(L) and NRX(R) are a diesel group of the AECL. The number of start demands for NRX(L) and NRX(R) are 2279 and 1123 which are much more than that of HANARO. The probability of a failure of HANARO is higher and the range between the upper and lower is wider than that of AECL.

Table 4 Failure to start probability (90% confidence bound)

| | |
|---|---|
| Number of Failure to Start | 5 |
| Number of DG years | 8 |
| Failures per DG year | 0.625 |
| Mean of Failure to start (demand$^{-1}$) | 3.68E-02 |
| Probability of Failure to Run($P_{0.05}$) (demand$^{-1}$) | 1.46E-02 |
| Probability of Failure to Run($P_{0.95}$) (demand$^{-1}$) | 7.57E-02 |

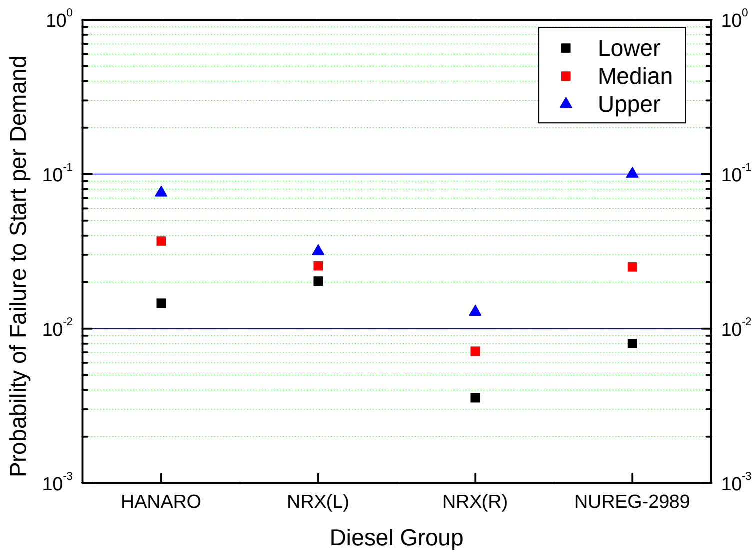


Figure 4 Probability of Diesel Failure to Start per Demand

3.2. Failure to Run

Failure to run means failure of a system to continue to function after it has successfully started. Data on diesel operating time has been collected from the reactor control room log for the power demands and from the test records for the test demands. Generally, diesel runs one hour during a periodic test and the power failure demands have a longer running time. To calculate a failure to run probability, this study examined all the events in which the diesel generator runs. And any failure, subsequent to a successful start, is classified as a failure to run. The number of failures occurring during these runs was divided by a cumulative run time to estimate the failure to run probability. The usual approximation concerning the failure rate of a running is to assume that the failures are occurring randomly. This means the time to failure has an exponential distribution. s is the number of failures, T is the cumulative run time and $\alpha$ is the significant level. If the confidence bound is 90%, $\alpha$ is 0.05. The probability of a failure to run rate is calculated using the chi square distribution. $P_L$ and $P_U$ are the probability at the lower and upper confidence limit.

$$P_L = \frac{\chi^2(\alpha/2, 2s)}{2T} \tag{8}$$

$$P_U = \frac{\chi^2(1-\alpha/2, 2r+2)}{2T} \tag{9}$$

Table 5 summarizes the failure to run of the diesel generator. The probability of a failure to run is calculated at 90% confidence limits. Average run time is the total run time divided by the number of successes to start. The mean of the failure to start is $3.22\times10^{-2}$ /H. The confidence interval of the probability of a failure to run is between $1.74\times10^{-2}$ /H at a lower confidence limit and $5.46\times10^{-2}$ /H at an upper confidence limit. This represents the maximum likelihood estimate of a failure to start with 90% confidence bounds. A comparison with the AECL and NUREG studies is shown in Fig. 5. The failure probability of the NUREG study shows that the industry average is $2.40\times10^{-3}$ /H. The failure probabilities for NRX(L) and NRX(R) are $3.34\times10^{-3}$ /H to $9.85\times10^{-3}$ /H and $2.88\times10^{-3}$ /H to $1.54\times10^{-2}$ /H respectively. The Total run time for NRX(L) and NRX(R) are 1849.4 and 683.5 hours which are much more than that of HANARO. The probability of failure to run of HANARO is higher than that of the NUREG and AECL study.

Table 5 Failure to Run Probability (90% Confidence Bound)

| | |
|---|---|
| Number of Failures to Run | 10 |
| Total Run Time(H) | 311.1 |
| Average Run Time (H) | 2.37 |
| Mean of Failure to Run ($H^{-1}$) | 3.22E-02 |
| Probability of Failure to Run($P_{0.05}$) ($H^{-1}$) | 1.74E-02 |
| Probability of Failure to Run($P_{0.95}$) ($H^{-1}$) | 5.46E-02 |

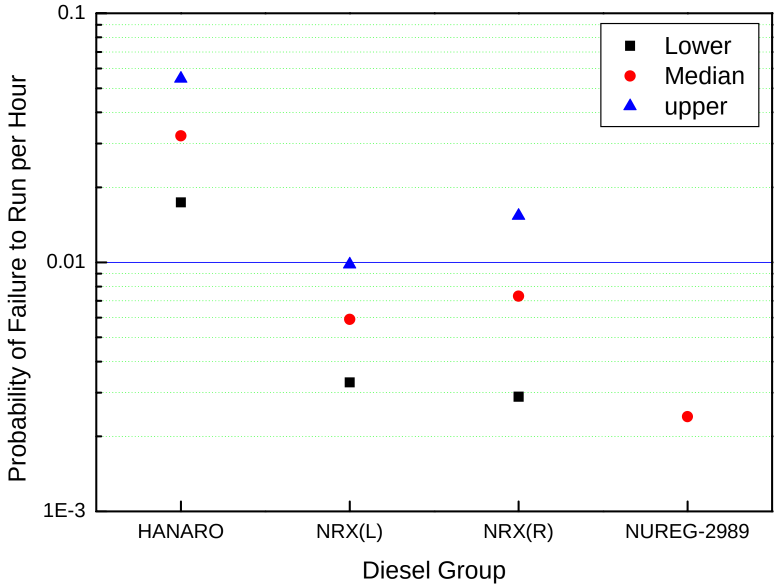


Figure 5 Probability of a Failure to run per Hour

3.3. Failure by Subsystem

The failure events have been analyzed by diesel generator subsystems which are classified into the diesel engine, generator, power distribution system, and protection and the monitoring system. The percentage of a failure to start and run by the subsystem is shown in Fig. 6. 60% of failures are caused by an engine system problem. Most of the engine system problems of the HANARO diesel generator are due to the fuel oil system and engine speed detection system.

## 4. Conclusion

4.1. Class 4 Power

The site-wide EWMA outage frequency has decreased from 1999 in a short term trend and has decreased from 1996 in a long term trend. The last two-year average is 18% less than that of 1998/99. The reduction rate since 1996 is a 0.48 outage per year. Site-wide EWMA outage durations have decreased since 1997 after 125 minute outage duration in 1996. The latest EWMA outage time is 33.38 minutes. 50% of the site-wide outage durations are less than 0.75 minute. For the site-wide Class 4 power, the latest failure rate is 2.36 per year and the mean time to repair is 23.78 minutes for the exponentially weighted moving average. The unavailability of the Class 4 power is 1.5E-4.

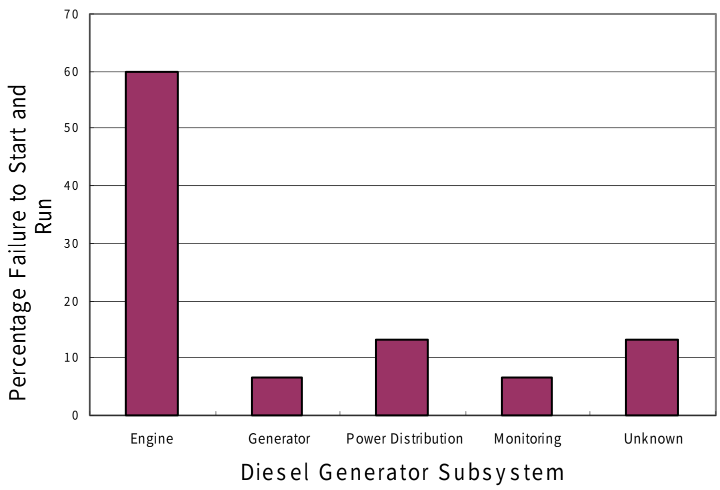


Figure 6 Percentage Failures by Subsystem

## 4.2. Class 3 Power

Since 1995, 15 failures, which consist of 5 failures to start and 10 failures to run, have occurred in the HANARO diesel generator. Most of the failures are due to an engine system problem. The EWMA number of a failure to start has been decreasing since 1998. The latest EWMA number for a failure to start is 0,748 per year. The probability of a failure to start is between $1.46\times10^{-2}$ and $7.57\times10^{-2}$ per demand with 90% confidence limits. The probability of a failure to run is between $1.74\times10^{-2}$ and $5.46\times10^{-2}$ per hour with 90% confidence limits.

# 5. References

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