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Applying Reliability Based Decision Making to ITM Frequency

FINAL REPORT BY:

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Foreword

Many NFPA codes and standards specify the minimum requirements for periodic inspection, testing, and maintenance (ITM) for fire protection systems, including for example, NFPA 25, Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems, and NFPA 72, National Fire Alarm and Signaling Code. These are often historical requirements that are not based on ITM data or on observed deficiencies. As NFPA develops new documents that involve integrated systems, the need for a more data based approach to ITM frequencies will be important.

A previous FPRF report *Fire Pump Field Data Collection and* Analysis and various other related research efforts exemplified the need to consolidate the multiple approaches used to collect ITM data, to support the analytics that can ultimately be used to apply reliability based decision making for specific fire protection equipment or systems.

This project identifies a framework for applying reliability based decision making to ITM frequency for fire pumps. The work contained herein summarizes fire pump failure assessment methodologies, parameters for collection of retrospective fire pump ITM data, development of a predictive failure model to assess fire pump availability, and recommended procedures for on-going data exchange.

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About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission. All NFPA codes and standards can be viewed online for free. NFPA's membership totals more than 65,000 individuals around the world.

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APPLYING RELIABILITY BASED DECISION MAKING TO ITM FREQUENCY

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REVISION RECORD SUMMARY

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0	Final Report

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1.0 PURPOSE AND SCOPE

1.1 Purpose

The purpose of this document is to develop a framework for applying reliability-based-decision-making using inspection, testing and maintenance (ITM) data to fire protection equipment and systems. Specifically, the report addresses the following tasks as directed by the NFPA Research Foundation awarded scope of work:

Task 2, Literature Review: The purpose of this task is to identify reliability modeling techniques and applications that can serve as examples of for the application to ITM activities associated with fire protection equipment.

Task 3, Summary of Failure Assessment Methodologies: The purpose of this task is to develop a summary of identified ITM methods documented in the literature. This summary is intended to highlight advantages and limitations of each methodology.

Task 4, Data Audit and Collection of Available Data: The purpose of this task is to collect, classify and identify ITM data that can be used for predictive modeling purposes.

Task 5, Establish a Predictive Failure Model: The purpose of this task is to identify and describe a predictive failure model that can be used for determining expected failures for equipment. The failure predictions are then use for determining equipment availability and optimized ITM schedules.

Task 6, Establish Protocols for On-Going Data Exchange: The purpose of this task is to provide recommendations for ITM data collection and maintenance in support of a broader use of performance-based ITM scheduling. This should improve the allocation of ITM resources, and increase fire protection reliability.

1.2 Scope

The research described in this report is focused on evaluating inspection, testing and maintenance strategies for fire pumps. Although this framework, which includes data collection protocols, data analysis and reliability modeling can be expanded to other fire protection systems, it has only been applied to fire pumps using the data obtained by the research team during the course of the project.

2.0 TASK 2: LITERATURE REVIEW

This section describes the literature review performed as part of this research. The purpose of this task is to review and summarize previous related work on the topic of ITM data collection and frequencies. It is noted that the literature associated with predicting reliability and availability of repairable components is extensive and can be found in industry handbooks and Reliability Engineering text books. The information in these sources is general and supports different applications such as the one within this scope of this research. It is therefore only reproduced in this document to the extent necessary for describing this research and the proposed model. Alternatively, this section focuses on ITM methods that have been applied in different industries by identifying their advantages and limitations. Three studies were identified and summarized as part of this research. This chapter provides a brief introduction to these approaches. The following chapter provide technical details on each of these approaches. The review is focused on addressing applicable data collection methods, concepts and protocols, and clarifying availability and reliability of existing retrospective data.

2.1 Fire Pump Field Data Collection and Analysis

As noted in section A.8.3.1.1.2 of NFPA 25, the Standard for Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems (Reference 1), a significant amount of discussion has been devoted to the topic of determining the appropriate testing frequency. In 2008 the development of a large set of fire pump data suggested a change in the testing frequency would have no significant effect on fire pump reliability. However, the report miss-represented the fire pump failure rate as the reliability (Reference 1). Therefore, in 2011 the NFPA Research Council authorized a study of fire pump testing data (Reference 2).

Reference 2, Fire Pump Field Data Collection and Analysis, was intended to provide credible and statistically valid fire pump performance data to support prescribed testing frequencies. The project focused on collecting data for the weekly and monthly non-flow fire pump testing. The 2012 study noted that the non-flow data is often recorded on paper while the performance tests are primarily recorded electronically. The process of collecting, correlating and recording any existing non-flow fire pump test data into a standardized format for analysis would be enormously time consuming. Therefore, the study focused on collecting data that was available in an electronic format. Data was then collected and provided in a standardized form indicating a test date and a respective testing pass, fail, or repair state. This resulted in a total of 38 data sets including 4145 non-flow tests of 96 fire pumps.

While focusing on the non-flow fire pump tests, the 2012 report notes that unlike the annual, performance test which requires the recording and analysis of pump specific pressure and flow data, a simple checklist may fulfill the non-flow testing requirements. The result is a subjective test analysis that depends heavily on an assumed expertise of the one testing the fire pump.

Ultimately, the data collected was used to make an estimation of the fire pump reliability given the current weekly and an extrapolated monthly testing frequency. Both frequencies resulting in an estimated fire pump reliability more than 95% which match well with other published reliability based ITM assessment methods.

The data collected in this 2012 study focused on collecting fire pump non-flow testing data and made an estimation of fire pump reliability. The development of the reliability results is reviewed below in Section 3.1.1.2.

2.2 Risk Based Reliability Centered Maintenance of DoD Fire Protection Systems

The *Risk-Based Reliability-Centered Maintenance of DoD Fire Protection Systems AFCESA/CES-TR-01-10* (Reference 3) documents the development and results of a methodology for optimizing fire protection systems, including fire pumps, ITM frequencies. This method, reviewed in detail in Section 3.1.2, uses subjective rankings made using an FMEA process, estimations of failure rates, availability, and resulting system performance improvement to estimate the appropriate ITM task frequency that maintain a 99% overall system reliability.

2.3 Fire Protection Equipment Surveillance Optimization and Maintenance Guide

The Electric Power Research Institute (EPRI) developed the *Fire Protection Equipment Surveillance Optimization and Maintenance Guide* (Reference 5) for adjusting test and inspection frequencies to be in better agreement with equipment performance and a desired reliability. This methodology, described in detail in Section 3.1.3, points to a basis for incrementally extending the ITM frequency if the current ITM interval results in a system reliability above a desired target reliability.

3.0 TASK 3: FAILURE ASSESSMENT METHODOLOGIES

This task documents a review and summary of existing fire protection system failure assessment methods. The concepts in these failure assessment methods are summarized and recommendations for a model data analysis approach standardized data collection framework are provided. Additionally, a rationale for defining key terms such as “failure” and “impairment” in relation to test frequency are reviewed.

3.1 Failure and ITM Assessment Methodologies

3.1.1 NFPA 25

NFPA 25, “Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems” provides the baseline for inspection, testing, and maintenance of water-based fire protection systems.

3.1.1.1 Prescribed Frequency

Inspection, testing and maintenance frequencies are provided for fire pumps in NFPA 25 (Reference 1). There are many different items identified for requiring ITM activities. Each of these activities are tested in two major activities – the non-flow (or churn) test and the flow (performance) test. The code prescribed testing frequencies are presented in Table 3-1.

Table 3-1: NFPA 25 Fire Pump Testing Frequency

Test	Frequency
Non-Flow	Weekly*
Flow	Annually

*Some electrically driven pumps may be tested at a monthly frequency.

3.1.1.2 Fire Pump Field Data Collection and Analysis

While these frequencies are not tied to a specific required pump reliability or availability, using the evidence collected as part of the 2012 *Fire Pump Field Data Collection and Analysis* Report (Reference 2), weekly inspections of electric and diesel engine fire pumps were found to be 99.4% and 99.0% reliable respectively. This study assumed the failure rate was independent of the test frequency and that on average the failure occurs at the midpoint for the test interval. Extrapolating to a monthly testing frequency, yearly reliabilities of 97.3% for electrically driven pumps and 95.6% for diesel driven pumps were estimated.

3.1.1.3 Risk Approved Analysis

NFPA 25 allows for the revision of test frequencies using an approved risk analysis that has been prepared and reviewed by qualified people. Any changes in frequency should consider changes in reliability/risk associated with life safety, property values, hazards, business interruption to the property and the overall fire system reliability.

Two possible means of developing performance-based ITM frequencies have been developed for Department of Defense (DoD) facilities (Reference 3 and 4) and for nuclear power plants (Reference 5).

3.1.2 Risk Based Reliability Centered Maintenance of DoD Fire Protection Systems

The *Risk-Based Reliability-Centered Maintenance of DoD Fire Protection Systems AFCESA/CES-TR-01-10* (Reference 3) documents the development and results – including updated frequencies in the *Operation and Maintenance: Inspection, Testing, and Maintenance of Fire Protection Systems UFC 3-601-02* (Reference 4) – of a methodology for optimizing ITM frequencies. The method is developed to determine ITM frequencies that maintain a 99% overall system reliability.

In this method, different possible failure modes for equipment and components are ranked and weighted using a failure modes and effects analysis (FMEA) process. The FMEA rankings are used to characterize the significance of a failure. The letters in the FMEA ranking column characterize both the probability of failure on demand (PFOD) for the component failure mode and the resulting system degradation. The PFOD ranking estimates the likelihood of a component failure in the identified failure mode. It was determined from combination of Air Force fire data, generic equipment failure data, and fire protection engineering experience (Reference 3). The rankings and their estimates are presented in Table 3-2.

Table 3-2: DoD PFOD Ranking

PFOD Ranking	PFOD Estimate
High (H)	$>10^{-2}$
Medium (M)	$>10^{-3}$ to 10^{-2}
Low (L)	$>10^{-4}$ to 10^{-3}
Very Low (V)	$<10^{-4}$

The degradation to the system represents the severity of the functional failure resulting from the failure modes – a measure of consequence (Reference 3). Table 3-3 identifies the possible degradation levels.

Table 3-3: DoD System Degradation Levels

System Degradation Level	Range of Effects
Total (T)	Complete loss of primary system functions
Partial (P)	Impairment of a primary system function, loss of a redundant component critical to the operation of a primary system function, or total loss of a secondary system function
Minimal (M)	Impairment of a secondary system function, loss of a redundant component critical to the operation of a secondary system function, delayed response of primary or secondary system function, or false trip of the system.

Examples of the rankings associated with different fire pump specific failure modes and causes are shown in Table 3-4.

Table 3-4: Example Fire Pump Failure Mode Rankings

Failure Mode	FMEA Ranking	Failure Cause	ITM Task (NFPA 1998)	NFPA Frequency
Fails to start	TL	Debris buildup resulting in an impeller jam	Pump churn test (Sections 5-3.2.1 & .2)	Weekly
Operates at degraded head/flow	PL	Driver operates at degraded rotational speed	Pump flow test (Section 5-3.3.1)	Annually
Fails to start	TV	Motor starter circuit failure	Pump churn test (Sections 5-3.2.1 & .2)	Weekly

Table 3-4: Example Fire Pump Failure Mode Rankings

Failure Mode	FMEA Ranking	Failure Cause	ITM Task (NFPA 1998)	NFPA Frequency
Starts too late	PV	Controller automatic start circuit failure resulting in the driver needing• to be started manually	Pump churn test (Section 5-3.3.1)	Weekly

These rankings are then measured against an event tree model specifically developed as part of the methodology to determine what frequencies are appropriate to maintain 99% system reliability. Fire pumps are included in this analysis. The resulting frequencies from the genesis, 1999 (Reference 3), report and the updated, 2010 (Reference 4), study are presented in Table 3-5.

Table 3-5: DoD Fire Pump Testing Frequency

Test	NFPA	1999 Frequency	2010 Frequency
Non-Flow	Weekly	Semiannually (6 Months)	Monthly*
Flow	Annually	5 Years	5 Years

*No discussion is provided in UFC 3-601-02 to justify the change in the non-flow test frequency.

The development of the ITM frequencies presented as part of this methodology are considerably dependent upon the subjective rankings made using the FMEA process, estimations of failure rates, availability, and system performance improvement due to the ITM task frequency.

The advantage of following this method is its ability to provide optimized ITM frequencies for a fire protection system at a reliability of 99% without any failure data. The disadvantage of following this method is that to make reliability decisions without data it relies a number of subjective assessments and weights. Additionally, the method is not easily tailored to application with individual systems.

3.1.3 Fire Protection Equipment Surveillance Optimization and Maintenance Guide

Similar to the DoD analysis, the Electric Power Research Institute (EPRI) has developed the *Fire Protection Equipment Surveillance Optimization and Maintenance Guide* (Reference 5) for adjusting test and inspection frequencies to be better accordance with equipment performance and a desired reliability. This method estimates the probability of failure on demand (PFOD) given the current non- optimized ITM frequency. The reliability of the system or component being optimized is calculated and measured against a *Target Reliability* and *Action Level*. The *Target Reliability* represents expected or desired reliability of a system or component. A system or component with a reliability above the *Action Level*, but below the *Target Reliability* is designated as functioning adequately. Reliability below the *Action Level* is not meeting expectations and the ITM frequency should be adjusted to reduce the time a failure remains undetected. If found to exceed the desired target value at the current ITM frequency, the methodology points to a basis for incrementally extending the ITM frequency.

Fire pumps are included in this analysis. The suggested revised frequencies are presented in Table 3-6.

Table 3-6: EPRI Fire Pump Testing Frequency

Test	NFPA	EPRI
Non-Flow	Weekly*	Monthly

Table 3-6: EPRI Fire Pump Testing Frequency

Test	NFPA	EPRI
Flow	Annually	1.5 - 2 Years

While the methodology ultimately recommends ITM frequencies for different fire protection systems, it does not appear to directly provide optimized schedules. Per the analysis, once a *Target Reliability* value is assessed and found to be exceeded, this methodology simply states that there is now basis for incrementally extending the ITM frequency period. Appropriately, following a change in an ITM frequency, future failure data must be analyzed and continually judged against the *Target Reliability* and *Action Level* until the appropriate frequency given the desired Target Reliability is reached.

Advantages of following this model are that it is evidence driven and provides not only an estimation of the reliability but also a method of calculating the confidence interval (uncertainty bounds) of the estimated reliability. However, this method has no predictive capabilities and only provides a representation of the current system reliability.

3.1.4 Aging Assessment for Active Fire Protection Systems

While not a method for revising ITM frequencies, the Sandia report – *Aging Assessment for Active Fire Protection Systems* (Reference 6) – reviewed 37 instances of fire pump failures at nuclear power plants over a 14-year period and found that only one could be classified as a failure on demand during the required actuation. The remaining 36 recorded failures took place during periodic testing or when the pump was running as part of a maintenance procedure. The report suggests a performance-based ITM program may minimize aging problems by highlighting the monthly startup test of a diesel-driven pump. The monthly test stresses and ages a pump that is designed for continuous operation and not cyclical operation.

3.1.5 Probabilistic Failure Model

A probabilistic failure model may also be used to numerically determine the reliability of fire protection systems like fire pumps. A model may be used to estimate the likelihood of failure thereby providing an estimate of reliability or availability of a fire pump. The development of the model depends highly on the evidence available for analysis, which can be used to support a one-time exercise or as a continuous process. The data collected may show a failure trend, such as an increasing, steady or decreasing time between failures. The system or component may be considered repairable or non-repairable. If repairable, is the item *as good as new* or *as bad as old* following repair? When evidence is available, a probabilistic failure model may provide a non-subject assessment.

It should be noted that the model is only as good as the data. A limited data set may not capture a complete history of possible failures and provide inappropriate predictions. As noted in the 2012 fire pump study (Reference 2) the subjectivity of the non-flow testing data could weaken any predictions made by the model.

3.2 Failure and Impairment

NFPA 25 classifications that may be used to describe the state of a fire pump include *impairment* and *deficiency*. The term *emergency impairment* refers to a fire protection system that is out of order due to an unplanned occurrence or the impairment is found while performing ITM activities, describes what would commonly be understood as failure of the fire protection system. Similarly, a *critical deficiency*, a condition that effects the ability of a fire protection systems ability to function as intended in the event of a fire, would likely be understood to represent the idea of a degraded level of performance.

On the other hand, a *noncritical deficiency* is a condition that does not affect the ability of the fire protection system to function in the event of a fire but does not meet the requirements of the standard for proper ITM activities, does not necessarily provide a grading or level of function. An example of a noncritical deficiency may be an inappropriate nameplate, which per the standard definition has no material effect on the pumps ability to function. However, a pump that shows a 6% degradation in pressure during a performance test would subjectively be judged as critically deficient the same as pump that showed a 50% degradation in pressure despite the objective measures. Of the failure and ITM methods reviewed above, the DoD method also provides an estimation of system degradation by ranking the loss of primary and secondary system functions.

3.3 Data Collection Parameters

The currently available retrospective data available for this research comes from the 2012 fire pump study (Reference 2). This data is limited to non-flow fire pump tests. Testing evidence identifies if a fire pump was found to successfully pass, failed or required repair during the test. In many, but not all cases, when the pump was found to fail the test or require repair a failure mode was identified.

This pass/fail evidence was used to determine the reliability of the fire pumps in the 2012 study and may be used to develop a predictive failure model in this current study. As discussed earlier, the subjective nature of the non-flow test data presents a weakness in reliability model for predicting failures.

4.0 TASK 4: CONDUCT DATA AUDIT AND OBTAIN AVAILABLE RETROSPECTIVE DATA

This section describes the data review and collection project task. The purpose of this task is to identify, review, and compile potential existing field data sources that relate to fire protection system reliability. Both the quality and quantity of existing field data needs given existing sources is reviewed with the intent of supporting the maximization of fire pump reliability.

4.1 Available Data

4.1.1 Non-Flow Test Data

The complete set of evidence collected during the 2012 *Fire Pump Field Data Collection and Analysis* (Reference 2) study has been reviewed. This evidence provides a total of 38 data sets including 4145 non-flow tests of 96 fire pumps in a standardized spreadsheet format identifying pass, fail, and repair. This data was judged adequate at the time of the 2012 study for providing a meaningful fire pump failure rate range with a 95% confidence.

The 2012 data was provided at a weekly interval for an average period of approximately one year. Tests are classified as either testing satisfactorily or not (for some data sets the test may also be listed as needing repair). Per the instructions provided in the standardized spreadsheet, a test is considered satisfactory if '*the fire pump started automatically, completed the run cycle without manual intervention, and was in suitable condition to respond to an emergency at the completion of the test.'* The decision to classify a fire pump as having successfully passed the test was made by those providing the data. For many data sets, failure modes were recorded indicating why the pump failed the test. Table 4-1 lists the standardized failure modes. It is noted that some of these failure modes would not generate a failure of the pump to perform on demand.

Table 4-1: Fire Pump Failure Modes (Reference 2)

Failure Mode	Description
Water Supply Failure	Includes conditions such as low suction pressure before start or while running, and low water level in suction tank or reservoir.
Electric Power Supply Failure	Includes conditions such as no electric power and loss of power phase(s)
Pipe, Fitting, and/or Valve Failure	Includes conditions such as leakage, damage, wrong open or closed position of valves
Controller Failure	Includes conditions such as isolation switch off, failure to start pump automatically, lights or indicators not normal, no alarms, transfer switch not normal
Pump Running Condition Failure	Includes conditions such as excessive vibration, unusual noises, excessive spray or no discharge from packing gland(s), overheating of packing boxes or bearings or pump casing
Pump Running Operation Failure	Includes conditions such as excessive time to accelerate to full speed, abnormal discharge pressure

Table 4-1: Fire Pump Failure Modes (Reference 2)

Failure Mode	Description
Relief Valve Failure	Includes conditions such as main relief valves fail to open, main relief valve fails to shut, circulation relief valve fails to flow water during churn
Diesel Engine Failure	Includes conditions such as low oil pressure, abnormal engine speed, high water or oil temperature, knocking or excessive noise
Diesel Engine System Failure	Includes conditions such as ventilation louvers not free to operate, fuel tank not 2/3rds full, fuel system has water in it, fuel tank float switch or solenoid valve not working, batteries or charger abnormal, oil level in right angle gear drive abnormal, crank case oil level abnormal, cooling water level or pump or system abnormal, water jacket heater not operating, exhaust system abnormal
Other	Includes unknown failure modes and failure modes not covered in the rows above. A description of the failure mode should be included in the comment section with a number identifier matching the "Comment Ref No".

The data collected as part of the 2012 study will be the evidence used to develop a probabilistic failure model for fire pumps. This failure model will then be used to determine the availability of a fire pump given different testing frequencies.

As noted above, the success/failure classification of a fire pump non-flow test is subjective and depends heavily on an assumed expertise of the one testing the fire pump. Therefore, a model prediction is only as good as the evidence used to develop the model.

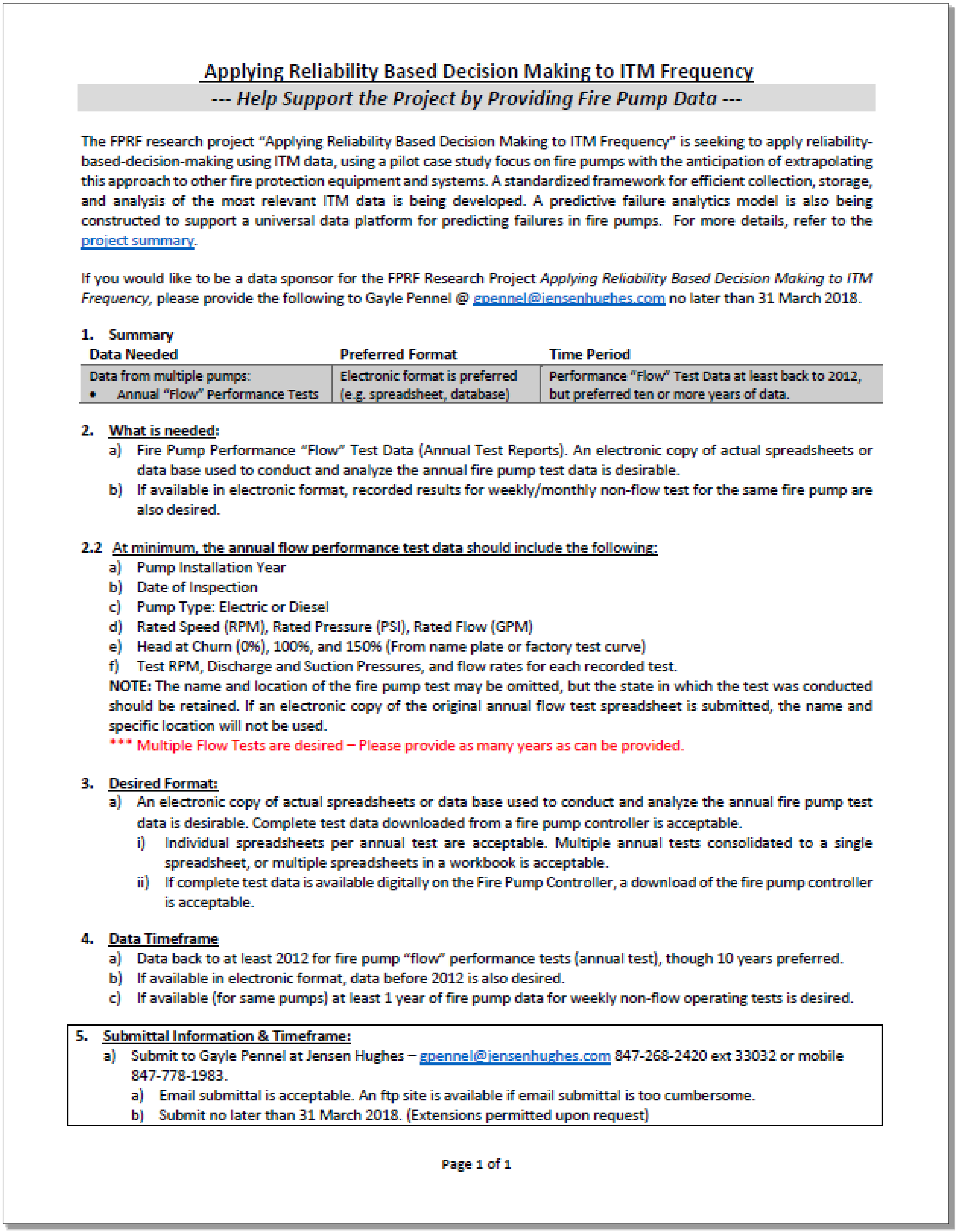
4.1.2 Performance Test Data

As the start of the project, a request was made to Project Technical Panel members and NFPA 20 and 25 Technical Committees for any electronic field data available that could be used in this research. A limited data set was collected. In partnership with the Fire Protection Research Foundation (FPRF) a document clarifying data requirements for developing a probabilistic failure model using the annual ‘performance’ flow test was distributed. The document is presented in Figure 4-1. As described in the document, the following information was requested to develop the failure model:

- Pump Installation Year
- Date of Inspection
- Pump Type: Electric or Diesel
- Rated Speed (RPM), Rated Pressure (PSI), Rated Flow (GPM)
- Head at Churn (0%), 100%, and 150% (From name plate or factory test curve)
- Test RPM, Discharge and Suction Pressures, and flow rates for each recorded test.

Unlike the non-flow tests, the evidence collected during a flow test is objectively used to determine of the fire pump has successfully passed the test or not. A fire pump fails the test if the test flow rates and pressure results are found to be lower than 95% of either the original unadjusted field test curve or those listed on the fire pump name plate.

Of the data received, a large subset was provided in a format that allowed for marginal manipulation and prompt inclusion in the database developed as part of this project. While this dataset included ITM statistics over 1500 pumps, only a small fraction was of data for a pump for more than a single year.



Applying Reliability Based Decision Making to ITM Frequency

--- *Help Support the Project by Providing Fire Pump Data* ---

The FPRF research project "Applying Reliability Based Decision Making to ITM Frequency" is seeking to apply reliability-based-decision-making using ITM data, using a pilot case study focus on fire pumps with the anticipation of extrapolating this approach to other fire protection equipment and systems. A standardized framework for efficient collection, storage, and analysis of the most relevant ITM data is being developed. A predictive failure analytics model is also being constructed to support a universal data platform for predicting failures in fire pumps. For more details, refer to the project summary.

If you would like to be a data sponsor for the FPRF Research Project *Applying Reliability Based Decision Making to ITM Frequency*, please provide the following to Gayle Pennel @ gpennel@jensenhughes.com no later than 31 March 2018.

1. Summary

Data Needed	Preferred Format	Time Period
Data from multiple pumps: • Annual "Flow" Performance Tests	Electronic format is preferred (e.g. spreadsheet, database)	Performance "Flow" Test Data at least back to 2012, but preferred ten or more years of data.

2. What is needed:

a) Fire Pump Performance "Flow" Test Data (Annual Test Reports). An electronic copy of actual spreadsheets or data base used to conduct and analyze the annual fire pump test data is desirable.

b) If available in electronic format, recorded results for weekly/monthly non-flow test for the same fire pump are also desired.

2.2 At minimum, the annual flow performance test data should include the following:

a) Pump Installation Year

b) Date of Inspection

c) Pump Type: Electric or Diesel

d) Rated Speed (RPM), Rated Pressure (PSI), Rated Flow (GPM)

e) Head at Churn (0%), 100%, and 150% (From name plate or factory test curve)

f) Test RPM, Discharge and Suction Pressures, and flow rates for each recorded test.

NOTE: The name and location of the fire pump test may be omitted, but the state in which the test was conducted should be retained. If an electronic copy of the original annual flow test spreadsheet is submitted, the name and specific location will not be used.

*** Multiple Flow Tests are desired – Please provide as many years as can be provided.

3. Desired Format:

a) An electronic copy of actual spreadsheets or data base used to conduct and analyze the annual fire pump test data is desirable. Complete test data downloaded from a fire pump controller is acceptable.

  i) Individual spreadsheets per annual test are acceptable. Multiple annual tests consolidated to a single spreadsheet, or multiple spreadsheets in a workbook is acceptable.

  ii) If complete test data is available digitally on the Fire Pump Controller, a download of the fire pump controller is acceptable.

4. Data Timeframe

a) Data back to at least 2012 for fire pump "flow" performance tests (annual test), though 10 years preferred.

b) If available in electronic format, data before 2012 is also desired.

c) If available (for same pumps) at least 1 year of fire pump data for weekly non-flow operating tests is desired.

5. Submittal Information & Timeframe:

a) Submit to Gayle Pennel at Jensen Hughes – gpennel@jensenhughes.com 847-268-2420 ext 33032 or mobile 847-778-1983.

  a) Email submittal is acceptable. An ftp site is available if email submittal is too cumbersome.

  b) Submit no later than 31 March 2018. (Extensions permitted upon request)

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Figure 4-1: Data Request Document.

5.0 TASK 5: PREDICTIVE FAILURE MODEL

This chapter describes the probabilistic model for predicting system or component unavailability. In this context, unavailability is defined as the fraction of time the system is down (i.e., not available to operate on demand). The model consists of a simulation of failures that occur over a period in which the system or component is subjected to routine inspections or testing.

The model was developed under the following general assumptions:

1. Systems or components are assumed to be “as bad as old” after a repair. That is, repairs do not restore the system or component to an “as good as new” condition. As such, repairs are considered to include the “minimal” improvements to bring the system or component back to operation.
2. Repairs are immediate. That is, the repair times are short relative to the mission time and therefore their contribution to the unavailability calculations are negligible. It should be noted that this is an assumption that does not need to be imposed in every model application.
3. Failures are not detected until the system is tested or inspected. This assumption is “application specific” as it is a characteristic of standby systems that are not continuously monitored (e.g., as in the case of some fire pumps). It should be noted that this is an assumption that does not need to be imposed in every model application.
4. Failures are always detected during testing and inspection. The probability that a component or system failure could go unrecognized is not included in the model. It should be noted that this is an assumption that does not need to be imposed in every model application.

5.1 Model Development

Consider the time line depicted in Figure 5-1. The round markers in the time line represent the routine scheduled test or inspection activities. The triangles represent equipment failures that occur over time. Recall that in this application, the system is in standby and failures will not be detected until the next scheduled test or inspection. The time to failure is governed by a probability distribution. Under this formulation, the model works by super-imposing failures over a time line of inspection or testing activities and tracking the time the system would be unavailable due to a failure occurrence. Notice that while the inspection interval is fixed, the failure occurrence is random. Failures occur as time progresses. Given the standby status of fire pumps, the failure will be detected at the next inspection point. The time between the failure and the next inspection point is assumed to be downtime in which the pump would not operate on demand. Downtimes are then tracked and used to calculate the unavailability of the system or equipment.

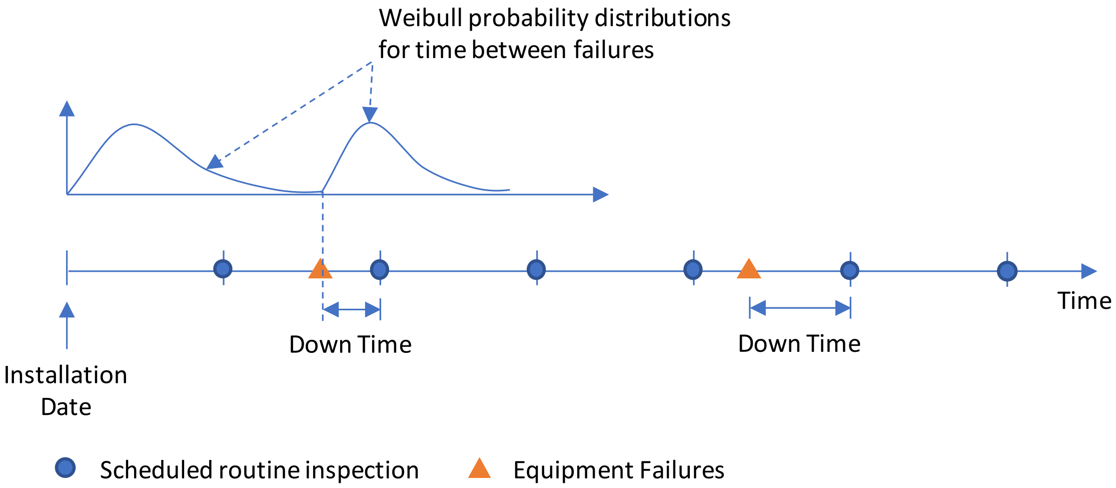

Figure 5-1: Conceptual effect of various inspection interval frequencies

5.1.1 Modeling Failures of Repairable System

Let's describe first the probabilistic model for predicting the failures. The equipment (e.g., the fire pumps) will be modeled as repairable systems – a system that may be brought back into operation following a failure with some repair action. Therefore, the failures are assumed to be dependent as the system ages. This behavior is usually modeled using a non-homogeneous Poisson process (NHPP).

The NHPP models a stochastic process. A stochastic process models a random variable as a function of time, or $f(T,t)$, where *T* is the random variable for the time to the next failure. Therefore, give a time t, $f(T)$ is a probability distribution for the time to next failure. In practice, different $f(T's)$ are modeled using conditional distributions from $f\left(t_i/t_i < t_{i-1}\right)$ where t_i is the time to next failure and t_{i-1} is the time of the last failure. Here, the failure rate may change as a function of time. This is particularly appropriate for the modeling of repairable items since it is expected that, on average, the time to the next failure will decrease as the item ages. However, that is not a requirement of the NHPP, constant or decreasing failure rates may also be modeled. The flexibility of the NHPP offers a general process for the modeling of fire pump failures. The Weibull distribution is a common distribution routinely used with the NHPP as it is also capable of dealing with increasing, decreasing and constant failure rate conditions.

5.1.2 The Weibull Distribution

The Weibull distribution can represent probabilities of failures in increasing, decreasing and constant failure rate conditions. It offers a more general form than that of the commonly used Exponential distribution which assumes a constant failure rate. For the Weibull distribution, the distribution for the first failure is determined as:

$$f(t) = \frac{\beta t_1^{\beta - 1}}{\alpha^{\beta}} e^{\left(\frac{t_1}{\alpha}\right)^{\beta}}$$

where β is the shape parameter and α is the scale parameter. For subsequent failures, the probability distribution is conditional as follows:

$$f\left(t_i|t_i > t_{i-1}\right) = \frac{\beta t_i^{\beta-1}}{\alpha^\beta} e^{\left(\frac{t_{1-1}}{\alpha}\right)^\beta - \left(\frac{t_i}{\alpha}\right)^\beta}$$

The second term inside the exponential is $\left(t_i/\alpha\right)^\beta$ and does not have the term t_0. Here, t_0 is 0 since the t_i refers to the time measured after the last failure. Therefore, t_0 is 0.

5.1.3 Numerical Estimation of Parameters

Kristsov (Reference 7) describes a very useful algorithm for determining the expected number of failures of a repairable system by solving the process described above. The algorithm calculates the expected number of failures using a Monte Carlo simulation. The formulation consists in generating n number of failure histories for a given repairable item. A failure history refers to the number of failures experienced by the repairable item in a period of analysis t_f.

For each failure history *H*, the time accumulator is set to 0 and failure times are generated using a random number generator from a corresponding probability distribution. Notice that any applicable distribution can be used and the parameters of the distribution are provided as inputs to the algorithm. For any failure history, the algorithm determines if the failure j is the first in the history. If $j = 0$, then the distribution $f(T)$ is used to generate the time for this first failure. The time for the second failure ($j \geq 1$) is generated using the conditional distributional distribution $f(T_i/T_i > T_{i-1})$ for the non-homogeneous Poisson process or $f(t)$ for the renewal process. The process continues by generating additional failures with their corresponding times. The failure times are accumulated until $t > t_f$. At this point, the number of failures in the history is stored for future use and the generation of the next failure history begins. Once the n failure histories have been generated, there are *n* calculated number of failures. Finally, the number of failures in each history are averaged and reported as the expected number of failures for the repairable item.

Recall that in the Non-Homogenous Poisson Process, the first failure is represented with a probability distribution $f(t)$. Subsequent failures are then represented by the conditional distribution$f(t_i/t_i > t_{i-1})$. As an example, the parameters for the Non-Homogeneous Poisson Process are estimated assuming the failure times follow a Weibull distribution. A similar procedure would need to be followed if failure times are characterized by a different distribution.

For a time terminated evaluation, e.g., predicting the next failure considering that the item has been operating for some time after the last failure:

$$L(t,\alpha,\beta) = \frac{\beta t_1^{\beta-1}}{\alpha^\beta} e^{-\left(\frac{t_1}{\alpha}\right)^\beta} \cdot \left\{ \prod_{i=2}^{n} \frac{\beta t_i^{\beta-1}}{\alpha^\beta} e^{-\left(\frac{t_{i-1}}{\alpha}\right)^\beta - \left(\frac{t_i}{\alpha}\right)^\beta} \right\} \cdot R\left({}^{T_e}/t_n\right)$$

The first term in the right-hand side is the Weibull distribution for the first failure. The second term in the right-hand side, which is inside the product, are the conditional Weibull distributions for failures 2 to *n*. Finally, the third term in the right-hand side is the probability that the item will not fail before the test is terminated. This last probability is calculated using the conditional Weibull from the time of the last failure until time T_e.

Expressing the equation above in logarithmic terms, differentiating with respect to *α* and *β*, setting the two differential equations to 0, and solving the system of equations produces the following estimates:

$$\alpha = \frac{t_n}{n^{1/\beta}}, \text{ and } \beta = \frac{n}{\sum_{i=1}^{n} \ln\left(\frac{t_n}{t_i}\right)}$$

For a failure terminated evaluation:

$$L(t,\alpha,\beta) = \frac{\beta t_1^{\beta - 1}}{\alpha^{\beta}} e^{-\left(\frac{t_1}{\alpha}\right)^{\beta}} \cdot \prod_{i=2}^{n} \frac{\beta t_i^{\beta - 1}}{\alpha^{\beta}} e^{-\left(\frac{t_{i-1}}{\alpha}\right)^{\beta} - \left(\frac{t_i}{\alpha}\right)^{\beta}}$$

The first term in the right-hand side is the Weibull distribution for the first failure. The second term in the right-hand side, which is inside the product, are the conditional Weibull distributions for failures 2 to *n*.

Expressing the equation above in logarithmic terms, differentiating with respect to α and β, setting the two differential equations to 0, and solving the system of equations produces the following estimates:

$$\alpha = \frac{t_n}{n^{1/\beta}}, \text{ and } \beta = \frac{n - 1}{\sum_{i=1}^{n-1} \ln\left(\frac{t_n}{t_i}\right)}$$

5.1.4 Calculation of Availability

The expected accumulation of failures over time is modeled once the model parameters have been estimated. Using these parameters, the equipment availability is estimated given different ITM frequencies. The steps to estimate the availability are:

1. Model the accumulation of failures for a fire pump.
2. The model described above predicts accumulation of failures per day for a fire pump (i.e., each unit of time accumulates a fraction of a failure). In this formulation, the failure accumulation represents the equipment deterioration process as it ages. Since the deterioration is modeled as fractions of failures that accumulate in time, the fire pump is expected to be out of service when the accumulated fraction reaches a value of 1.0.

   There is no limit placed on the model limiting the number of expected accumulation of failures to 1.0. Just as observed in the ITM data reviewed in Task 4, multiple failures may occur in various time intervals. Therefore, upon reaching a value of 1.0, the model continues to predict the accumulation of fractional failures as the equipment deteriorates.

   The accumulation of fractional failures is presented graphically in Figure 5-2.

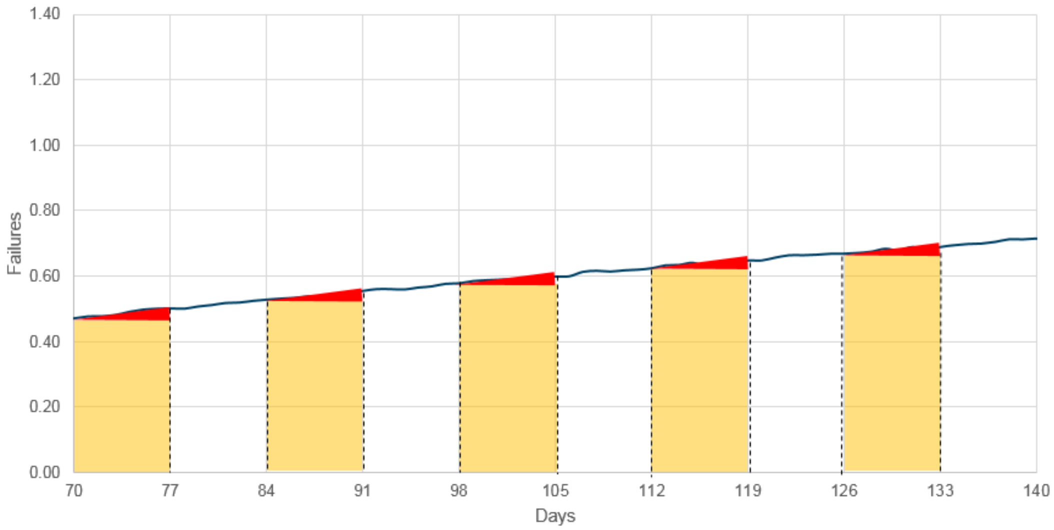

Figure 5-2: Accumulation of Fractional Failures

In Figure 5-2 the solid line represented the total accumulation of failures as time advances. The yellow blocks represent that accumulated fraction of failures from all previous time intervals (shown here bi-weekly for visual clarity.) The red areas above the orange blocks represent the accumulation of fractional failures (i.e., incremental failures) for the time interval of interest (a week in this example). As the equipment ages the accumulation of failures (red area) are added to the accumulated fraction of failures from previous time intervals (orange blocks).

3. Determine the fraction of an inspection interval the pump would be unavailable if a failure occurred.

The fraction of the ITM interval the pump would be unavailable is calculated by determining the time between when the failure may occur and the next ITM or testing occurrence and dividing it by the ITM period. The fraction of the ITM interval the pump would be unavailable for a weekly ITM interval is presented as an example in Table 5-1.

Table 5-1: Fraction of ITM Period Unavailable – Weekly

Day of ITM Period	1	2	3	4	5	6	7
Days Unavailable Following a Failure	7	6	5	4	3	2	1
Fraction of ITM Period Unavailable	1	0.86	0.71	0.57	0.43	0.29	0.14

The *Fraction of ITM Period Unavailable* in Table 5-1 represents the fraction of the weekly interval a fire pump would be unavailable depending on what day out of the interval it failed. For example, if the fire pump failed on the 3rd day of the inspection interval it would be unavailable for 5 days before being identified during the next inspection.

4. Estimate the unavailability of the fire pump per day given the individual day accumulation of failures and the fraction of the inspection interval the pump would be unavailable.

Combining the daily fractions of accumulated failures and inspection period unavailable results in an estimation of unavailability for the fire pump for that inspection period. By using the daily fractions of accumulated failures, the unavailability may be estimated for multiple inspection intervals using various fraction of inspection periods.

5. The above process is repeated many times in a Monte Carlo simulation to obtain averages that are representative of the different failure histories generated by the probability distributions governing the equipment failure times.
6. Select the appropriate availability for your analysis.

   In Tasks 2 and 3 a number of different failure assessment methodologies were reviewed and discussed in detail. Many of the methodologies reviewed included *target reliabilities* as part of their analysis. The values highlighted in the methodologies reviewed ranged from 95%-99%. For cases where test and repair times are short, the availability value approximates the reliability value (i.e., failures are the only significant contribution to down times). Per assumption 2 in Section 5.0 (repairs are immediate), target reliabilities will be assumed as appropriate target availabilities for this analysis. EPRIs *Fire Protection Equipment Surveillance Optimization and Maintenance Guide* notes that a target reliability of 95% is generally consistent with the reliability goals for safety equipment. For period of a year, a 95% availability would result in the fire pump being out of service (unavailable) for approximately 18 days.

5.2 Examples

As part of the 2012 *Fire Pump Field Data Collection and Analysis* (Reference 2) data for the weekly non-flow tests were collected. This data included the installation date of the fire pump. In these examples, the weekly, non-flow, test data for three fire pumps installed in 1976, 1980, and 1995 are used with the model to determine the availability of the fire pumps.

Note: These examples are intended to test the model fire pump failure accumulation predictions and availability results for individual pumps and are presented to show the capability of the model described in Section 5.1 and availability calculation as described in Section 5.1.4. The results of these examples should not be used generically for any fire pumps.

5.2.1 Constant Failure Rate

Figure 5-3 depicts the failure dates for a diesel fire pump installed in 1982 for the non-flow tests performed during 2010. This fire pump experienced 6 failures during the period of recorded data (see blue circles, Figure 5-3). The spacing of the failures suggests a constant failure rate (i.e., failures are occurring at a constant interval). Also presented in Figure 5-3 is NHPP prediction of accumulating failures (red line) generated by the model.

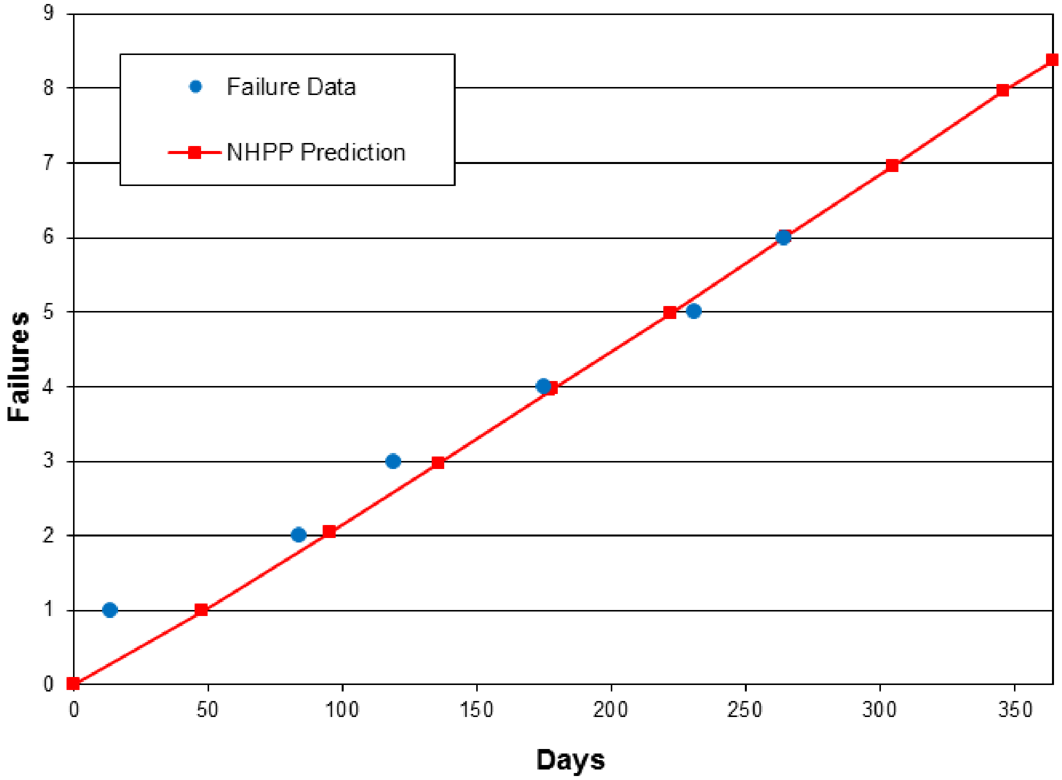

Figure 5-3: Constant Failure Rate Model Prediction

The failure data and resulting model alpha and beta parameters estimated assuming 0 days after the final failure are presented in Table 5-2. This is a failure terminated analysis. Note, this fire pump was installed in 1982, however the available inspection data is from 2010. The equipment age for the model developed in this example is assumed to begin with the first inspection period from the available data set.

Table 5-2: Failure Data – Constant Failure Rate

Failure Number	Days between Failures	Equipment Age	Alpha	Beta
1	14	14	48	1.05
2	70	84		
3	35	119		
4	56	175		
5	56	231		
6	33	264		

5.2.2 Decreasing Failure Rate

Figure 5-4 shows the failure dates for a diesel fire pump installed in 1976 for the non-flow tests performed during 2007-2009. This fire pump experienced 9 failures during the period of recorded data (see blue circles, Figure 5-4). The data suggests a decreasing failure rate – the time separating failures is increasing. Also presented in Figure 5-4 is NHPP prediction of accumulating failures (red line) developed using the failure data.

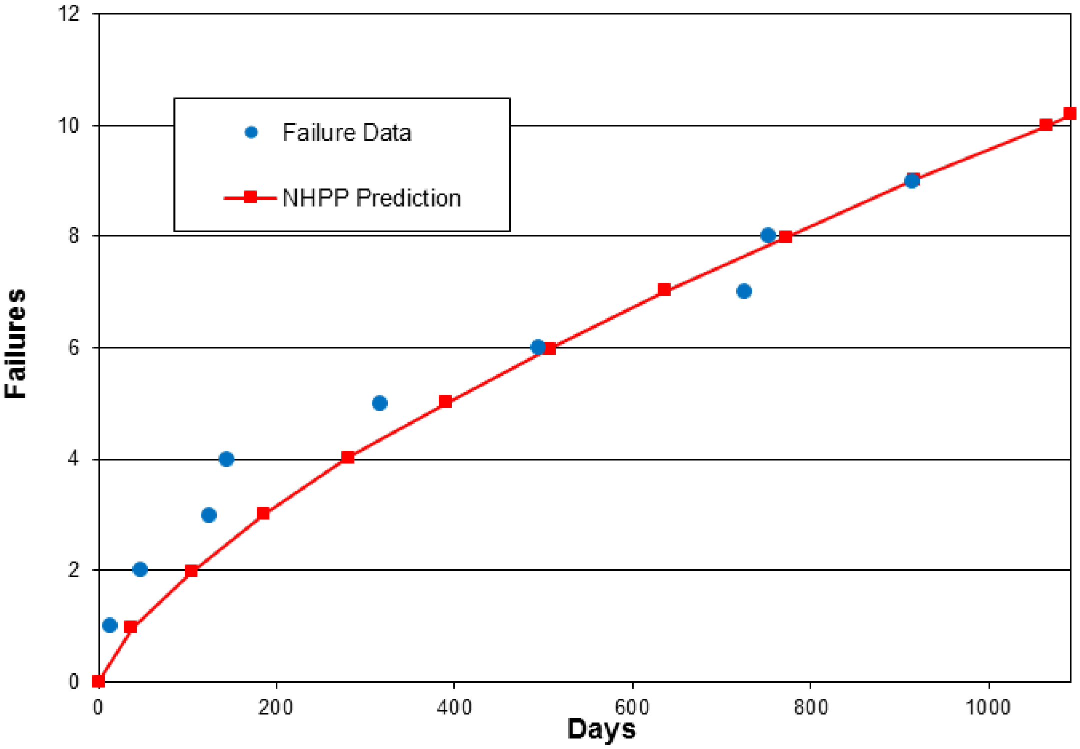

Figure 5-4: Decreasing Failure Rate Model Prediction

The failure data and resulting model alpha and beta parameters estimated assuming 0 days after the final failure are presented in Table 5-3. This is a failure terminated analysis. Note, this fire pump was installed in 1976, however the available inspection data is from 2007-2009. The equipment age for the model developed in this example is assumed to begin with the first inspection period from the available data set.

Table 5-3: Failure Data – Decreasing Failure Rate

Failure Number	Days between Failures	Equipment Age	Alpha	Beta
1	13	13	38	0.69
2	34	47		
3	78	125		
4	20	145		
5	172	317		
6	178	495		
7	231	726		
8	27	753		
9	162	915		

5.2.3 Increasing Failure Rate

Figure 5-5 shows the failure dates for a diesel fire pump installed in 1995 for the non-flow tests performed during 2010. This fire pump experienced 3 failures during the period of recorded data (see blue circles, Figure 5-5). The data suggests an increasing failure rate – the failures are occurring more frequently as time advances. Also presented in Figure 5-5 is NHPP prediction of accumulating failures (red line) developed using the failure data. With only a few data points, and those points suggesting an increasing failure rate the model predicts multiple failures before the end of the yearly inspection interval.

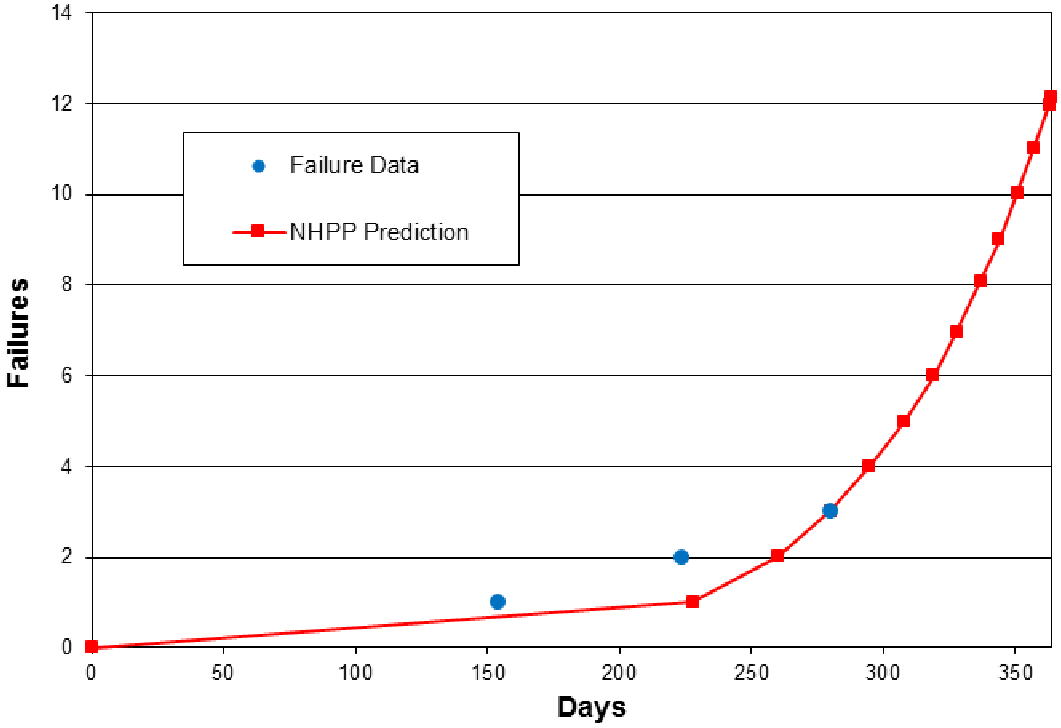

Figure 5-5: Increasing Failure Rate Model Prediction

The failure data and resulting model alpha and beta parameters estimated assuming 0 days after the final failure are presented in Table 5-4. This is a failure terminated analysis. Note, this fire pump was installed in 1995, however the available inspection data is from 2010. The equipment age for the model developed in this example is assumed to begin with the first inspection period from the available data set.

Table 5-4: Failure Data – Increasing Failure Rate

Failure Number	Days between Failures	Equipment Age	Alpha	Beta
1	154	154	228	5.34
2	70	224		
3	56	280		

5.2.4 No Recorded Failures

Figure 5-6 depicts the failure dates for a diesel fire pump installed in 2008 for the non-flow tests performed during 2010. This fire pump experienced 0 failures during the period of recorded data (see blue circles, Figure 5-6). Also presented in Figure 5-6 is NHPP prediction of accumulating failures (red line) generated by the model.

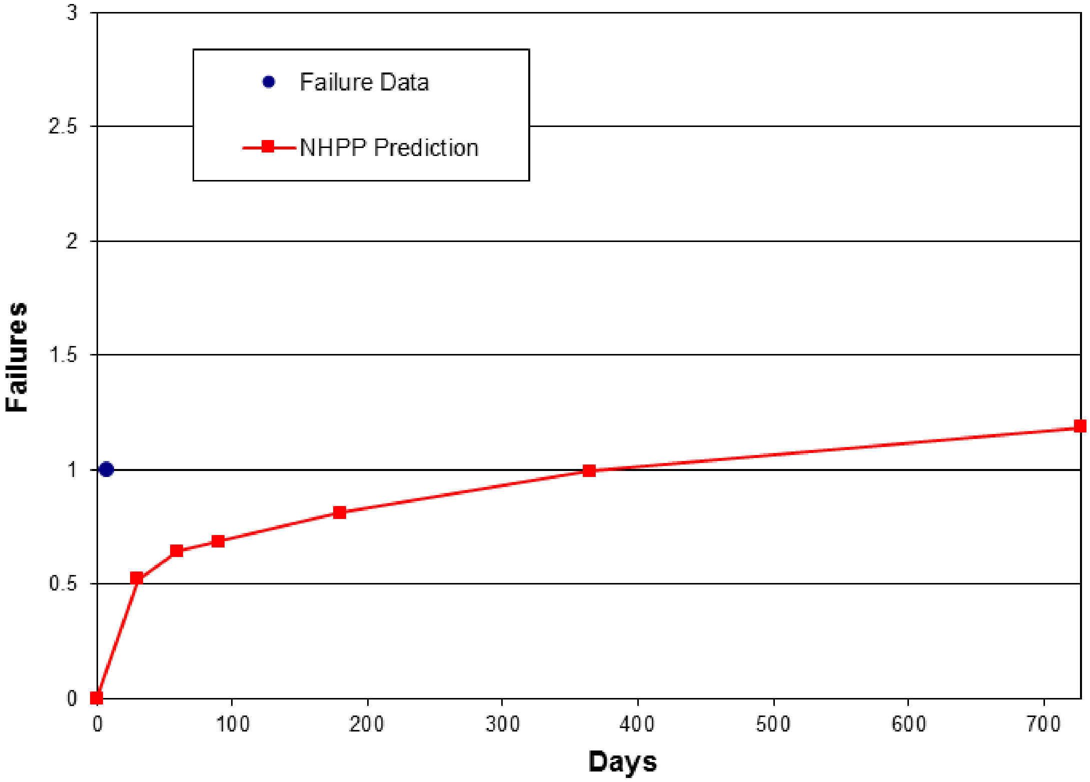

Figure 5-6: No Recorded Failures Model Prediction

Note that in Figure 5-6 and Table 5-5 a single failure is shown. The estimation of model parameters requires evidence of a failure to develop the probability distribution for the time to next failure. With no recorded failure, an assumed failure is postulated at the start of the period of available ITM data. Since it is unknown if there were any failures prior to the start of the interval of recorded ITM data, a single inspection period (7 days) is assumed to have occurred prior to the assumed failure (Equipment Age = 7 Days in Table 5-5). As this is a failure terminated analysis, the resulting model alpha and beta parameters estimated assuming 364 days after the assumed failure. The failure data and model parameters are presented in Table 5-5. Note, this fire pump was installed in 2008, however the available inspection data is from 2010. The equipment age for the model developed in this example is assumed to begin with the first inspection period from the available data set.

Table 5-5: Failure Data – No Recorded Failures

Failure Number	Days between Failures	Equipment Age	Alpha	Beta
1	7	7	371	0.25

5.2.5 Availability

Table 5-6 lists the resulting estimated *Availability* per *Inspection Interval* (Frequency). The number of *Days Unavailable* the pump would be expected to be out of service may be estimated for a period of a year by multiplying the availability value by 364 days.

Table 5-6: Availability for Fire Pumps

	Constant (Section 5.2.1)		Decreasing (Section 5.2.2)		Increasing (Section 5.2.3)		No Failures (Section 5.2.4)	
Inspection Interval	**Availability**	**Days Unavailable**	**Availability**	**Days Unavailable**	**Availability**	**Days Unavailable**	**Availability**	**Days Unavailable**
Weekly	0.940	22	0.984	6	0.920	29	0.997	1
Monthly	0.750	91	0.866	49	0.761	87	0.997	1
Quarterly	0.368	230	0.455	198	0.665	122	0.997	1
Annually	0.132	316	0.100	328	0.626	136	0.997	1

Using the results presented in Table 5-6, the appropriate inspection interval for a desired availability (or number of days the fire pump would be expected to be out of service) may be selected. In the case of the first three pumps, the data suggests that the availability drops significantly with changes in inspections intervals. This is due to the relatively large number of reported failures within a year. If for example, a given pump experiences nine failures in a year, it is expected that the unavailability will be high if inspected monthly. For the case of a pump with no recorded failures, while the modeling suggests an increase in the inspection interval would not affect the availability (i.e., the inspection intervals can be increased), care should be taken as it may simply be that the interval of recorded data is not long enough to reliably capture the true state of the pump. Increasing the inspection intervals in small increments may be appropriate.

5.3 Model Verification and Validation

Verification and validation (V&V) provides a measure of confidence in the results predicted by a model. Verification is the process of determining if the model appropriately represents the developer's conceptual description – to determine if the model was "built" correctly. On the other hand, validation is the process of determining that the model can reproduce the phenomena of interest – to determine if the correct model was "built."

5.3.1 Verification

When the model, as described in this report is constructed for use in determining the cumulative fraction of failures and/or the unavailability of various inspection intervals, verification could be achieved by comparing the outputs to the results described throughout this report.

5.3.2 Validation

To evaluate how capable the model is at reproducing failure predictions two comparisons are made for data associated with six pumps. Data from six fire pumps with multiple failures, installed between the 1960s and 2000s (see Figure 5-7), are used to numerically estimate parameters for predictive failure model. First, the failure predictions for each pump calculated ignoring the last actual failure data point are compared to the last observed failure. That is, for all fire pumps, the final ITM failure data point was excluded from data set used to estimate the model parameters. Failures were then predicted and compared with the last observed failure. The data used as part of this validation study is presented in Table 5-7.

The second comparison was made with a model prediction using an average of the alpha and beta parameters of each of the individual models. Table 5-8 lists the last pump failure time, the individual model alpha and beta parameters, the failure time predicted by the model, and the difference between the known final failure and those predicted by the individual and average model. The results shown in Table 5-8 highlight that when the individual pump models are combined, the variability between the predicted failure time and the actual failure time increases.

The model bias and uncertainty statistics for the failure date calculated using the six pumps are shown in Table 5-9. The statistics provided were determined following the methods outlined in the Supplement to NUREG-1824 (Reference 8) as described below. The validation approach described in this reference was developed in support of performance-based fire modeling applications and is applied in this research as a metric for determining the predictive capabilities of the model. For a set of *n* experimental measurements, E_i, and a corresponding set of model prediction, M_i, the following:

$$\overline{\ln\left(\frac{M}{E}\right)} = \frac{1}{n}\sum_{i=1}^{n}\ln\left(\frac{M_i}{E_i}\right).$$

Using the formulation above, the standard deviation of the model error $\tilde{\sigma}_m$ can be computed as:

$$\tilde{\sigma}_M^2 + \tilde{\sigma}_E^2 = \frac{1}{1-n}\sum_{i=1}^{n}\left[\ln\left(\frac{M_i}{E_i}\right) - \overline{\ln\left(\frac{M}{E}\right)}\right]^2,$$

The bias factor is:

$$\delta = \exp\left(\overline{\ln\left(\frac{M}{E}\right)} + \frac{\tilde{\sigma}_M^2}{2} - \frac{\tilde{\sigma}_E^2}{2}\right),$$

This method required an estimation of the uncertainty in the measured data point, $\tilde{\sigma}_E$, in this exercise the recorded failure date. In this analysis the failure date is unknown and only captured when the non-flow test is performed. Therefore, for each data collection period the maximum time a fire pump could be in a failed state would be for one full week. For the average year long period of data collection, the uncertainty in the recorded failure period is assumed to be 1/52 to represent 1 week out of a 52-week (364 day) period.

In Figure 5-8, a comparison of the bias (solid red and blue lines) and uncertainty results (dashed red and blue lines) are presented for the individual model predicted failure ages (red circles) and the averaged model predicted failure ages (blue circles). In each case, a bias to under-predict is made clear by comparing the plotted results to the Perfect Match Line (black line). This line signifies where the failure times recorded during the non-flow tests and those predicted by the model were equal. Any values above this line represent an over prediction by the correlation. Over predictions refer to the calculations of more failures than what was observed.

In these examples, the under predictions are small and within the assessed model uncertainty. At the same time, the bias provides a tool for “correcting” the model with the average bias value when applying it for determining ITM schedules.

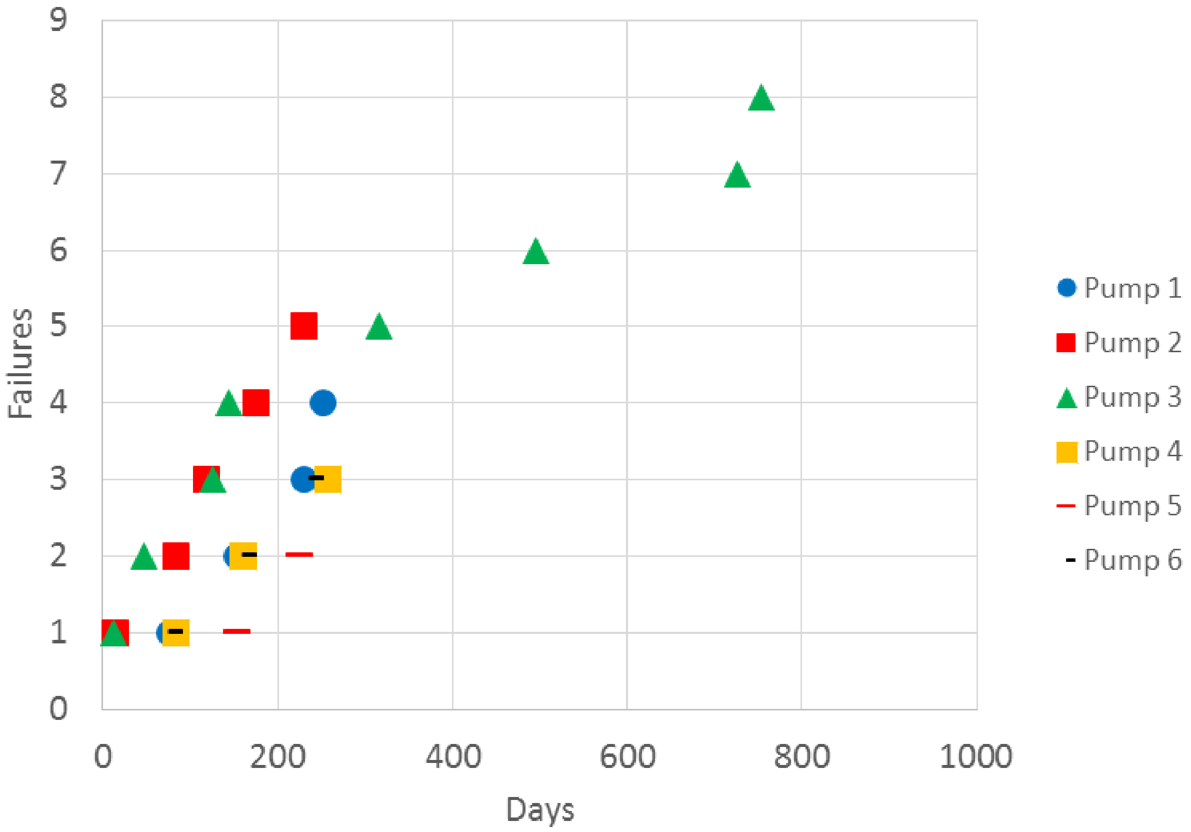

Figure 5-7: Model Validation Input Failure Data

Table 5-7: Validation Model Development Failure Data

Failure Number	Pump 1		Pump 2		Pump 3		Pump 4		Pump 5		Pump 5	
	Days between Failures	Equipment Age	Days between Failures	Equipment Age	Days between Failures	Equipment Age	Days between Failures	Equipment Age	Days between Failures	Equipment Age	Days between Failures	Equipment Age
1	77	77	14	14	13	13	83	83	154	154	77	77
2	77	154	70	84	34	47	77	160	70	224	84	161
3	77	231	35	119	78	125	98	258	-	-	77	238
4	21	252	56	175	20	145	-	-	-	-	-	-
5	-	-	56	231	172	317	-	-	-	-	-	-
6	-	-	-	-	178	495	-	-	-	-	-	-
7	-	-	-	-	231	726	-	-	-	-	-	-
8	-	-	-	-	27	753	-	-	-	-	-	-

Table 5-8: Individual and Averaged Model Predictions

Fire Pump	Number of Failures, Total	Alpha	Beta	Final Failure Age, Days	Individual Model Prediction Age, Days	Individual Difference, Days	Average Alpha	Average Beta	Averaged Model Prediction Age, Days	Averaged Difference, Days
Pump 1	5	135	2.13	357	289	68	116	2.01	259	98
Pump 2	6	49	1.02	294	300	-6			284	10
Pump 3	9	37	0.69	915	900	15			347	568
Pump 4	4	143	1.77	321	312	9			232	89
Pump 5	3	199	4.58	280	252	28			202	78
Pump 6	4	136	1.87	350	285	65			232	118

Table 5-9: Bias and Uncertainty of Individual and Averaged Model Predictions

Model	Bias	Model Uncertainty	Experimental Uncertainty
Individual	0.92	0.10	0.02
Averaged	0.70	0.31	0.02

Finally, the model uncertainty (estimated as the $\pm 2\tilde{\sigma}_M$ around the bias) associated with the average model is relatively higher. This is driven primarily by the difference between the final recorded failure and the model prediction for Pump 3. Comparing the model parameters alpha and beta, the data from Pump 3 is expressing a failure rate different from the other 5 pumps. This highlights the challenges associated with combining failure data from different pumps for generic purposes.

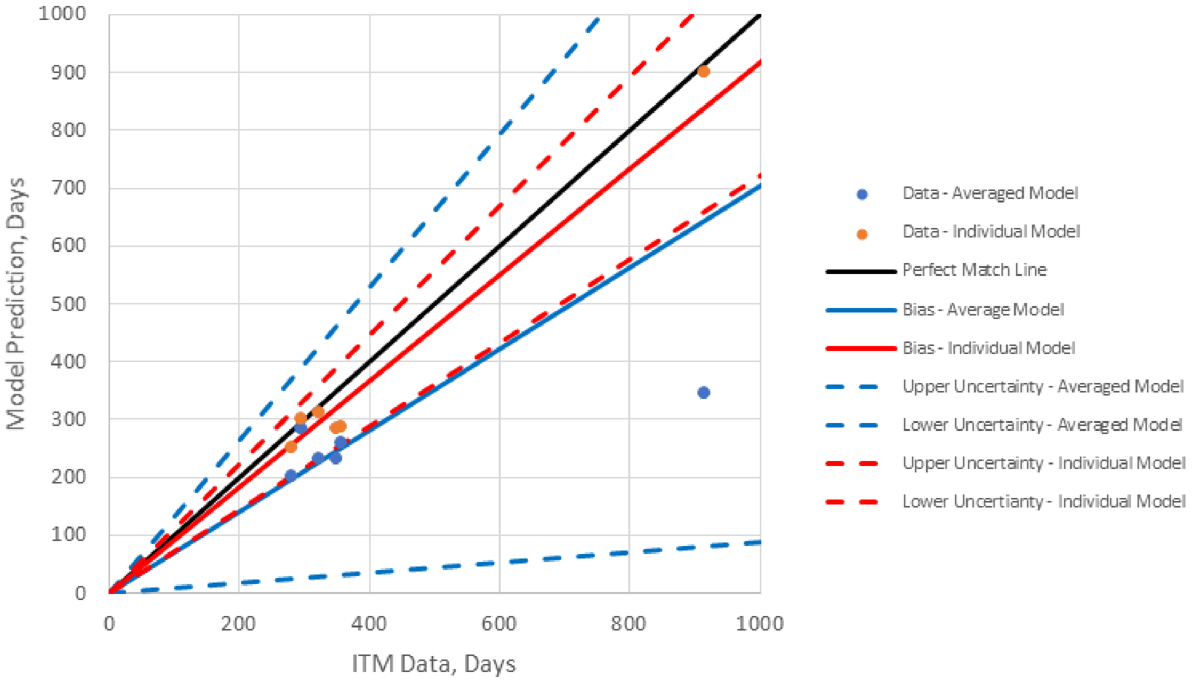

Figure 5-8: Recorded Failure Date vs. Model Failure Date – Bias and Uncertainty

Here the bias, δ, and model uncertainty, $\tilde{\sigma}_M$, may be used to correct the model prediction for an estimate of the mean true value of the predicted failure dates as (Reference 8):

$$\mu_T = \frac{M}{\delta}$$

6.0 TASK 6: PROTOCOLS FOR ON-GOING DATA EXCHANGE

This chapter describes the development of protocols for on-going data collection in support of a performance-based estimator of inspection, testing and maintenance activities. The development of these protocols considers benefits and perceived barriers to a standardized framework for ITM data collection for recommending a generic data collection platform that builds on approaches already described in standards such as NFPA 20 and NFPA 25.

6.1 Challenges in Data Collection

Some of the traditional challenges in collecting ITM data are identified first in order to establish protocols that can be successfully implemented. The following challenges are perhaps the most prominent ones:

- Data format: Currently there is no required standardized format for collecting reliability data. ITM data may be recorded by hand on paper, using a mobile application, or other electronic means. Each of these follow a different format.
    - Having access to the data in the appropriate format is an essential component to enabling data to influence decision-making regarding ITM frequency. A key challenge is obtaining the raw data to assess the performance of equipment over several years.
- Multiple parties involved: This affects the ownership of data analysis and maintenance. Usually, there are a total of four parties involved in the inspection, testing, and maintenance process. These parties are:
    - The End-User (e.g., the facilities manager). The facilities manager needs access to all inspection reports to prove compliance to the local AHJ upon request, to be aware of the state of the equipment (e.g. operational efficiency), and to be aware of any required maintenance needs.
    - The Fire Protection Contractor or Inspector. The contractor performs tests in accordance with the appropriate codes, record the results, inform the owner of the performance analysis, provide documentation of the test results, and recommend any maintenance required to meet the performance criteria.
    - The Inspection Reporting Company (e.g. a third-party entity who collects, records, and stores the fire pump data and inspection/test reports). The third-party data collector hosts the data collection software used by the fire protection contractor. The inspection reporting company provides the equipment (i.e. scanners, barcodes, etc.) to record all information and data points from the fire pump inspection or annual performance test. As the information is being recorded by the fire protection contractor into the inspection reporting software, the data is logged into the inspection reporting company's secure data infrastructure where the database of inspection reports are stored for their client.
    - The Authority Having Jurisdiction (e.g. a fire marshal or code enforcement agency). In some jurisdictions require the inspection and test results be submitted for review and enforcement purposes. The submittal may be made by the fire protection contractor or inspector, or by an inspection reporting company. Submittals could be paper or electronic where the jurisdiction is set-up to handle electronic submittals.

- Data Confidence: The success or failure for some ITM tasks is sometimes determined following a subjective assessment (e.g., non-flow tests). For these and similar cases, predictions or decisions using such evidence should be carefully considered as they could carry considerable uncertainty.

- Failure Mode: When possible, each recorded failure should be associated with the type of failure that occurred and the ITM task that identified the failure. This will allow for prioritization of appropriate ITM tasks to be developed.
- No standard analytical model for defining the specific data that is available. The performance-based allowance in NFPA 25 for example is not specific on the type of analysis that can be performed for determining ITM schedules. This promotes the lack of consistency in the data collection process.

For each inspection, test, and maintenance activity, the results must be analyzed by the service provider and the results presented to the owner, and in some cases the local authority having jurisdiction. The report provided to the owner should include any appropriate recommendations to correct any observed deficiencies and deficiencies uncovered by testing.

6.2 Benefits of Appropriate Data Collection and Maintenance Protocols

Some of the benefits associated with a structured ITM data collection and maintenance approach include:

- Optimization of ITM Tasks: As demonstrated in this project, consistently collecting ITM and failure data allows for the frequency of ITM tasks to be optimized to a desired availability of the system.
- For many systems, multiple ITM tasks are required and at varying intervals. When the failure data is collected in a manner that allows for the identification of the failure mode, the analysis could can suggest strategies to optimize the ITM activities. This can result in an optimization of the time personnel are out performing ITM tasks by highlighting those ITM tasks that are most immediately required.

Benefits are not limited to optimizing the ITM frequency. These benefits may also provide general system operation and design improvements including:

- Evidence Driven Analysis: The consistent collection of ITM and failure data provides an objective foundation for decision making. It lessens the need for subjective assessments based on memory or out of date experience.
    - When the ITM and failure data can be correlated to failure modes, the data allows for trends to be observed which may highlight areas where changes in design or maintenance practices are appropriate.
    - A collection of data can assist in determining that the actual problem is being corrected as different solutions are attempted, and not simply the symptom.
  - Code Enforcement: Electronic systems can track what inspections are being made, and where fire protection and life safety issues exist, thereby allowing the enforcing personnel to focus where the need for enforcement is.

6.3 Protocols for On-Going Data Exchange

The following sub sections describe the recommended protocols for on-going data collection and maintenance in support of ITM analysis. These protocols are based on the following objectives:

- A centralized data exchange should be established and maintained. That is, multiple levels of data ownership among the facility support chain should be avoided.
- The data collection and storage must be integral to the inspection, testing, and maintenance procedures used by the service provider.

- The data collection must be electronic, i.e. not paper based.
- Centralized data exchanges must use a common data base format, or have an integral conversion to a common data base format. For example, NFPA 20 added an annex in the 2016 Edition that provided a standardized Modbus format for storing data in the fire pump controller. In the 2017 edition, NFPA 25 found the Modbus format in NFPA 20 was too limiting and added a connectivity annex utilizing a database type format for storage inspection, testing, and maintenance data. In the 2019 Edition of NFPA 20, the Modbus format for controllers was retained, but a database format based on NFPA 25 was added to encourage data storage outside of the fire pump controller.
- Achieving a common data base format will require an organization to create and maintain a common data base format. The format will need to be updated frequently.
- A standardized list of known failures and failure modes must be developed and made an integral part of recording inspection, testing, and maintenance results and common data base format. This list may vary depending on the system or component under analysis. In addition, the failure definition should clearly capture a condition that would prevent the equipment from successfully operating on demand.
- Appropriate/Applicable reporting capabilities should be built in.
- The data must be secured with access limited for each party to predetermined information that maintains the appropriate autonomy of the client.

6.3.1 Data Exchange Minimum Requirements

Standards such as NFPA 20 and NFPA 25 include data collection recommendations for supporting ITM studies. Within these recommendations, the general information recommended based on this study to support the predictions from ITM models is reviewed in Table 6-1.

Table 6-1: Minimum General Requirements

Item	Requirements	Notes
Facility Information	• Facility Information • Facility Owner • Facility Name • Facility Location (Address)	General tracking information is important to ensure consistency of data. This information may also be helpful in the development of trends should consistent failures be observed.
Equipment Information	• Equipment ID (Serial Number) • Equipment Manufacturer • Equipment Type • Equipment Model	Similar to the facility information, general equipment information is critical to ensuring the consistency of data and may be useful in the development of trends. For Fire Pumps the equipment type is split between *Electric* and *Diesel*
ITM Criteria Information	• ITM Task Description • ITM Task Frequency • Initial ITM Task Date • Clear Success Criteria for ITM Task	It must be clear what signifies a successful completion of an ITM task so that correct Pass/Fail decision may be reached. For some ITM tasks this may simply require working through a checklist of tasks. For others it may require recording values associated with the equipment and measuring them against set criteria or component/system specific ratings. The frequency of the ITM task is required so an estimation of the time the system could have been out of service may be estimated. For the fire pump performance (annual, flow) test the critical information is the 0% (churn), 100%, 150% (or peak %) Rated Flow, the Measured Net Pressure, and the Rated

Table 6-1: Minimum General Requirements

Item	Requirements	Notes
		Speed (RPM).
Failure Characterization	- Failure Mode	When a failure is recorded during an ITM task, if possible associating it with a failure mode will allow for failure predictions to be weighted by specific failure modes and could help in the prioritization of ITM tasks. These failures may also be categorized as *critical* and *noncritical* deficiencies as described in Section 3.2 which allows for only failures that truly result in counting conditions that effect the ability of the fire protection system to function.
Extended Period of Data	- The period of data used should be as long as possible – a longer period of data is better capable of capturing the degradation of the equipment. - For new equipment ITM data of equipment of similar models and operating conditions may be used to supplement the data set - When no or limited data is available, the ITM frequency used should be the frequency prescribed by the appropriate NFPA standard	

6.3.2 Incorporating Codes and Standards with Inspection, Testing, And Maintenance Requirements into the Data Exchange

This section includes a partial list of NFPA standards containing installation and/or inspection, testing, and maintenance requirements. This clearly suggests that ITM requirements have been documented in a relatively large number of standards. The data associated with the requirements in each of these codes and standards is unique. In addition, service providers develop their own recording techniques and formats. Consider as an example the case of NFPA 72. Section 14.2.9 NFPA 72 (2016 Edition) allows for a performance-based program for ITM. The specific technical recommendations on how to determine ITM schedules are not described in the code. However, the code establishes a basic framework that supports the analysis of analysis described in this research. Specifically:

1. Allowance of a performance based program for ITM
2. Requirements on clear documentation of the ITM program
3. Requirements on records management, which includes storage of ITM records for a period of time.
4. Recommendations for prescriptive ITM schedules, which can be used as a starting point for a performance based analysis while reliability data is collected over time.

It is noted however that some of the requirements may not fully support the model described in this research. Consequently, some requirements may need to be updated if a model for predicting ITM schedules for detection and signaling systems is developed. For example, the length of time required for storing ITM data may affect the ability to understand the system's performance over time.

The following is a list of a NFPA codes containing installation and/or inspection, testing, and maintenance requirements. This clearly suggests that ITM requirements have been documented in a relatively large number of standards. As stated earlier, this list may not be all inclusive.

- NFPA 3: Standard for Commissioning of Fire Protection and Life Safety Systems. This standard requires commissioning of fire protection and life safety systems.

- NFPA 4: Standard for Integrated Fire Protection and Life Safety System Testing. This standard requires integrated testing of fire protection and life safety systems.
- NFPA 10: Standard for Portable Fire Extinguishers Handbook
- NFPA 11: Standard for Low-, Medium-, and High-Expansion
- NFPA 12: Standard on Carbon Dioxide Extinguishing Systems
- NFPA 12A: Standard on Halon 1301 Fire Extinguishing Systems
- NFPA 13: Standard for the Installation of Sprinkler Systems
- NFPA 13D: Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes Handbook
- NFPA 13R: Standard for the Installation of Sprinkler Systems in Low-Rise Residential Occupancies
- NFPA 14: Standard for the Installation of Standpipe and Hose Systems
- NFPA 15: Standard for Water Spray Fixed Systems for Fire Protection
- NFPA 16: Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems
- NFPA 17: Standard for Dry Chemical Extinguishing Systems
- NFPA 17A: Standard for Wet Chemical Extinguishing Systems
- NFPA 18: Standard on Wetting Agents
- NFPA 18A: Standard on Water Additives for Fire Control and Vapor Mitigation
- NFPA 20: Standard for the Installation of Stationary Pumps for Fire Protection. This standard requires acceptance testing for fire pumps.
- NFPA 22: Standard for Water Tanks for Private Fire Protection
- NFPA 24: Standard for the Installation of Private Fire Service Mains and Their Appurtenances Handbook Commentary Related Content
- NFPA 25: Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems Handbook Commentary. This standard requires periodic inspection, testing, and maintenance for water based fire protection systems.
- NEC 70: National Electrical Code NFPA 70B: Recommended Practice for Electrical Equipment
- NEC 70E: Standard for Electrical Safety in the Workplace
- NFPA 72: National Fire Alarm and Signaling Code. This standard requires acceptance testing and periodic testing and maintenance of fire alarm systems.
- NFPA 2001: Standard on Clean Agent Fire Extinguishing Systems. This standard requires acceptance testing and periodic inspection testing, maintenance and training of clean agent systems.
- NFPA 2010: Standard for Fixed Aerosol Fire-Extinguishing Systems
- NFPA 2112: Standard on Flame-Resistant Clothing for Protection of Industrial Personnel Against Short-Duration Thermal Exposures from Fire

- NFPA 2113: Standard on Selection, Care, Use, and Maintenance of Flame-Resistant Garments for Protection of Industrial Personnel Against Short-Duration Thermal Exposures from Fire

In addition to the NFPA standards, the International Fire Code and other international codes contain Inspection, Testing and Maintenance Requirements.

6.3.3 Recommendations

The following recommendations are made for the establishment of a standardized framework for ITM data collection:

- Set up and maintain an Inspection Test and Maintenance of Fire Protection Systems Data Exchange. The initial data exchange should be based on the Connectivity Annex in NFPA 25 – 2017 Edition and the database format in the Connectivity Annex of NFPA 20 – 2019 Edition.
- Set up and maintain a Data Exchange Standard to establish, maintain and expand the data base format to include life safety systems and non-water based fire protection systems. The committee members of the Standard should include a representative for each standard who fully understands the inspection, testing and maintenance requirements in the individual codes.
- Work with service providers and report providers (Inspections On-Line and Building Reports, etc.) to integrate inspection testing and maintenance activities with data submission.
- Provide training to service providers utilizing the Data Exchange for standardized use of the inspection, testing, and maintenance recording software.
- Submit changes requiring electronic reporting of inspection, testing and maintenance activities to the Authority Having Jurisdiction and the Inspection, Testing and Maintenance of Fire Protection System Data Exchange.
- Develop guidance on data use for decision making. Data collection will allow trend analysis using information about individual equipment or groups of equipment (i.e., data classified by occupancy, type of equipment, etc.). Once data is collected, careful consideration should be given on the appropriateness of if and how data should be combined for generic ITM decision making.

7.0 SUMMARY AND CONCLUSIONS

The research documented in this report consisted of the development of a framework for applying reliability-based-decision-making using inspection, testing and maintenance (ITM) data to fire protection equipment and systems. Specifically, the research addressed two areas associated with ITM of fire protection systems: 1) The evaluation of analytical models for predicting ITM activities, and 2) the identification of specific data protocols for supporting analytical models. To do so, the research was organized in five tasks, which are summarized below.

Tasks 2 and 3, Literature Review and Summary of Failure Assessment Methodologies: The research identified a number of methodologies that have been documented and sometimes fully implemented in the corresponding industries. These methodologies have specific advantages and limitations. Perhaps the key challenges in implementing these approaches are: 1) the need for reliability data collection and maintenance and 2) the identification of a reliability or availability criteria for supporting the decision-making process.

Task 4, Data Audit and Collection of Available Data: Part of this research involved collecting and managing reliability data to evaluate and test predictive failure models. Consistent with the scope of work, which limited the research to fire pumps, reliability data was collected and analyzed to support modeling activities. As part of this process, recommendations for improving data collection were formulated. It is noted that a performance-based program for supporting ITM activities requires quality data collected and maintained in a consistent basis. This data needs to have the following characteristics. First, failures and failure modes need to be clearly defined so that there is confidence one the data used in the predictive models. Second, equipment performance data needs to be collected and maintained in a clearly defined format so that the data management efforts are minimized.

Task 5, Establish a Predictive Failure Model. A predictive failure model for the specific operational conditions of fire pumps (i.e., a repairable standby system subjected to routine inspection and testing with relatively short repair times) was developed and tested. The model is based on routinely used reliability and availability approaches. The research suggests that such model can be used for establishing performance-based ITM schedules provided that an availability criterion is defined and relevant/applicable data is available as input. It is noted that the model can be modified for use in other systems with different operational configurations. Careful consideration should be made when combining data from multiple sources for generic applications. In addition, future research is recommended to test the predictive model with other fire protection systems and expand the recommended data structures for supporting other systems. An approach for model validation was also described. The approach provides a tool for assessing the predictive capabilities of the model once more data is collected and the model is used for supporting the decision-making process. The validation approach generates an average model bias that can be used for correcting failure predictions.

Task 6, Establish Protocols for On-Going Data Exchange. The predictive model described in this research requires time between failures of a given equipment. Although this requirement may appear simple, data collection and analysis over time requires a rigorous process and a standard format. Specific recommendations were formulated for supporting this effort. This research recommended a well-defined data exchange protocol consistent with the guidance in existing standards governed by a standard to reduce the variability in data collection and management and increase the use of performance-based ITM tools.

Based on the limited results of this study, the following recommendations for future research are provided:

1. Establish a comprehensive system for reliable data collection program in support of model validation. The model described in this report should be further evaluated with additional data comprehensively collected for validation purposes. The recommended validation approach has been also described in this report. This effort will increase confidence in the recommended model by the stakeholders.

2. Expand the use of the model to other fire protection components or systems. Studies similar to the one documented in this report, which includes preliminary testing of the model with limited data should be started so that potential advantages and limitations in predictive failures in other systems or components are identified.

8.0 REFERENCES

1. National Fire Protection Association. *NFPA 25, Standard for the Inspection, Testing, and Maintenance of Water-based Fire Protection Systems*. National Fire Protection Association, 2017.
2. Pennel, G., *Fire Pump Field Data Collection and Analysis*, Aon Fire Protection Engineering, The Fire Protection Research Foundation, 2012
3. Dugan, Kenneth, et al. *Risk Based Reliability Centered Maintenance of DOD Fire Protection Systems*. AFCESA/CES-TR-01-10, RISK TECHNOLOGIES LLC KNOXVILLE TN, 1999.
4. UFC 3-601-02, *Operation and Maintenance: Inspection, Testing, and Maintenance of Fire Protection Systems*, Department of Defense, 2010.
5. *Fire Protection Equipment Surveillance Optimization and Maintenance Guide*, EPRI, Palo Alto, CA: 2003. 1006756.
6. Ross, Steven B., S. P. Nowlen, and T. Tanaka. *Aging assessment for active fire protection systems*, *SAND95-1361,* Sandia National Laboratories*,* 1995.
7. Kristsov, “A Monte Carlo Approach to Modeling and Estimation of the Generalized Renewal Process in Repairable System Reliability Analysis”, UMD PhD Dissertation, 2000)
8. NUREG-1824, Supplement 1, “Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications: Draft Report,” NUREG-1824 / EPRI 3002002182, Salley, M. H., NUREG-1824, Draft Report, RES, NRC, Washington, D. C., November 2014.