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Asset Management Framework for the United States Army Corps of Engineers Lock and Dam Electrical Equipment

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ASSET MANAGEMENT FRAMEWORK FOR THE UNITED STATES ARMY CORPS OF ENGINEERS LOCK AND DAM ELECTRICAL EQUIPMENT

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APPROVAL OF THESIS

We, the faculty supervising the work of Megan Bates affirm that the thesis, *Asset Management Framework for the United States Army Corps of Engineers Lock and Dam Electrical Equipment*, meets the high academic standards for original scholarship and creative work established by the Masters in Engineering Management and the College of Engineering and Computer Sciences. The work also conforms to the formatting guidelines of Marshall University. With our signatures, we approve the manuscript for publication.

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ABSTRACT

The focus of this thesis is to design an efficient and effective preventative maintenance program for the electrical equipment that the United States Army Corps of Engineers (USACE) operates at the locks and dams. This thesis presents the concept of asset management and designs a framework to manage the electrical assets at USACE. The methodology was tested, and the results validated the framework proposed in this thesis. The framework was tested on two separate projects and the results were the same optimized strategies, which shows that the framework is robust and can be implemented into each project and can give an effective preventive maintenance program for the electrical components. The significance of this work is to perform asset management on the electrical equipment on the lock and dams USACE operates and owns, which has not been implemented before. While corrective and preventative maintenance programs have been compared previously for electrical equipment, most analyses have been conducted on production plants. The result of conducting this study is a recommended framework for conducting asset management at USACE locks and dams.

CHAPTER 1-INTRODUCTION

This thesis contains redacted content for security reasons. An explanation of the redactions is provided in Appendix E.

1.1. Background

The United States Army Corps of Engineers (USACE) builds and maintains locks and dams on waterways to support the movement of critical commodities. USACE also provides recreation opportunities at campgrounds, lakes, and marinas, builds and maintains much of America's infrastructure, and, provides military facilities where needed. The Corps also researches and develops technology for the war fighters while protecting America's interests abroad by using engineering expertise to promote stability and improve quality of life. Given the extent of USACE maintained infrastructure, this thesis aims to investigate, develop, and recommend a framework based on infrastructure asset management principles for USACE to use in managing electrical equipment on locks and dams.

The concept of corrective and preventative maintenance is well known and has been researched extensively in projects across the world. The current USACE maintenance program for electrical equipment is a "fix-as-fails" strategy, which means that USACE does no maintenance until the electrical equipment fails completely or cannot operate effectively. The purpose of this thesis is to design an efficient and effective preventative maintenance program for the electrical equipment USACE operates at the locks and dams. Cost and efficiency of current practices were evaluated to the cost and efficiency of the recommended program to evaluate the efficacy of the recommendations. A secondary goal of this thesis is to recommend a concise readily implementable preventative maintenance procedure. While corrective and preventative maintenance programs have been compared previously for electrical equipment, most analyses are conducted on production plants. This paper will specifically focus on government owned locks and dams. The locks and dams provide navigation and flood protection to the public, and there is no production at the locks and dam. This thesis will consider government funding and budgeting as constraints. The comparison will consist of actual costs and data from USACE including inputs from the lock and dam project personnel, who would be performing the preventative maintenance.

1.2. Problem Statement

The USACE maintained locks and dams do not currently have a preventative maintenance program for electrical equipment. The current maintenance strategy is “fix-as-fails”, which means that USACE waits for the equipment to fail and then replaces it. When the equipment fails, it results in high maintenance costs, potentially significant disruption to navigable waterways, and possible safety hazards to surrounding communities. Replacement parts must be ordered, overtime is needed, and multiple employees are needed to make the repairs as quickly as possible. If the failure happens during a high-water event, the damage would be detrimental not only to USACE, but to the community around the project, as well as the economy. The motivation behind this thesis is the hypothesis that the current program uses resources and time in a very inefficient manner and presents a safety hazard to personnel.

The work presented in this thesis outlines an opportunity for improvement. The objective is to design an efficient and effective preventative maintenance program for the electrical equipment USACE operates at the locks and dams. Then, to compare cost and efficiency of the current maintenance program to the preventative maintenance program. The secondary objective is to recommend a concise and readily implemental preventative maintenance procedure. By implementing the research of this thesis, USACE’s assets management for the Arc Flash

Program was improved resulting in greater mission efficiency and project reliability. If the components (assets) are maintained and kept in good operating condition, this lessens the dangers posed by the electrical components and can possibly lower the arc flash hazard of the equipment. There will also be an improved record kept of the components so USACE will have more detailed records.

1.3. Methodology

The overall methodology is shown in **Figure 1**, and each step is detailed in the next sections.

Step 1.
- Define performance measures.

Step 2.
- Define what electrical equipment needs maintained and rank the importance of the electrical equipment.

Step 3.
- Create a database of electrical equipment.

Step 4.
- Collect equipment condition and enter condition in data base.

Step 5.
- Create an electrical preventative maintenance program that can be implemented at USACE.

Step 6.
- Cost comparison and optimization.

Figure 1- Methodology Steps.

1.3.1. Performance Measurement

The first step in the methodology is to define performance measures. Performance measures describe the degree of achievement towards a specific outcome. Performance measures let a company know where they are. Targets are the condition threshold where a component is considered acceptable for use. [redacted]

[redacted]

1.3.2. Electrical Equipment Criticality Analysis

The second step was to do a critical analysis: to define what electrical equipment needs maintained; and, to rank the relative importance of the electrical equipment. Operational Condition Assessment (OCA) documents were collected from multiple projects to get a variety of the different electrical equipment at the projects. Arc flash one-line diagrams were used to get an updated list of the electrical equipment. An arc flash one-line diagram is a single line diagram that shows how each piece of electrical equipment is powered and what that piece of equipment powers at each project. The diagrams are kept up to date and have the current pieces of electrical equipment at the project. Project walkthroughs were performed to ensure that all electrical components are captured, and that their information is recorded. Then the smaller electrical components inside of the equipment were evaluated to determine which components can be maintained. After the electrical equipment was chosen, the order of importance was established. The criteria to prioritize equipment is: what pieces of equipment are pertinent and will fail the lock/dam, the equipment that will cost the most money to repair, and the safety hazard of the equipment. A failure mode effects analysis (FMEA) was used to investigate the reliability of the equipment. USACE's electrical safety program was considered as a source of information as well.

1.3.3. Database

The third step was to create a database of assets (electrical equipment) that is project-specific to be included in the asset management plan. The database came from multiple resources, including OCA reports, Arc Flash one-lines and a visual inspection of the project. The name, type of equipment, current condition, and age of the equipment were stored in the database. In addition, a measure of how accessible the piece of equipment is was developed and stored in the database.

1.4. Equipment Conditions

The fourth step was to collect current or recent equipment condition data. The OCA reports, which rate the equipment from A-F, and Arc Flash reports were used to get current condition of equipment. These ratings were examined and compared to the condition: if the project had up to date meggering data, thermography, vibration, and motor analysis tests then, that data was used. If there was not any equipment condition data, tests were done at the project to get current condition of the equipment. To finalize and get missing information, a visual inspection of the electrical equipment was done at the project. Photos were taken to document current condition.

1.5. Isograph Availability Workbench-RCM Module

The fifth step is to create an electrical preventative maintenance framework and program that can be implemented at USACE. The Recommended Practice for Electrical Equipment Maintenance NFPA 70B, electrical maintenance code was used as a guide for the maintenance needed to be performed on the equipment. Other USACE documents and standards were considered, such as the electrical safety program, arc flash program, and insulation resistance program. The preventative maintenance program will get feedback from electricians who were preforming the tasks. The order of importance of the electrical equipment was determined. The criteria used to determine high priority was: what pieces of equipment are pertinent and will fail the lock/dam, the equipment that will cost the most money to repair, and the safety hazard of the equipment. Then, preventive maintenance procedures were created. The tasks or job required to maintain each piece of equipment was determined along with the frequency with which these tasks should occur. These durations could occur weekly, monthly, quarterly, or annually. Then, preventative maintenance schedules were created. It was expected that high priority equipment was scheduled first, then the tasks that take less time but are needed to be done more frequently were scheduled. The maintenance schedule must be realistic and consider time needed for emergency maintenance and day to day activities. Then, the project personnel must be trained in the preventative maintenance program so they can understand all their task and responsibilities.

The original framework included a MATLAB and Microsoft Excel code to evaluate the strategies and maintenance costs along with the dormant Weibull failure distribution. Upon further investigation, the Isograph Reliability Workbench was discovered. The program was thoroughly researched to ensure the program could be used to validate the framework in this thesis. The program included everything that would have been implemented in the code, and has everything that was needed to validate the framework presented in this thesis.

1.6. Cost Comparison and Optimization

The sixth step is cost comparison and optimization. Cost data on USACE's current "fix-as-fails" maintenance strategy was collected. Labor and parts data were collected from Facilities Equipment Management System (FEMs). Data on incidents such as electrical equipment failings that have happened at USACE was collected. Overtime costs were included in the cost comparison. Data was collected on the current labor and parts, replacements costs of equipment and compared to industry savings and evaluated to see if there is an opportunity for significant savings. Then, the current strategy of USACE's maintenance program was compared to the cost of a preventative maintenance program. The lifecycle cost with and without preventative maintenance was compared. The preventative maintenance costs include labor, time, purchasing of tools to perform maintenance, and possible upgraded parts, along with other items identified throughout the conduct of this thesis. A cost benefit analysis was performed, and recommendations made based on the results of that analysis.

CHAPTER 2-LITERATURE REVIEW

This chapter of the thesis details the existing state of knowledge regarding concepts in asset management, electrical systems components, and, how the application of asset management principles have been used to manage electrical equipment.

2.1. Infrastructure Asset Management

Asset Management is the combination of management, financial, economic, engineering, and other practices applied to physical assets with the goal of providing the essential level of service in the most cost-effective way, as detailed by Amekudzi and Meyer. [1] According to Swasti R. Khuntia1 José Luis Rueda et al., asset management can also be defined as the process of maximizing the return on investment of equipment over the life cycle, by maximizing the component's performance and minimizing capital and operational expenses. [2] Asset management relies on data and then is used in long term planning. Data management includes pre-process data, clean data, and data-mining use. Data interpretation includes asset management statistical models, ageing models, condition models, and health index estimation.

In this thesis, Isograph Availability Workbench RCM Module was used to analyze cost and give recommendations for maintenance based on cost and availability. The asset condition data collection program that USACE uses, Operational Condition Assessment, was used to collect condition and age of components. Different maintenance strategies were compared and optimized.

The asset management actions review includes asset management policy, strategy, plans, optimal planning, and dispatch to assets. The actions typically considered by asset management are maintaining, renewing, disposing, and acquiring. The goal of asset management is to increase the life cycle, improve maintenance, and prepare an effective business plan for investment on new assets. [2]

2.2. Performance Measures

A company has goals and objectives that they want to meet. Goals are the outcomes the company is trying to achieve. Performance measures support the goal and are used to compare different strategies over time relative to the company's objectives. [3] An objective is a detailed and quantifiable statement that supports the accomplishment of a goal. A performance measure is a metric used to track the advancement of meeting the objective. Performance measures link the decisions to the outcomes and serve the following purposes: they are used to translate broad goals into measurable objectives, to track performance over time, as a basis to select a target, to compare strategies to help make decisions, and to see if a specific strategy may accomplish goals. [3] Performance measures should be unambiguous and linked to clearly quantifiable metrics, so they are ready for USACE to implement into its schedule/procedure. Some performance measures that were evaluated in this thesis are resources needed for each strategy, the life extension period of the component, and cost of each strategy.

2.3. Critical Components

A critical component is a piece of equipment that could contribute to the failure of a lock and dam. A panel of electrical and mechanical engineering experts was convened from USACE Navigation Systems Research Program and the Reliability Models for Major Rehabilitation Program to determine the critical components of a lock which was the number of hours of navigation delay it would take to repair or replace the component. Then, the components were screened based on a minimum of 4-hour navigation delay. The electrical systems at USACE consist of four categories: power, motor control, sensors & switches, and electromechanical drives. The Component categories are shown in **Table 1**.

Power
Power Utility
Power Receptacle
Service Transformer
Automatic Transfer Switch
Manual Transfer Switch
Switchgear
Circuit Brekaers
Power Panelboard
Burried/Submerged Cables
Cables-Duct/Cable Tray
Cables-Portable/Flexible
Cables-Twisted
Cables-Coax
Cables-Fiber Optic
Bus Duct (electronic)
Switchboards
Motor Control Centers
Motor Starters-Full Voltage
Motor Starters-Reduced/Variable
Motor Starters Variable Frequency Drive
Programmable Logic Controller (PLC) systems
Sensors and Switches
Selsyn Motor
Traveling Nut Limit Switch
Rotating Can
Encoder Resolver
Hydraulic Cylinder Poisition Sensor
Rotating Limit Switches
Proximity Switch (mag/photo)
Mechanical Promiximty Plunger Switch
Linear Displacement Transducer
Pressure Switch (hydraulic systems)
Water Level Transducer (all types)
Inclinometer
Relay-Based Control Panel
Supervisory Control and Data Acquisition
Electromechinal Drives
Electric Motors (New & Revuilt)
Standby Generator Sets
DC Rectififer (Brakes)

Table 1-Electrical Components

As part of prior research, a panel of electrical and mechanical engineering experts was convened from USACE Navigation Systems Research Program and the Reliability Models for Major Rehabilitation Program to determine the characteristic life of the electrical equipment. [4] The panel assumed the life cycle is the expected life until failure, normal maintenance is done, operations are normal, the environment is good, the dam/lock is not underwater, the equipment has been in service for 50-60 years (has been in use for 50-60 years), power outage of more than 4 hours is assumed, and the equipment is properly designed. These assumptions are not consistent across USACE but were used for their study. The data that was collected can be used in Weibull models to predict the reliability of components. The life characteristic of each component is shown in **Table 2**. [4]

Component	Life (in years)
Service Transformer	25
Automatic Transfer Switch	55
Manual Transfer Switch	30
Switchgear	65
Circuit Breakers	78
Power Panelboard	63
Cables-Burried Submerged	78
Cables-Duct/Cable Tray	60
Cables-Portable/Flexible	80
Bus Duct	28
Switchboards	95
Motor Control Centers	83
Motor Control	83
Motor Starters-Full Voltage	83
Motor Starters-Reduced Variable	63
Motor Starters-VFD	50
PLC Systems	35

Table 2- Characteristic Life for Electrical Components

USACE has a large and diverse civil works infrastructure. The maintenance needs exceed the available resources. The Operational Condition Assessment is used to document the current asset condition and functional reliability. It is also used to predict future conditions. The operational condition refers to a condition state, which is the degree of severity of a deficiency, and the level that deficiency hinders the components performance is noted. The assessment is to use existing data and determine the components operability and readiness. The OCA standard scale is defined in **Table 3**. [5]

Rating		Descriptor
A	9	Excellent
A-	8	
B	7	Good
B-	6	
C	5	Fair
C-	4	
D	3	Poor
D-	2	
F	1	Failing
CF	0	Completely Failed

Table 3 -OCA Rating Scale

The A rating definition is the component has been recently installed and there are not any signs of wear on the component. The B rating definition is the component performs the function it is supposed to do well and if there are any deficiencies it is just signs of expected wear. The C rating definition is that the component is showing early signs of deficiency or early signs of failing. The D rating definition is that a component is increasing the likelihood of failure and is worsening the component's performance or operation. The F rating definition is that the component has severe effects on performance or operation and that there was imminent failure. The CF definition is that a component has completely failed, and/or is not performing its intended task. The minus OCA rating (A-, B-, C-, and D-) are for components that meet the description of the current OCA rating but show beginning signs of the next lower OCA rating.

2.4. Reliability

Reliability is the probability that the equipment will perform its function without failure for a specified period of time. Functional failure is the inability of the equipment to meet its specified performance standards. Tools and techniques that can be used to calculate reliability are a criticality analysis, failure mode effects analysis (FMEA), root cause failure analysis (RCFA), and life cycle costing (LCC).

Given that reliability is based on a probability, the selection of a probability distribution is critical to properly modeling the likelihood of future failures. A Weibull analysis is used to discover current trends, predict future failures and to learn trends to correct or to compensate and improve reliability. [6] Calculations for depreciation, taxes and discount values were used to find the net present value. The reason these are necessary is that time has an impact on money. [7]

One problem with applying the traditional Weibull formula to locks and dams is that it does not consider durations for time when electrical components are not in use. For example, some dam gates are only operated once a month or once a year. USACE has researched how long electrical components have lasted in real world applications at the dams and identified the Dormant Weibull function as a promising alternative to the traditional Weibull function (**Equation 1**).

$$Q_n = 1 - (e\left(\frac{(n-1)(\tau) - \gamma}{\eta}\right)^{\beta})(e - \left(\frac{n(\tau) - \gamma}{\eta}\right)^{\beta})$$

Equation 1-Dormant Weibull

Q_n : Probability of failure over the entire interval *n*
η: Characteristic life parameter
β : Shape Parameter
γ : Location Parameter
τ: Inspection Interval or time since last operated
n: Number of times the component operated in its life

The characteristic life is the point in time when it is expected that 63.2% of the components under study will fail.

The second key element in the formula is the beta shape parameter.

$\beta < 1$: Implies quality problems, usually at the beginning of the component's life.

$\beta = 1$: Random failures or failures independent of time in service.

$\beta > 1$: Wear out failures at a definite or predictable end of life. Typically age related due to service conditions such as corrosion, wear, or fatigue cracking [6].

The third key element in the formula is the location parameter. Location parameter is the difference in years between when the component was originally installed and when it was replaced. For example, if a component was originally installed in 1950 and was replaced in 1995, the location parameter would be 1995 – 1950 = 45 years. If the component is still original, then the location parameter = 0.

The fourth key element in the equation is the inspection interval. Time (years) in between when the component was last inspected or operated properly to present. For example, a component was last operated 1 month ago τ = 1 month/12 months per year = .0833. This formula predicts a component's probability of failure as of this year. [8] The Weibull shape factor for electrical components is a general form for all the same components.

2.5. Electrical Preventative Maintenance

In the manual "Electrical Preventative Maintenance" by Gennon, IEEE reports that the failure rate of electrical components is three times more for systems that do not have preventative maintenance programs. [9] The two main causes of electrical distribution failures are loose connections and exposure to moisture. Both issues can be corrected with an electrical preventative maintenance program. According to Gennon, an electrical preventative maintenance program is cost effective; it is more cost effective to make repairs to equipment before the equipment fails. Failed equipment can damage what is downstream of it, and often the equipment needs to be replaced. Emergency repairs are also very costly due to overtime and temporary work that needs to be done prior to repairs. Failed equipment can also cause unplanned outages which can be costly. The electrical preventative maintenance program can improve equipment efficiency and reduce electric bills. A loose or dirty connection can cause high power losses. By implementing a program to clean and tighten connections, these energy costs can be decreased. [9]

2.6. Preventative Maintenance at USACE's Hydropower Operations

The project specific maintenance plans are based on specific manufacturer's recommendations. The plan is updated and reviewed every 5 years. According to EC 1130-2-218, preventative maintenance is defined as the systematic care, servicing, and inspection of assets, facilities, equipment, and components for the purpose of detecting and correcting incipient failures and accomplishing minor maintenance. The frequency of preventive maintenance is generally less than one year. The maintenance management system includes equipment inventories, repair histories, inspection reports, inspection frequencies, and standards for equipment maintenance. The program standardizes maintenance tasks for the major hydropower equipment. However, specific manufacture's maintenance manuals and recommendations must be considered when designing a maintenance program and determining how often the maintenance tasks should be performed. [10]

2.7. Equipment Failure Mechanisms

The equipment that is considered [redacted] is listed in this section and described in more detail (including failure mechanisms and inspection techniques) in the next sections of this chapter.

- Cables
- Automatic Transfer Switch (ATS)
- Manual Transfer switch (MTS)
- Circuit Breakers (CB)
- Motor Starters
- Traveling Nut Limit Switch
- Generators
- Motor Control Center (MCC)
- Switchgears
- Power Panelboards
- Electric Motors
- Brakes

The interlock system at USACE locks and dams were not considered in this thesis.

2.7.1. Cables

Cables can consist of many different types of components. Some are necessary for operation, such as the conductor that carries the electrical current and the insulation which protects against short circuit events and the environment. Depending on the type of cable and its purpose, a conductor shield, insulation shield, cable shield, and jackets can be installed to help provide more protection. Cables consist of a conductor, conductor shield, insulation, insulation shield, metallic shielded, and sometimes a jacket. Cables can be in trays, buried in ducts or conduit, under water, or suspended from bridges. [11]

Power cables are subject to electrical, mechanical, thermal, and environmental stress. These factors lead to insulation deterioration. The insulation deterioration and constant stress put on the cables lead to cable break down. Bends in cable that are too tight can decrease the cross-sectional area of insulation in certain places, which can lead to insulation breakdown. Also, over time the mechanical stress can crack the insulation as it ages leading to failure. Cable failure rate can be related to a bathtub curve. There are three separate phases the cables go through during their lifecycle. The burn-in phase which results from defects during manufacturing or poor installation. The second phase is the useful life stage which is when the cable is in the best condition. Failures during this stage happen for many different reasons like environmental stress. The third stage is the wear out stage. The bulk dielectric strength degrades, the rate of this failure relies on voltage, thermal stresses, maintenance, system age, cable system technology, and environment. According to Finding the Root Cause of Power Cable Failures, external damage had been the largest failure factor of cables from 2009 to 2011 in China [12]. This relates to USACE greatly because cables are located outside in harsh weather elements.

The failure of cables is usually preceded by a deterioration phase. This phase can last multiple years. Insulation resistance can directly reflect onto cable condition. [12]

The cables at USACE are direct buried cables, aerial, in cable trays, in conduit, in the [redacted] The cables that are in the lock walls, especially the [redacted], are subject to deterioration faster because they flood during high water events. Sometimes the [redacted] flood and get wet. The [redacted] can get wet from water runoff. The cables in the lock wall trenches are also subject to deterioration faster because they are also laying in water, have vegetation covering them, and are in direct sunlight.

To extend the life of cables, thorough inspection and maintenance must be done, and then repairs should be made as needed before the entire cable fails. The cut/crushed cable should be removed, and spare cable should be kept on hand to replace damaged cable. The cause of every cable failure and date of failure should be recorded to help better form preventative maintenance plans to catch the failures before they occur. [13] A scheduled program of testing insulation resistance is recommended to prevent shocks, ensure safety and reduce downtime. The test helps detect deterioration of insulation. The cable insulation can be damaged from pulling cable through raceways, years of use, and the environment. When new cable is installed, insulation resistance tests must be performed to ensure there is no initial damage to the cable. Next, the cable should be tested annually to collect data and a comparison should then be performed to see if the measurements are trending downward. [14] Insulation Resistance tests aren't considered maintenance, at least not in a way that will extend its life; rather, they are a tool to monitor condition. There is no maintenance that can be done on cables; therefore, reliability is the focus when working with cables. While the cable's life is not extended by insulation resistance testing, personnel can get an idea of when to replace it before failure occurs, which, if it's a critical feeder, could be crucial in avoiding financial and other consequences.

2.7.2. Automatic Transfer Switch (ATS)

An automatic transfer switch (ATS) is a device that automatically switches the main source of power to a secondary source of power when there is an outage. The failure of an automatic transfer switch is when the switching device does not switch from one source to another. ATS's usually have a voltage sensor circuit to detect the loss of power. When the voltage sensor detects the loss of power, the transfer is initiated and the ATS switches the load to the other source of voltage. If the ATS switching device fails open, then there is no transfer because the voltage sensor does not detect any loss of voltage. [15] A common ATS failure mode is transient voltage, which is a short duration of voltage increase. This can cause equipment to fail or malfunction. A typical building experiences 10 voltage transients per month according to NEMA. An ATS consists of integrated circuits and other components with very low tolerances for transient voltage. Exposure to the transient voltage is a component failure which damages the controls on the ATS which makes the display panel fail and the ATS to become inoperable. [16]

At USACE, the ATS transfers commercial to generator power. When the utility power goes out, the automatic transfer switch sends a control to the generator that starts the generator and gives the project power.

To extend the life of the automatic transfer switch, routine maintenance should be conducted. The ATS should regularly be operated under load. The device should have periodic inspections that check for abnormal wear, corrosion, discoloration, and loose hardware. It's also important to ensure the power contactor is free of any dust, dirt, grease, and moisture. [17] Transfer Switches should be replaced before they completely fail. The transfer switch should be monitored closely during generator testing. [18]

2.7.3. Manual Transfer Switch (MTS)

A manual transfer switch (MTS) is a switch between power sources by using the manual controls located on the face of the switching device or by using an external operator (a lever, switch). An MTS has failed when the transfer does not happen or when the MTS trips. Tripping is when the contacts are open in the neutral position.

To extend the life of the manual transfer switch, the device should be periodically inspected for dust, dirt, soot, grease moisture, or corrosion. The material/metal inside of the manual transfer switch should be checked for uneven wear, discoloration, or loose hardware. All terminals and connectors should be checked for looseness or signs of overheating. If the switch is not operated often, then the switch should be switched to the secondary source and returned to the primary source. [19]

At USACE, the manual transfer switch transfers commercial to generator power. When the utility power goes out, the project personnel must go to the manual transfer switch and turn the MTS to the on position. The manual transfer switch then starts the generator and gives the project power. The project must have power to operate the equipment, especially the gates; if there is high water or a time the gates need to be operated, it is critical they are receiving power.

2.7.4. Circuit Breakers

Circuit breakers are very important to an electrical system and are connected to almost every system currently in place. Circuit breakers are used to protect equipment and personnel from overcurrent, arc flash, and electrical shock hazards. The data in “Relationship Between Historical Trends, Equipment Age, Maintenance, and Circuit Breaker Failure Rates” shows failure rates predisposed by historical manufacturing trends, equipment age, and amount of annual maintenance performed. [20] Failure rates for circuit breakers are less stable than expected. An average of the failure rates gives an estimate of the equipment performance. The performance changes over time. The data in “Relationship Between Historical Trends, Equipment Age, Maintenance, and Circuit Breaker Failure Rates” is from USACE Power Reliability Enhancement Program’s database of equipment failure rates. The data has been collected for more than three decades. The database contains information about many different types of circuit breakers. The studies have shown that it is common to have failures in the first 10 years and after 25 years of use, but not between years 10 and 25. [20] Circuit breaker failure rates change in three categories: as a function of time or use, equipment age, and maintenance. The maintenance program takes an hour and a half of maintenance on each breaker a year. In critical infrastructure where outages are expensive, maintenance hours should be increased to reduce the failures. In a non-critical or redundant infrastructure, the maintenance hours could be less. The data in "Effect of Historical Trends, Equipment Age, and Maintenance on Circuit Breaker Failure Rates" suggests that preforming a small amount of maintenance is more damaging than beneficial. Yet, as the amount of maintenance increases, the failure rates decrease. [21] There are two main failure modes for circuit breakers: fail to close and fail to open. Fail to close is when the circuit breaker did not close during demand. Fail to open is when the breaker did not open on demand. The causes of these failures are design, human error, internal to the component (inside the circuit breaker), external environmental cause, and unknown causes. The internal to the component cause is often the most common cause of failure. This failure relates to the hardware of the component and normal wear of the component, corrosion, and lack of lubrication. The most common cause of this type of failure involved wear, dirt, and lack of lubrication inside the circuit breaker. [22]

Circuit breakers are used at USACE for overcurrent protection and protect other electrical equipment and project personnel. The failures would be related to equipment age, environment and lack of maintenance. There is no current maintenance performed on circuit breakers and some of the breakers are 80 years old. The breakers are corroded and full of dirt, bug nests and other miscellaneous things, an example of which is shown in **Figure 2.**

Figure 2-Breaker full of insect nests

Molded case circuit breakers require little maintenance. The circuit breaker should be inspected and maintained whenever it has interrupted current near its rated capacity. The circuit should at least be operated once per year. Insulating parts should be cleaned, arc chutes should be visually inspected, operating mechanism should be lubricated with light machine oil, wiring connections should be inspected for tightness, and if there are contacts that are worn or burned, they should be replaced. [23] To maintain molded case circuit breakers, personnel should perform the following: visual inspection, cleaning, operability checks and testing, component adjustments, verification of the tightness of connections, adjustment of the operating handle/linkage, and lubrication of the operating handle mechanism. Most of the aging mechanisms related to molded case circuit breakers can be monitored by wear of the external breaker operating handle, bimetallic annealing, high resistance connections, and fatigue cracking of external components. Most molded case circuit breakers are sealed, therefore access to most internal components is limited. The maintenance for molded case circuit breakers is periodic cycling, cleaning, visual inspections, and lubrication of internal components. [24]

2.7.5. Motor Starters

The motor starter is composed of contactors and relays that handle the high currents associated with starting and running the motor. Motor starters use power semiconductors, springs, coils, and contacts to control the power to the motor. [25] Overcurrent failure due to engine stall, over current failure due to slow movement of engine, and extended cranking of a motor are all failure modes of all types of motor starters. The most common failure mode is thermal acceleration which accelerates the thermal failure mechanism. [26] The failure mode that would relate most to USACE is the relays and contactors burning out.

2.7.6. Traveling Nut Limit Switches

[redacted] Their purpose is to stop the motor when the gate reaches predefined gate openings to prevent damage to machinery and the dam structure. At the raised position, the Upper Travel Limit Switch should open. Should the limit switch fail and not open or the circuit fails, the Upper Overtravel Limit Switch is a backup limit switch that should open at the over-travel raised position. At the closed position, Lower Travel Limit Switch should open. Should the limit switch fail and not open, or the circuit fails, Lower Overtravel Limit Switch is a backup limit switch that should open at the over-travel raised position. A failure of the limit switch would be over traveling the gate off its guide rails, resulting in the gate to fall multiple feet and be destroyed. Another failure would be that the gate would be lowered too far and structurally damage the bottom of the gate.

A failure of the limit switch can be caused by strong vibration or impact, which would cause the contacts to open on their own, or, wearing of parts. Harsh environments like temperature and humidity can cause failure. Water, oil, dust, and chips can cause failure by getting into the limit switch. Gases can cause failure by the springs breaking in a limit switch or their characteristics may deteriorate.

To prevent failures of a limit switch, the switch and enclosure should be designed for the environment it was in. Seal the limit switch and use a protective cover to make sure no foreign material gets inside. If the temperature or humidity was harsh, purchase limit switches that are rated for that condition. Use gold or alloy contacts in corrosive gas atmospheres to prevent the springs breaking. [27]

The main failure mechanisms at USACE would be environmental. Limit switches for the dams are usually in the pier houses or out in the environment on the motor machinery.

2.7.7. Generators

According to "Research Information Letter No. 161, Results of a Diesel Generator Aging Study" there are multiple stressors that cause generators to fail. [28] Generic stressors that cause generators to fail are listed in order of importance. The generic stressors are: vibration, thermal shock and stress, and extreme dynamic loading (27%); manufacturing and defects (18%); quality control and installation errors or processing environmental conditions of dust, humidity, fuel or lube oil contamination, and other normal engine room conditions (17%); maintenance errors or omissions, which resulted in accelerated aging and eventual failure (9%); adjustment, misalignment or calibration errors (6%); and, design and component selection or application errors (5%). The other 18% was related to miscellaneous failures. A recommendation from "Research Information Letter No. 161, Results of a Diesel Generator Aging Study" is that preventative maintenance should be increased to limit the aging and wear results of the vibration stressor. Although vibration cannot be eliminated, it can be addressed through calibration and preventative maintenance. Maintenance needs to be focused on the systems with the higher failure rates for optimal results. [28]

There are three main failure modes for generators: failure to run, failure to start, and failure to stop. The causes of these failure modes are environmental stress, state of other components, design, human error, internal component, maintenance, procedure inadequacy and unknown. The coupling factor field describes the mechanism that shows the problems together and finds the sources that cause multiple components to be affected. The dominant coupling factor is hardware, then operation, then environment. [29]

[redacted] generators are used for emergency power. [redacted] In a high-water event, the chances of loss of commercial power increase dramatically. At some projects, the only way to operate gates are with power (no manual crank). The failure cause that would relate to USACE is deficient procedures for maintenance and testing. Another failure cause that would relate to USACE is environmental stress and states of other components. Most other components in USACE systems [redacted]

To increase the life of the generator, routine maintenance needs to be done every 400 hours. Load bank testing needs done periodically to burn off the deposits left by light loads. [30] The typical maintenance cycle includes a general inspection and service of the following critical systems: fuel system, coolant system, lubrication system, air system, starting system (batteries and charger), and alternator. Maintenance should be done weekly, monthly, biannually, and annually to increase the life of the generator. [31] Fuel, lubrication system, cooling system, exhaust system, battery system, electrical system, and prime mover should be inspected weekly. During monthly testing, the generator should be run for at least 30 minutes at not less than 30%

of the generator's nameplate rating load. The generator testing and inspecting should follow the manufacturer's directions on how to maintain and test the specific generator. [32]

2.7.8. Motor Control Center (MCC)

A motor control center (MCC) is a multi-compartmented enclosure that provides power distribution and control to equipment. Every motor control center is specific to each project. The control center contains switch gear to select between commercial and emergency power and instruments to indicate pertinent facts relative to the electric supply. In addition, the center contains circuit breaker type disconnects for all main branch circuits, a distribution lighting panel and additional control and instrumentation. Data from General Electric, Westinghouse, Gould/ITE, Cutler-Hammer, and Klockner-Moeller was collected in Aging Management Guideline for commercial and nuclear powerplants: Motor Control Center. The "Aging Management Guideline for commercial and nuclear powerplants: Motor Control Center. Final Report" shows that the main failures in MCCs are breakers, contactors, thermal overload relays, miscellaneous relays, wiring, controls transformers and terminal blocks. The largest failure for breakers was attributed to the breaker operating handles/linkages which is from normal age/wearing. The largest failure of starters/contactors were associated with auxiliary contact assemblies which is from binding or sticking. The largest failure for thermal overload relays were attributed to the overload heater elements which is from normal age/wearing. The largest failure for miscellaneous load relays were attributed to the relay coil which is from loss of calibration of the relay. The largest failure mode for wiring is failure of the wiring termination or connector. The largest failure mode for the motor control center was loosening and broken or deformed subcomponents. Since the number of failures of control transformers, fuse holders, switches and terminal blocks were so low, no inferences can be concluded. A license event reports the main failure in terminal blocks and wires were caused by loose connections or terminal block mountings. The main failure mode for miscellaneous relays were high resistance leading to coil failure and dirt contacts leading to cycling. The fuse holder failed because of metal fatigue. The most frequent cause of MCC component failures was from dirt causing the electrical components to become stuck. A significant number of failures also came from normal wear and operation.

To maintain the MCC for operation, visual inspection, cleaning, adjustments, lubrication, measurement of component properties, operability checks and testing, and component replacement must be performed. To maintain the structural components of the MCC, visual inspection, cleaning and vacuuming, lubrication, component/subcomponent replacement, and verification of the tightness of components must be performed. To maintain electrical connection bolt integrity at terminals and disconnects, the connections should be checked for tightness, a visual inspection should be performed for signs of overheating, damage and deterioration testing should be done, and infrared thermography should be done. The power stabs should be checked for a light coating of non-oxidizing grease and the mechanical and electrical integrity of the connections. If there is contamination on the stabs, it should be removed. Contact surfaces should be inspected for signs of corrosion and oxidation. To maintain magnetic starters/contractors, personnel must perform visual inspection, cleaning, and operability checks. To maintain thermal overload devices, visual inspections, component adjustments, operability checks and testing, and cleaning should be completed. To maintain relays visual inspection personnel must perform, operability checks and testing, resistance and continuity measurements, calibration, and cleaning. To maintain the control transformers, personnel must perform visual inspection, insulation resistance testing, resistance, and continuity testing, tightening connections, and cleaning. To maintain terminal blocks, visual inspection, tightening of connections, and cleaning should be completed. [33]

[redacted] Some MCCs are [redacted] and currently have no maintenance done to them. The most common failures experienced at USACE would be due to lose connections, no grease on components, and dirt on components.

2.7.9. Switchgears

A switchgear is the combination of fuses, circuit breakers, switches, or relays used to isolate and protect control equipment. Switchgear components also include a bus bar compartment, switchgear compartment, cable compartment and other support, such as a power transformer or control transformer. The bus bar compartment can have damaged isolation bushing due to dirty bushing, worn out mechanical components of the breaker, or the seal could be damaged. The switch and breaker compartment usually fail because the contact breaker is unsterile or there is leakage from the breaker. The switch and breaker compartment bolt, nut and ring breaker usually become loose because the breaker moves a lot during operation. Arcing contact can be caused by a short circuit. This usually occurs because of damage from isolation, unbalanced phases, loss of contact, and unsterile breaker contact. The arcing contact can happen to all compartments. [34]

To extend the life of switchgear, maintenance needs to be done. To prevent bus bar compartment damage, a partial discharge check, visual check, cleaning the isolation bushing, voltage function test, and isolation replacement bushing should be done. To prevent switch and breaker compartment failure, personnel should conduct infrared thermography, function test, breaker condition visual check, and grease the contact breaker with contact grease. To prevent switch and breaker compartment bolt, nut, and ring breaker from becoming loose, partial discharge, infrared thermography, visual check, and function test should be done. To prevent arcing contact on all the compartments, partial discharge, infrared thermography, visual check, clean the switch gear regularly, contact endurance and resistance, and a function test should be done. [34]

The main failure at USACE would most likely be bus bar compartment having dirty bushing, worn out mechanical components of the breaker, or the seal could have damage, the switch and breaker compartment contact breaker is unsterile or there is leakage from the breaker, the switch and breaker compartment bolt, nut and ring breaker usually become loose because the breaker moves a lot during operation. Most of the equipment is original; therefore, the enclosures are corroded and there are holes in the metal, which allows the environmental elements into them.

2.7.10. Power Panelboards

A power panelboard is a panel that supplies power to components. A panelboard is made up of wires, circuit breakers, and terminal blocks. Power spikes and surges can damage panels leading to lost controller programs and damaged electronics. A tripped breaker or blown fuse is another failure of panelboards. The third cause of failure is cut or grounded wires in the system. This causes tripped breakers, blown fuses, or shortened power supply. Another type of failure for panelboards is tripped overloads on power units. Loose or disconnected wires, caused from vibration over time, is another cause of failure. The last cause of failure in panelboards is carbon buildup on relay or contactor contacts, which blocks the conductance. [35] The parts inside the panelboard will have a shorter life expectancy than the panelboard structure itself. A circuit breaker installed in a panelboard can be replaced as needed while the panelboard can continue to operate. [36]

The most common failure at USACE would be tripped breakers, loose connections or wires, and carbon or foreign material build up. There is no maintenance done on the panels currently because once a panel is installed it is usually not opened again for inspection. This can lead to lose connections and carbon build up without anyone being aware of the problem. Some panels in harsh environments experience corroded enclosures or doors left open, animals' nest in the panels, or dirt build up.

To extend the life of a panelboard or to prevent failures, maintenance should be performed. The cover should be on and closed. The breakers should be inspected and so should the connections. A thermal check should be performed to ensure correct temperatures. [37]

2.7.11. Electric Motors

An electric motor is a piece of machinery that converts electric power into mechanical energy. The mechanical energy then raises gates, moves gates, and powers hydraulic units. At USACE, there are many applications for an electric motor. The two most common causes of motor failure are winding insulation breakdown and bearing wear. The most common causes of these failures are transient voltage, voltage imbalance, harmonic distortion, reflections on drive output PWM signals, sigma current, operational overloads, misalignment, shaft imbalance, shaft looseness, bearing wear, and improper installation. [38] Components of motors also deteriorate with time and from the stress of operating. The insulation weakens overtime due to voltage unbalance, temperature, and voltage disturbances. The moving surfaces have contact and over time this creates wear. Wear is aggravated by dirt, moisture, and corrosive fumes. [39] [40]

To increase the life cycle of motors, bearings and motor couplings should be given special attention. Personnel must follow manufacturer's guides regarding how to lubricate bearings. Couplings need to be aligned. Motors should not be exposed to operating conditions in excess limitations defined by National Electrical Manufacturer's Association, NEMA. NEMA sets limits for temperature, voltage variation, voltage unbalance and frequency of starts. [41]

At USACE, the failure modes that would be most common would be the environment, [redacted] The motors for the locks [redacted] which is also exposed to the environment.

2.7.12. Brakes

Brakes are used to stop the Tainter gates and roller gates on dams. If a coil fails in a brake it is usually due to heat which causes the insulation of the coil wire to deteriorate. The heat is caused by high ambient temperature, high cycle rates, slipping, or applying to high of a voltage. The same long life is expected for bearings if they are not used past their ratings. Most of the wear on brakes is on the faces of the mating surfaces. Brakes should be enclosed so as they wear, they do not cause contamination in the room they are housed in. Oil and grease should be kept away from the contact surface because this would reduce the coefficient of friction which would decrease the torque resulting in possible failure. Sometimes dust or other containments can get between the contact surfaces causing loss of torque. If the brakes haven't been operated in a while, rust can develop on the surface, but the rust usually rubs off after a few cycles, so this is not a large concern for failure. [42]

2.8. Electrical Preventative Maintenance Standards

Before any of the next maintenance strategies are done, strategies are done, personnel should follow USACE's electrical safety procedure, the National Fire Protection Association (NFPA) 70E Standard for Electrical Safety in the Workplace, and the NFPA 70 National Electrical Code. The NFPA 70E and NFPA 70 can be found at the NFPA's website. The USACE Electrical Safety Program can be found online at USACE's website. The next section of the literature review will discuss the multiple strategies considered for preventative maintenance of each piece of equipment. Strategy 1 (base case) was considered the do-nothing strategy. The remaining strategies will come from industry standards, codes, and existing electrical preventative maintenance programs.

An electrical preventive maintenance program should be performed in accordance with recognized industry standards and safety procedures. This includes, but is not limited to: the newest issues of the following National Fire Protection Association (NFPA) 70B Recommended Practice for Electrical Equipment Maintenance; National Fire Protection Association (NFPA) 70 National Electrical Code; National Electrical Manufacturer's Association (NEMA) Standard AB4 Procedures for Verifying Field Inspections and Performance Verification of Molded-Case Circuit Breakers; International Electrical Testing Association (NETA); Maintenance Testing Specifications for Electrical Power Distribution Equipment and Systems; IEEE Std P1415 Motor Maintenance and Failure Analysis (draft) National Electrical Manufacturer's Association (NEMA) Standard MG1; International Electrical Testing Association (NETA) Maintenance Testing Specifications for Electrical Power Distribution Equipment and Systems; OSHA Applicable Standards; IEEE STD 1415 IEEE Guide to Introduction Machinery Maintenance Testing and Failure Analysis − National Fire Protection Association (NFPA) 70B Recommended

Practice for Electrical Equipment Maintenance; International Electrical Testing Association (NETA) Maintenance Testing Specifications for Electrical Power Distribution Equipment and Systems; and, EEE STD 43 IEEE Recommended Practice for Testing Insulations Resistance of Rotating Machinery. [43]

2.8.1. Maintenance Strategies of Cables

Strategy 1: This is the do-nothing strategy, which shows how the cable condition deteriorates over time if no maintenance is administered. This strategy is used to compare to other strategies.

Strategy 2: This is the maintenance recommendation from the NFPA 70B 2016 Edition. The cable insulation should be visually inspected for damage. The cables should also be insulation resistance tested or dc over-potential tested annually. Records should be kept so they can be compared year to year. [44] According to USACE LRH Insulation and Resistance Testing Program, feeders should be evaluated in a pass/fail test. The minimum insulation resistance (in Megohms) for cables was determined from the following IEEE formula:

$$[(Rated\ voltage\ of\ cable\ in\ kV) + 1] * \frac{1000}{length\ of\ cable\ (ft)}$$

Equation 2-minimum insulation resistance (in Megohms)

If a cable reading (in Megohms) falls below the minimum resistance calculated for the specific cable, then it is suggested that the cable has failed the insulation resistance test and be replaced. [45]

Strategy 3: This is a maintenance recommendation from an existing industry electrical preventative maintenance program. For cables in manholes, sharp bends, physical damage, oil leaks, cracked jackets, and, poor ground connections weaken the cable supports should all be checked. At entrance and end points the cable should be inspected for wear. The manhole should also be checked for moisture and spalled concrete. For aerial cables, the supports should be checked for excess wear and mechanical damage from vibration. At dead ends, the cable should be checked for worn insulation, sharp bends, or cracks. For cables in raceways, check the raceway for proper mechanical support. Check the cables for insulation or cracks at support points and inspect the raceway joints for clean and tight connections. Additional tests to perform on cables include insulation resistance test, dielectric absorption test, and a power factor test. Records should be kept identifying trends over time. [43] According to USACE LRH Insulation and Resistance Testing Program, feeders should be evaluated in a pass/fail test. The minimum insulation resistance (in Megohms) for cables was determined from the following IEEE formula:

$$[(Rated\ voltage\ of\ cable\ in\ kV) + 1] * \frac{1000}{length\ of\ cable\ (ft)}$$

Equation 3-minimum insulation resistance (in Megohms)

If a cable reading (in Megohms) falls below the minimum resistance calculated for the specific cable, then it is suggested that the cable has failed the insulation resistance test and be replaced. [45]

2.8.2. Maintenance Strategies of Automatic Transfer Switch

Strategy 1: This is the do-nothing strategy, which will exhibit the ATS condition with no maintenance, and is used to compare to other strategies.

Strategy 2: This is a maintenance recommendation from NEMA Standard KS 3. The switch needs to be examined for dust, dirt, soot, or moisture. If there are signs of these then the switch should be cleaned by using a lint free dry cloth, brush, or vacuum cleaner. Do not blow into the switch. The containments should be eliminated. A proper enclosure should be used that is appropriate for the environment the switch is in. The switch and terminators need to be examined for signs of overheating. If there are signs of overheating, then the terminal and connecting straps can be cleaned. A mechanical operating test should be done to ensure the switch mechanism is operating freely. The switch should be operated ON and OFF two or three times. The handle should operate smoothly without binding. If there is a mechanical trip provision, the trip provision should be operated within manufacturer's instructions. An insulation resistance test can be done to determine the adequacy of the insulation. The switch must be repaired or replaced if the contacts are not open with the switch in the OFF position, the contacts are not closed with the switch in the ON position, the switch does not reset, or the mechanical trip provisions (if provided) do not trip the switch. [46]

Strategy 3: This is a maintenance recommendation from NFPA. According to the NFPA 110, 8.3.4 the connections on an ATS need to be tightened and checked, the unit should be inspected for burn marks and erosion, dust and dirt need to be removed, and contacts should be replaced when required.

Strategy 4: This is a maintenance recommendation from an existing transfer switch maintenance procedure. The physical and mechanical condition of the transfer switch should be inspected. Make sure that all switch covers, and barriers are installed and properly fastened. The switch should be clean and free of obstacles. The switch needs to be examined for dust, dirt, soot, or moisture. If there are signs of these, then the switch should be cleaned by using a lint free dry cloth, brush, or vacuum cleaner. Do not blow into the switch. The lubrication on moving current carrying parts and sliding surfaces should be verified. If needed, apply the appropriate lubrication. Insulation resistance tests should be done on all control wires and compared to previously obtained results. The control devices should be inspected for correct settings and operation. For automatic transfer tests, loss of power should be simulated, then return the switch to normal power. Next, simulate loss of emergency power. The engine start sequence, timing delay, normal source voltage sensing and frequency sensing relays, automatic transfer operation, interlocks and limit switch, engine cool down, and alternate source voltage sensing and frequency sensing relays should be verified for the correct operation. [47]

2.8.3. Maintenance Strategies of Manual Transfer Switch (MTS)

Strategy 1: This is the do-nothing strategy. It will show the MTS condition when no maintenance is administered. This strategy is used to compare to other strategies.

Strategy 2: This is a maintenance recommendation from NEMA Standard KS 3. The switch needs to be examined for dust, dirt, soot, or moisture. If there are signs of these then the switch should be cleaned by using a lint free dry cloth, brush, or vacuum cleaner. Do not blow into the switch. The contaminants should be eliminated. A proper enclosure should be used that is appropriate for the environment the switch is in. The switch and terminators need to be examined for signs of overheating. If there are signs of overheating, then the terminal and connecting straps can be cleaned. A mechanical operating test should be done to ensure the switch mechanism is operating freely. The switch should be operated ON and OFF two or three times. The handle should operate smoothly without binding. If there is a mechanical trip provision, it should be operated within manufacturer's instructions. An insulation resistance test can be done to determine the adequacy of the insulation. The switch must be repaired or replaced if the contacts are not open with the switch in the OFF position, the contacts are not closed with the switch in the ON position, the switch does not reset, or the mechanical trip provisions (if provided) do not trip the switch. [46]

Strategy 3: This is a maintenance recommendation from an existing transfer switch maintenance procedure. The physical and mechanical condition of the transfer switch should be inspected. Make sure that all switch covers, and barriers are installed and properly fastened. The switch should be clean and free of obstacles. The switch needs to be examined for dust, dirt, soot, or moisture. If there are signs of these then the switch should be cleaned by using a lint free dry cloth, brush, or vacuum cleaner. Do not blow into the switch. The lubrication on moving current carrying parts and sliding surfaces should be verified. If needed, apply the appropriate lubrication. The manual operation of the switch should be checked before it operates electrically. Both power sources need to be de-energized. Insert the manual handle and operate the switch between source one and source two. The switch should move smoothly. Verify the mechanical interlocking in-between source one and source two. Insulation resistance tests should be conducted on all control wires and compared to previously obtained results. The control devices should be inspected for correct settings and operation. [47]

2.8.4. Maintenance Strategies of Molded Case Circuit Breakers (MCCB)

Strategy 1: This is the do-nothing strategy, which displays the molded case circuit breaker condition with no maintenance, and is used to compare to other strategies.

Strategy 2: This is the maintenance recommendation from the NFPA 70B 2016 Edition. The MCCB should be visually inspected for damage. The MCCB should be kept clean of external contamination. The case of the breaker should be inspected for cracks. The connections should be checked periodically for tightness and signs of overheating. The circuit breaker should be operated manually to keep the contacts clean and lubrication performing properly. If there is a trip to test button, then that should also be manually operated. [44]

Strategy 3: This is a maintenance recommendation from NEMA Standard AB4. The circuit breaker enclosure will need to be opened to inspect and perform maintenance. Inspect the circuit breaker for dust, dirt, soot, grease, or moisture. If any of these are seen on the breaker then the breaker needs to be cleaned by using a lint free, dry cloth, brush, or vacuum cleaner. Do not blow into the circuit breaker to clean it. Inspect the circuit breaker for signs of overheating or corrosion. If there are signs of this, then maintenance must be performed. The mechanical components must be inspected to make sure the circuit breaker mechanism is operating freely. The handle should operate smoothly without sticking. Large duty circuit breakers (225A or larger) should be electrically trip tested. NEMA also recommends doing an insulation resistance test and individual pole resistance test on the breakers. NEMA states the breaker should be replaced if the contacts are not open with the breaker in the tripped or OFF position, the contacts are not closed with the breaker in the ON position, the breaker does not reset, or the mechanical trip provisions (if provided) do not trip the breaker. The two tests for a circuit breaker are an insulation resistance test and an individual pole resistance test (millivolt drop) [48]

2.8.5. Maintenance Strategies of Motor Starters

Strategy 1: This is the do-nothing strategy, which displays the motor starter condition with no maintenance, and is used to compare to other strategies.

Strategy 2: This is a maintenance recommendation from an existing industry electrical preventative maintenance program. The contactors in the starter panel should be inspected and cleaned. The panel should be cleaned by a smooth cloth or a very fine emery paper. The entire panel should be cleaned with a wet cloth and brushed should be used when hand cannot reach. A vacuum should be used to remove dust. The connections should be checked. If there are any loose connections, tighten by using a screwdriver. If the wires are loose, reconnect them. The terminal box on the motor should be inspected for loose connections. If there are loose connections, use the correct size spanner to tighten the connections. The overall condition of the starter panel should be visually inspected. [49]

2.8.6. Maintenance Strategies of Limit Switches

Strategy 1: This is the do-nothing strategy, which displays the limit switch condition with no maintenance, and is used to compare to other strategies.

Strategy 2: This is a maintenance recommendation from an existing industry electrical preventative maintenance program. The roller lever should be checked for loose lever mounting screws, improper roller rotation, other problems, or damage. The head should be checked to make sure the head mounting screws are tightly fastened and the exterior of the head is not damaged. The cover should be checked to make sure the head mounting screws are tightly fastened and the exterior of the head is not damaged. The housing should be checked for exterior damage. To address this issue, replace the limit switch. The terminal box should be checked for electrical continuity, proper insulation, loose terminal screws, cracking and any corrosion. To address these items, replace the limit switch. The operation of the limit switch should be checked. The over-travel should be checked, and the roller lever should be manually operated to ensure it operates smoothly. To address these, readjust the over-travel and replace the limit switch if the roller lever does not operate smoothly. [50]

Strategy 3: This is a maintenance recommendation from an existing industry maintenance manual. The limit switch should be checked for valve actuator alignment, wiring is insulated, connected, and terminated properly, all screws are present and tight, and conduit connections are installed properly and are dry. The internal devices should be checked for condensation. The limit switch should be visually inspected during open/close cycle and the identification labels should be checked for wear and replaced if necessary. [51]

2.8.7. Maintenance Strategies of Generators

Strategy 1: This is the do-nothing strategy, which displays the generator condition with no maintenance, and is used to compare to other strategies.

Strategy 2: This is a maintenance recommendation from NFPA 70B. Stator and rotor windings life depends on how close the condition is to the original. The windings need to be inspected for dirt, dust, moisture, oil, or grease. If these are present, the windings should be cleaned with a solvent solution. The winding tightness in the slots and pole pieces need to be checked. The insulation surfaces should be checked for cracks, crazing, flaking, or powdering. If there is evidence of this, use a coat of air-drying varnish to restore the insulation. The mechanical winding supports should be checked for tightness and insulation. Squirrel-cage rotors need to be checked for excessive heating, for discolored or cracked rotor bars, or for cracked end rings. The machine should be observed while in operation and examined for maloperation, such as sparking, chatter of brushes in the holder, and cleanliness. Brushes and holders should be examined for fit and free play. If there are brushes worn down, they should be replaced. The brush studs should be examined and if they are loose, they should be tightened. Brush faces should be checked for chipped toes or heals and for heat cracks. If any brush faces are damaged, then they should be replaced. Brush spring pressure should be checked by using the brush spring balanced method. If the pressure is incorrect it should be corrected with the manufacturer's instructions. The brush shunts should be examined to see if they are properly secured to brushes and holders. The collector rings insulation resistance should be checked between the ring and shaft. Cleaning should be done with a solvent cleaner and stiff brush to the collector rings. The brush holder end play should be checked. If the rings are worn unconventional with the shaft, then the ring face should be machined. The commutator concentricity should be checked with a dial gage. The commutator surface should be checked for high bars, grooving, evidence of scratches, or roughness. Depending on the roughness level, the commutator can be hand stoned or turned in the lathe. The commutator should be checked for high mica. If there is high mica, it should be undercut. In sleeve bearings, the oil should be drained, the bearing flushed, and new oil added at least once a year. The bearing insulation should be checked by doing a bearing temperature check. Ball bearings and roller bearings should be inspected at the time of greasing. The bearing housings should be opened to check the condition of the bearings and grease. The bearing and housing parts should be thoroughly cleaned, and new grease should be added. After being cleaned, the apparatus should be dried before being placed in operation. External heat can be used to dry the apparatus. Electric space heaters or infrared lamps can be used to keep the apparatus dry but should be distributed so it does not overheat the insulation. The apparatus should be inspected for mud, and any dust from storms or floods should be cleaned away. A hose can be used to wash it. When indicated by visual inspections and testing, the equipment should be disassembled and the winding should be cleaned, dried, and reinstalled, and the bearings should be checked and relubricated.

Strategy 3: This is a maintenance recommendation from an existing industry electrical preventative maintenance program for generators and large motors. According to the NFPA 70B, 20-17.5 motors should be infrared scanned annually. According to FIST Volume 3-4, 2.2 motors should be meggered annually. The concrete foundation should be checked for cracks. The base should be checked for broken, loose or weakened parts. The anchor bolts should be checked and tightened. The base should be checked for sound absorbing adequacy. The frame should be checked for cracks and loose or broken parts. The frame should be cleaned and repainted when necessary. The frame ground connection should also be checked. The laminations should be inspected for looseness and the clamping bolts should be tightened. If the laminations vibrate and cannot be stopped by tightening the clamping bolts, then put varnish between the loose laminations. Check for damaged laminations at the air gap. Squirrel cage rotor bars need checked for loose or broken bars or end connections. The filed circuit connections need to be checked and tightened if necessary, and the voltage drop should be checked at each pole by applying alternating current at the collector rings. The overall rotor resistance should be checked. The air gap should be checked at the four quadrature positions and recenter the rotor if needed. If the machine is horizontal, the bearings might need replaced if that bottom air gap is smaller than the top. The rotor air fans should be inspected for cracks. The holding bolts should be inspected and tightened. The windings should be inspected for damaged insulation, dirt, oil, and moisture. If there is dust, it should be blown out with clean dry air pressure not exceeding 40 lbs. per square inch. The exposed parts of the windings should be cleaned thoroughly with a nonflammable solvent. The windings should be revarnished if the insulation is brittle, hard, or dull. The insulation should be checked for separation, cracking, brittleness, or corona. The wire and string banding on direct current armature windings should be checked. The end-turn lashing of alternating current stator coils should be checked. If end turns vibrate excessively then apply lashing. The slot wedges should be checked, and if they are loose, they need to be replaced. If the coils in slots are loose tighten them by rewedging. The collection rings and brush operation should be checked daily. If needed wipe the collector rings. If the brushes are short, then replace them. If the collector rings have a good polish, then they should be left alone. The brush spring tension and brush fit should be checked. The brush holders can be reset if not properly spaced. The brush neutral position needs to be checked. If there is carbon or metallic dust, then it needs cleaned. Replace and sand in new brushes if needed. The bearings should be checked daily for temperature, lubrication, and oil level according to Facilities Instructions, Standards, and Techniques (FIST) Volume 2-4. During preventative maintenance the bearings clearances should be checked. The oil should be checked for dirt, sludge, and acidity. Filter or replace the oil as needed. The end play should be checked on horizontal machines. If bearings are rough, then they should be replaced or refinished. The bearing oil piping and cooling water piping should be inspected for leaks. The shaft should be inspected for wobbling and alignment. The insulated bearings insulation should be inspected. The oil film resistance should be checked occasionally. The keys, setscrews, and coupling bolts should be tight. The flexible parts of the couplings need to be checked for wear and fatigue. The belt or silent chain tension needs adjusted. The grease in the gear box should be flushed out and renewed. The chains, belts and gears need inspected. The alignment between driving and driven machine should be checked. The bearing cooling coils, and surface air coolers should be checked for leaks. The cooling water flow should be checked.

The external supply and piping need to be checked for leaks. The cooling coils should be flushed out with air and water. Then test the bearing coils, for leaks by applying air pressure to coils. Look for air bubbles rising in the oil and a drop in air pressure. The indicators, gauges, and relays should be checked for correct operation and sticking, dirty contacts. The calibration should be checked. Detailed records should be kept tracking armature temperature against the generator load. If the temperature readings begin to rise over 5 degrees Centigrade for the same loading conditions, then there could be a problem and further investigation should take place. [52]

2.8.8. Maintenance Strategies of Motor Control Centers

Strategy 1: This is the do-nothing strategy, which displays the motor control center condition with no maintenance, and is used to compare to other strategies.

Strategy 2: This is the maintenance strategy from the NFPA 70B Standard. Motor control equipment should be inspected and repaired at the same time as the motors it controls. Enclosures in a poor environment should be inspected for dust, dirt, and corrosive conditions. If there is dust and dirt, then it should be removed with a vacuum cleaner. Enclosures that are badly corroded should be clean and refurbished or replaced. Foreign material such as dirt, debris or hardware should be removed from the outside top surfaces, so it doesn't fall into the enclosure. The equipment inside the enclosure should be inspected for dust, dirt, moisture or other contaminants. If any of these are found the cause should be eliminated. The ventilation passages should be checked for obstructions and if any are found, remove them. If a cooling or heating system is installed to maintain a safe environment, then the system needs to be inspected to make sure it is working properly. The bus bar and terminal connections should be inspected for tightness. If there are lose connections, they should be tightened to the manufacturer's recommendations. The bus bar support insulators and barriers should be inspected to make sure they are free of debris. If there is debris, it should be cleaned/removed. The insulators should also be checked for signs of cracking. The power and control wiring should be inspected for signs of overheating. If there are damaged conductors, they should be replaced. Disconnects should be examined on the line and load side. If there is excessive debris on the disconnect, it should be cleaned. If there is mechanical operation, then the mechanical mechanisms should be operated manually to make sure they operate smoothly. The thermal element should be operating correctly. If not, the cause should be identified and corrected. The thermal element should be replaced if necessary. Push buttons, selector switches, indicating lights, timers, and auxiliary relays are on motor starters. To inspect them, check for loose connections, proper mechanical operation of operators and contact blocks, inspection of exposed contacts, signs of overheating, and replacement of pilot lamps, if necessary. If there are mechanical interlocks, they should be examined to ensure they are free to operate smoothly. If there are signs of excessive wear or deformation, then they should be replaced. [44]

Strategy 3: This is a maintenance recommendation from Eaton preventative maintenance program. If there is soot, smoke, or stained areas they should be inspected, and then investigate then cleaned. The exposed surfaces should be vacuumed or wiped clean. Any foreign material needs to be removed from the enclosure, not rearranged. The control equipment should be clean and dry if there is dust and dirt, then it should be removed from inside and outside the cabinet without using any liquid cleaner. Foreign material should be removed from the outside top and inside bottom of the enclosure. If there are liquids inside the enclosure, then the source should be found, and conduit should be sealed, or space heaters should be added. Examine inside the enclosure for overheated joints, charred insulation, discolored terminals, etc. and all electrical connections should be tightened. The terminals that are discolored should be cleaned. Wires and cables need to be inspected for chafing against metal edges. If there is temporary wiring, then it should be removed or permanently secured. Any mechanical movement should be checked for freedom of motion and functional operation. Indicating lamps, mechanical flags, doors, and latches should be inspected. The contacts should be inspected for erosion. [53]

2.8.9. Maintenance Strategies of Switchgears

Strategy 1: This is the do-nothing strategy. It will display the switchgear condition with no maintenance, and is used to compare to other strategies.

Strategy 2: This maintenance strategy comes from NFPA 70B. The grounding of the switchgear should be verified by visual inspection. If system is ungrounded, reground the system using NEC. On the switchgear enclosure, all doors and access panels should be inspected, and the hardware should be in place and in good condition. There should be screen coverings on the ventilation. The roof or wall seams should be checked for leakage. If there are openings they should be repaired by caulking or grouting. The heating and ventilation system needs to function properly to prevent moisture. The heater should be checked to ensure it is in good condition. If there is a thermostat, it should be checked to ensure it is operating properly and is in good condition. The ventilation should be clear of obstacles, and the air filters should be clean.
If there is damage from dielectric stress it will be seen in the form of corona or tracking. Inspect for corona discharge, which are white powdery deposits on the surface. If there is evidence of this, the surface can be wiped off with solvent. Tracking is indicated by arcs on the surface of

insulation, shown as one or more irregular carbon lines in the shape of tree branches. If the damage, is not too bad it can be repaired by adding track resistant varnish. To see thermal damage the switchgear should be inspected for discoloration, cracking and flaking of varnish coatings, embrittlement of tapes and cable insulation, delamination of materials or finishes, generalized carbonization of materials or finishes, melting, oozing, or exuding of substances from within an insulating assembly. An infrared thermography inspection can also be used to detect potentially damaging heat. Insulation materials that are damaged should be replaced. The three most important items to remember for switchgear maintenance is to keep it clean, keep it dry, and keep it tight. [44]

Strategy 3: This is a maintenance recommendation from an existing industry electrical preventative maintenance program. The environment the switchgear is in will determine how often maintenance is needed. The enclosure panels and structure need to be well maintained. A vacuum is to be used to clean all loose dirt and debris. The vents and fan grills are to be cleaned of dust and dirt. The ventilations opening should not be obstructed. The heater elements should be cleaned, examined for damage, and tested. If there is damage the heater elements should be replaced. Inspect insulators and conductors for signs of cracking, broken physical pieces and other deterioration. Clean the dirt with lint free rags. If there are containments that will not come off with the rag use solvents. Examine the insulators and conductors for signs of moisture. Repair and replace the damaged insulators and conductors as needed. Inspect bolts and connecting devices for signs of corrosion, overheating and deterioration. Make sure the bolts and connections are tight according to the manufacturer’s recommendations. Examine conductors for cracking, overheating, and deterioration. Ensure that conductors are clean and dry. If there is dirt or dust, remove it with a lint free rag. The electrical room the switchgear is kept in should also be inspected. It should be clean from dirt or dust. The doors and windows should be in good condition. The room should also be inspected for water seepage. The top of the electrical equipment enclosures should be checked for water damage. [43]

2.8.10. Maintenance Strategies of Power Panelboards

Strategy 1: This is the do-nothing strategy, which displays the power panelboard condition with no maintenance, and is used to compare to other strategies

Strategy 2: This maintenance strategy comes from NFPA 70B, 16.3. Enclosures in a poor environment should be inspected for dust, dirt, and corrosive conditions. If there is dust and dirt, then it should be removed with a vacuum cleaner. Enclosures that are badly corroded should be clean and refurbished or replaced. Foreign material such as dirt, debris or hardware should be removed from the outside top surfaces, so it doesn't fall into the enclosure. The equipment inside the enclosure should be inspected for dust, dirt, moisture, or another contaminant. If any of these are found the cause should be eliminated.

Strategy 3: This is a maintenance recommendation from Schneider Electric Switchboard preventative maintenance. In the electrical room the fixed part and level of support need to be inspected. In the enclosure the interlocking device, cover panel, general appearance, dedusting need to be inspected. If there are indicating lights or mechanical indicators they need to be inspected. An inspection of heating, power connections, busbars, terminations, busbar supports, downstream power connections, the grounding of the switchgear, and cable connections should be performed. The switchgear needs dusted and cleaned. The switchgear needs to be operated to ensure it is working correctly. A visual inspection of the switchgear should be performed to inspect the wearing parts, main contacts, and arcing chamber. [54]

Strategy 4: This is a maintenance recommendation from an industry electrical preventative maintenance. Records of all installed switchboards and their maintenance schedule, nameplate data of all the equipment and its major components, instruction books, renewal parts lists, bulletins and drawings, a list of all items which need be inspected, record of past inspections and test results should be kept. Insulation resistance tests of the switchboard breakers can be used to see the deterioration of insulation. Spare parts of vital parts of the switchboard should be kept on hand. [55]

2.8.11. Maintenance Strategies of Electric Motors

Strategy 1: This is the do-nothing strategy, which will display the electric motor condition with no maintenance, and is used to compare to other strategies.

Strategy 2: This is a maintenance recommendation from General Electric electrical preventative maintenance program. There are three levels of maintenance to be done to a motor. The first level is every 4,000 hours or semi-annually and it includes training, documentation, standard visual inspection, standard cleaning tasks and functional tests. The second level is every 8,000 hours or annually and it includes training, documentation, and open inspection of motor subassemblies, spectral analysis to detect malfunctions, standard visual inspection, standard cleaning tasks and functional tests. The third level is every 40,000 hours or every 5 years and it includes training, documentation, complete visual inspection, advanced cleaning if needed, additional tests if needed, dissemble and overhauling major parts (for example the rotor,) repair or refurbishment, stator wedge insulation tightness, and a spare parts list. The visual inspection should include the following: check that the holding-down bolts are tight; check all visible fixings and bolts; including those holding the cover to the baseplate; the cooler to the cover (if any); inspect the terminal cubicle; bus bar for any insulation failure due to overheating; check for any corrosion of metal parts inside the panels; check for any dust accumulation or foreign matter; look for leakage of oil from the bearings along the shaft; clean around the bearing area; and if the machine has cartridge-mounted bearings; clean around the bearing insulation at the cartridge feet; and, ensure all covers fitted. Standard cleaning includes clean the stand-off insulators with a clean dry cloth, use a vacuum cleaner to remove dust and dirt from wiring and electrical components, and inspect cabinet air filters. The filters can be vacuumed or replaced as required. After cleaning, look at the parts for pitting or signs of metal deposits, and if they are pitted do not reuse parts. The exterior of the motor needs cleaned as well. If there are air filters they should be replaced or cleaned and reconditioned. If the motor is open ventilated the screen should be cleaned of any buildup. Standard function tests include insulation resistance and polarization index, wining resistance, RTD resistance, PDA test offline, dissipation factor, stator core loop test, stator core EL CID test, AC Hipot testing, absorption test, rotor AC drop voltage test, wedge tightness, borescope inspection of vent slots, borescope inspection of rotor poles, and stator roundness/air gap checks. [56]

Strategy 3: This is a maintenance recommendation from an existing industry electrical preventative maintenance program. During preventative maintenance the equipment should be locked and tagged out. The readings should be taken, and all data recorded. The mounting and flange bolts to ensure proper torque should be checked, equipment base should be checked for soundness, a visual inspection of pump grout for soundness should be done, mechanical seal leaks should be checked, oil and grease seals condition should be checked, and packing for excessive leakage should be checked. Gauges should be operated to make sure they are operational. The coupling guard should be removed, and the alignment should be checked. The coupling assembly and motor should be lubricated. The oil should be changed as recommended from operations. Ensure the auxiliary equipment is functioning correctly. The motor should be ran then the bearing temperatures should be checked and the motor should be listened to for mechanical or hydraulic noise. Then lastly, make a note of any findings that require additional work. [57]

Strategy 4: This is a maintenance recommendation from an existing industry electrical preventative maintenance program for generators and large motors. According to the NFPA 70B, 20-17.5 motors should be infrared scanned annually. According to FIST Volume 3-4, 2.2 motors should be meggered annually. The concrete foundation should be checked for cracks. The base should be checked for broken, loose or weakened parts. The anchor bolts should be checked and tightened. The base should be checked for sound absorbing adequacy. The frame should be checked for cracks and loose or broken parts. Clean and repaint the frame as necessary. The frame ground connection should also be checked. The laminations should be inspected for looseness and the clamping bolts should be tightened. If the laminations vibrate and cannot be stopped by tightening the clamping bolts, then put varnish between the loose laminations. Check for damaged laminations at the air gap. Squirrel cage rotor bars need checked for loose or broken bars or end connections. The filed circuit connections need to be checked and tightened if necessary, and the voltage drop should be checked at each pole by applying alternating current at the collector rings. The overall rotor resistance should be checked. The air gap should be checked at the four quadrature positions and the rotor should be recentered if needed. If the machine is horizontal the bearings might need replaced if that bottom air gap is smaller than the top. The rotor air fans should be inspected for cracks. The holding bolts should be inspected and tightened. The windings should be inspected for damaged insulation, dirt, oil, and moisture. If there is dust it should be blown out with clean dry air pressure not exceeding 40 lbs. per square inch. The exposed parts of the windings should be cleaned thoroughly with a nonflammable solvent. The windings should be revarnished if the insulation is brittle, hard, or dull. The insulation should be checked for separation, cracking, brittleness, or corona. The wire and string banding on direct current armature windings should be checked. The end-turn lashing of alternating current stator coils should be checked. If end turns vibrate excessively then apply lashing. The slot wedges should be checked and if they are loose, they need to be replaced. If the coils in slots are loose tighten them be rewedging. The collection rings and brush operation should be checked daily. If needed wipe the collector rings. If the brushes are short, then replace them. If the collector rings have a good polish, then they should be left alone. The brush spring tension and brush fit should be checked. The brush holders can be reset if not properly spaced. The brush neutral position needs to be checked. If there is carbon or metallic dust, then it needs cleaned. Replace and sand in new brushes if needed. The bearings should be checked daily for temperature, lubrication, and oil level according to FIST Volume 2-4. During preventative maintenance the bearings clearances should be checked. The oil should be checked for dirt, sludge, and acidity. Filter or replace the oil as needed. The end play should be checked on horizontal machines. If bearings are rough, then they should be replaced or refinished. The bearing oil piping and cooling water piping should be inspected for leaks. The shaft should be inspected for wobbling and alignment. The insulated bearings insulation should be inspected. The oil film resistance should be checked occasionally. The keys, setscrews, and coupling bolts should be tight. The flexible parts of the couplings need to be checked for wear and fatigue. The belt or silent chain tension needs adjusted. The grease in the gear box should be flushed out and renewed. The chains, belts and gears need inspected. The alignment between driving and driven machine should be checked. The bearing cooling coils, and surface air coolers should be checked for leaks. The cooling water flow should be checked. The external supply and piping need to be checked for leaks. The cooling coils should be flushed out with air and water. Then test the bearing coils for leaks by applying air pressure to coils. Look for air bubbles rising in the oil and a drop in air pressure. The indicators, gauges, and relays should be checked for correct operation and sticking, dirty contacts. The calibration should be checked if there is doubt. Detailed records should be kept tracking armature temperature against the generator load. If the temperature readings begin to rise over 5 degrees Centigrade for the same loading conditions, then there could be a problem and further investigation should take place. [52]

2.8.12. Maintenance Strategies of Brakes

Strategy 1: This is the do-nothing strategy, which displays the brake condition with no maintenance, and is used to compare to other strategies.

Strategy 2: This is a maintenance recommendation from an industry electrical preventative maintenance program. The brake condition should be checked monthly for condition of brake airline filters and lubricators. The brake shoe thickness and brake ring condition need to be checked once a year. The brake cylinders should be operated to check for binding and sticking. If they are sticking, disassemble and repair. The hydraulic lines should be checked for leaks. The brake lining should be checked for wear and oil contamination. The brake drums should be checked for scoring and smooth drums or uneven wear patterns. The brakes need to be verified that they will hold with a loss of power. The dust and dirt should be cleaned from brakes. The springs should be inspected for damaged springs. [58]

2.9. Discussion of Literature Review

This literature review presented the concept of asset management and the performance measures that were evaluated. The critical components that would be evaluated were presented as well as the significance of each component. The literature reviewed detailed the failure mechanisms of each component and the preventative maintenance strategies used to prevent failures. Based on the failure mechanisms of the critical components and strategies that were presented, a methodology was developed and was tested by using the data that is detailed in Chapter 3.

CHAPTER 3-DATA

This chapter represents steps 3 and 4, outlined in the methodology in Chapter 1. This chapter details the data gathered in support of the study detailed in this thesis.

3.1. Sample Projects

Two sample projects were chosen based on the two most common types of projects USACE operates. The first project is a flood risk management (FRM) dam, which was completed in 1973. The purpose of this dam is flood risk reduction, fish and wildlife enhancement, recreation for the public, and water quality improvement. The consequences of not maintaining the project are inability to sufficiently execute flood damage reduction, which would lead to failure of the structure, resulting in a life safety concern for people in the downstream area. The dam's pertinent electrical equipment includes an intake structure with [redacted] sluice gates, power source, and a spillway with [redacted] Tainter gates.[59] The spillway includes [redacted] motor controllers, [redacted] motors, a spillway breaker stand and multiple power cables. The intake structure includes a generator, motor control center, multiple cables, and [redacted] pumps for the sluice gates. The power distribution includes a service disconnect, spillway breaker, and multiple cables.

The second project is a navigational (NAV) lock and dam, that USACE operates. A NAV dam is used to transport goods across navigable waterways. The locks were open for navigation in 1962. The lock and dam's pertinent electrical equipment includes a dam with [redacted] Tainter gates, [redacted] lock chambers, and power source. The power source includes a generator, automatic transfer switch, motor control center and multiple cables. The dam includes multiple cables, a [redacted] distribution panel, [redacted] distribution panels, nine motor controllers, and [redacted] motors. The lock includes [redacted] control stations which have [redacted] panels, multiple cables and [redacted] transformer disconnects.

3.2. Arc Flash Data

The Arc Flash Hazard Program is a portion of a total Electrical Safety Program that includes electrical safe working practices. This includes policies, practices, documentation, and standard operating procedures. The arc flash analysis is done every five years. During the analysis the engineer will take photos of the equipment to get model information and current condition of the equipment. [60] The photos were used to get a visual inspection of the condition of each piece of equipment. In-between the years of the analysis, if a project does any electrical changes, then the project must include an electric modification form, which informs the engineer of the change; then, the engineer will analyze the change and add it to the system if needed. Electrical changes include adding equipment, removing equipment, and rewiring or moving equipment. Therefore, it is assumed that the arc flash one-line diagrams are accurate, and they were used to obtain the proper equipment. The one-line was simplified and put into flow charts to include only the pertinent electrical equipment for each project, which are detailed in the next chapter.

3.3. Meggering/Cable Evaluation Data

The purpose of meggering is to test the cable's installation. Once this is completed, it establishes a baseline for annual insulation resistance testing. The primary benefit of insulation testing is to identify insulation problems by evaluating trends in the data over their lifetime. These tests can also uncover damaged insulation indicated by low readings. Insulation testing is performed on cables and motors that have been identified as critical to project operation. The purpose of a cable evaluation is to measure the condition of the electrical cables at a project. The inspection consists of close visual examination, photographs, electrical testing, and information from project personnel about equipment failures and electrical equipment upgrades. There is a megger testing report for The lock and dam from August 2019, which is where the condition of cables and accompanying photos were obtained.

3.4. Operational Condition Assessment Data

USACE uses OCA's as a snapshot in time of the project to predict future conditions. The operational condition refers to condition state or a deficiency and the level which the deficiency damages the component, and assessment refers to use of existing data such as periodic inspection and assessments to determine the components operability. [61] The OCA rating scale was previously explained in Chapter 2. The OCA rating was gathered and considered when inputting condition of the equipment into the analysis.

3.5. Periodic Inspection/Assessment Data

A periodic inspection is an engineering inspection done at dams and civil works projects, and is conducted every five fiscal years. The inspection includes the operation of all pertinent equipment, photos taken, and a summary of findings. A periodic assessment is done in conjunction with every second inspection and additionally includes potential failure modes analysis and a risk assessment. A periodic assessment is conducted every ten fiscal years. These inspections ensure that dams are systematically and routinely evaluated, and safety issues can be detected in a timely manner. [62] The most recent periodic inspection and assessment were examined for the equipment condition at each project. These inspections and assessment were compared to the arc flash reports and used as a source of input data.

3.6. Part Cost & Labor Data

The cost of equipment was collected from multiple sources, including from invoices the Facilities Management Systems (FEM), and the project's five-year layout, which includes all the purchased parts the project has bought in the past five years. If the price had not been previously purchased or could not be found, then the part was obtained from manufactures that USACE frequently buys from. The labor data was collected from USACE's pay scale.

3.7. Other

The age of the equipment was collected throughout the previous sets of data. If there was any information that was needed, the project personnel were contacted directly to get missing information.

CHAPTER 4-IMPLEMENTATION/ANAYLSIS

This chapter represents the fifth step in the methodology outlined in Chapter 1. The effects of a piece of equipment that could fail on a lock or dam is much more broad than just operational or financial. The entire project was analyzed as a system instead of individually. If a major component of the project fails, then it leads to inoperability of the entire lock or dam. This leads to economic and safety concerns. After evaluating what was needed to be analyzed for this thesis, the Isograph Availably Workbench-RCM Module was chosen. The analysis of the workbench is detailed in section 4.3.

4.1. Project Flowcharts

The arc flash one-line diagrams were converted into simplified flowcharts of the pertinent electrical system at each project. For some components at the projects, there is a redundant system. For example in **Figure 3**, the 480V service breaker would fail but the spillway would still be able to operate because the intake structure supplies power to the spillway. The projects contain many interconnected components, so that if one component were to fail, then it would create a domino effect for the components downstream. For example, in **Figure 4**, if a motor controller would fail then the motor would not be able to operate.

In **Figure 3**, the dam system overview is given. There is utility power that feeds the 480V service breaker and intake structure. The 480V service breaker feeds the spillway breaker and the spillway breaker feeds the spillway. The intake structure then feeds the spillway.

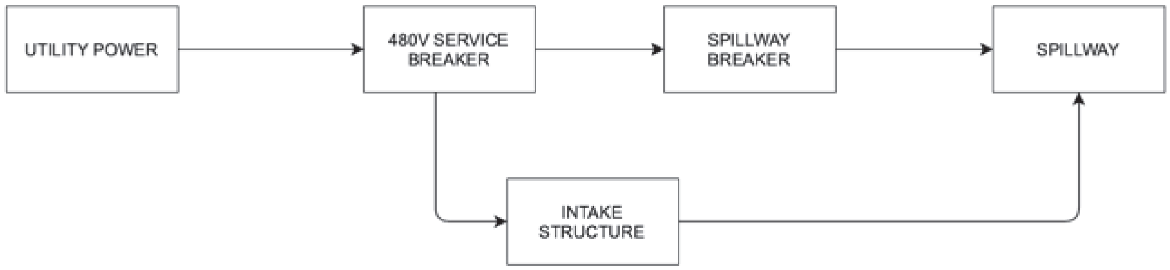

Figure 3-Dam System Overview

In, **Figure 4** the dam's spillway is shown. The utility power from the spillway breaker feeds the spillway breaker stand. The spillway also can get generator power from the intake structure shown in **Figure 5**. The spillway breaker stand feeds [redacted] motor controllers and each motor controller feeds a motor.

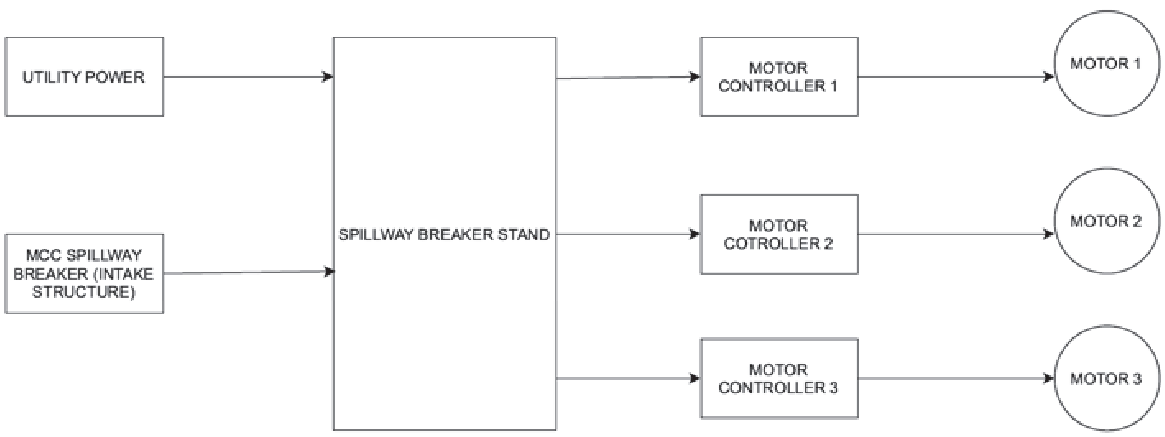

Figure 4-Dam Spillway

In **Figure 5**, the dam's intake structure is shown. The intake structure gets utility power from the 480v service breaker and has a generator inside for secondary power. Both sources feed the motor control center. The motor control center then feeds hydraulic pumps that operate the [redacted] The motor controller also supplies generator power to the spillway.

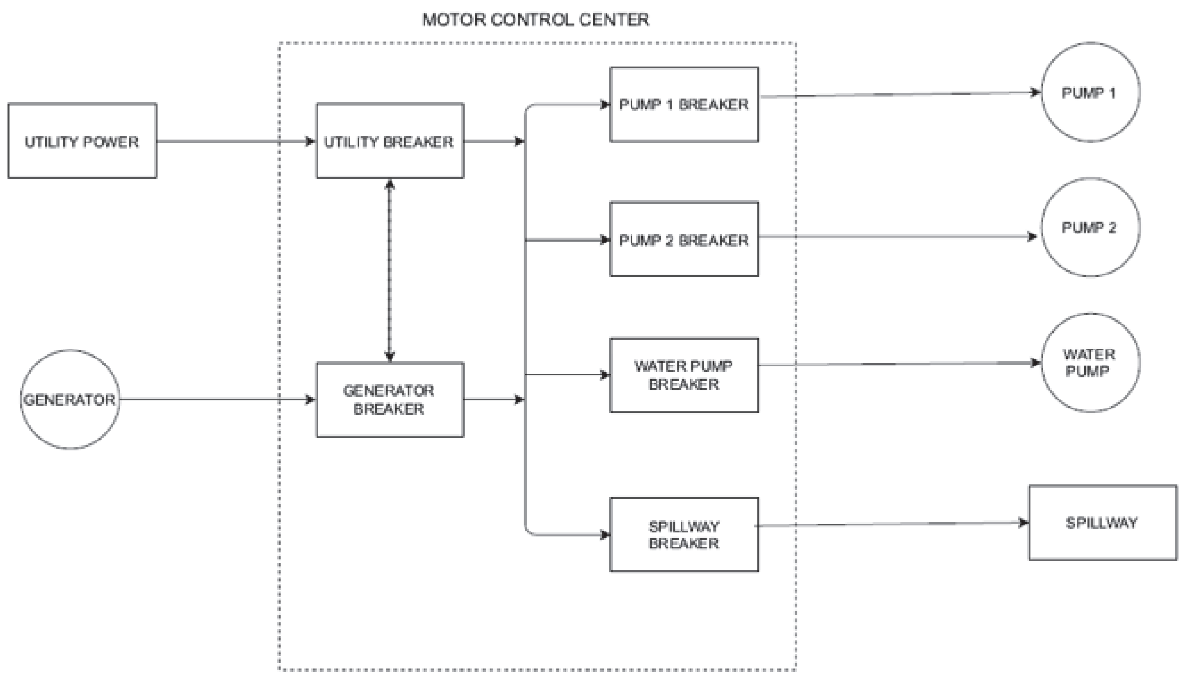

Figure 5-Dam Intake Structure

In **Figure 6**, the lock and dam's system overview is shown. A generator and utility service feeds an automatic transfer switch which powers the motor control center. The motor control center controls the locks and the dam.

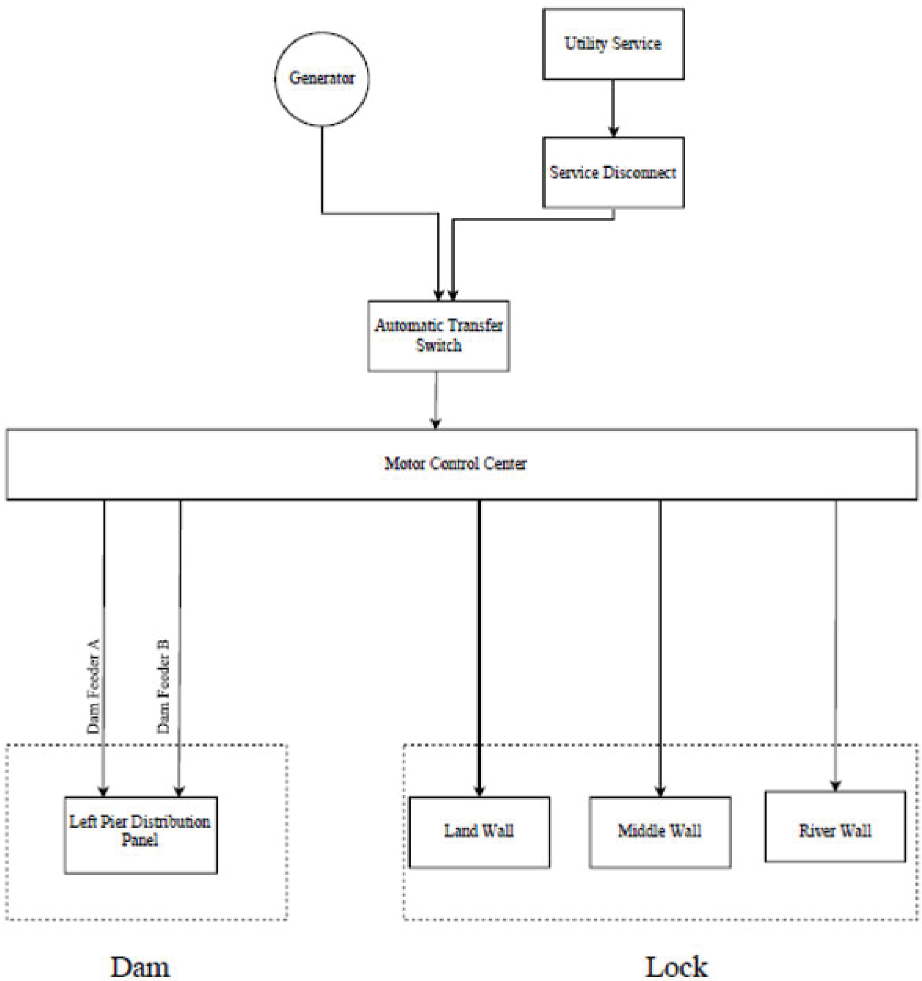

Figure 6- Lock and Dam System Overview

In **Figure 7**, the lock and dam's dam is shown. There are feeds coming from the motor control center that supply the dam [redacted] distribution panel with power. The [redacted] pier distribution panel, supplies the dam with power. Feeders go to every dam pier to supply the power panels in each pier with power. From the power panels they each feed a motor controller and the motor controller feeds a motor [redacted]

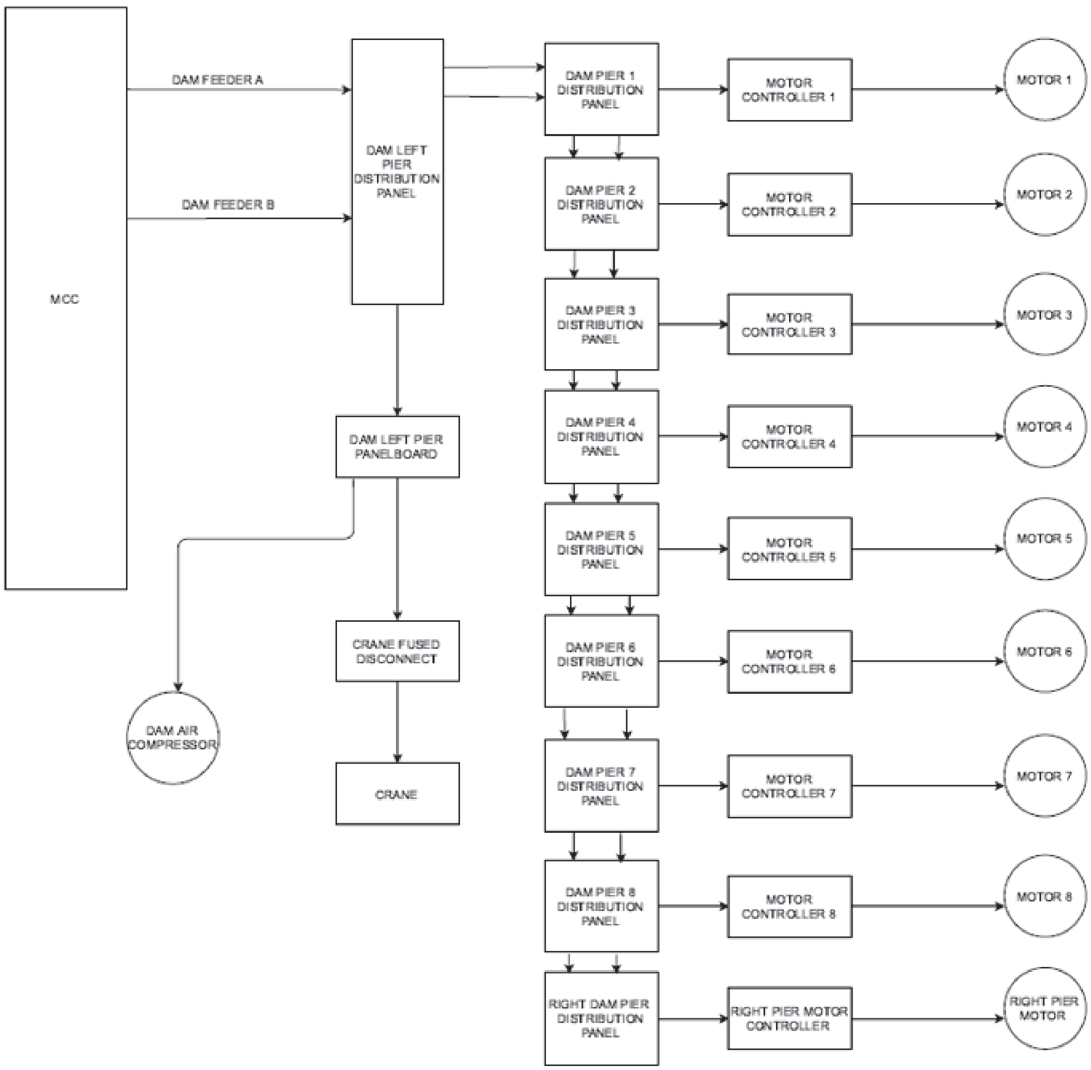

Figure 7- Lock and Dam-Dam

In **Figure 8**, the lock and dam's Lock is shown. The lock is powered by the motor control center.

The motor control center feeds separate control stations. [redacted]

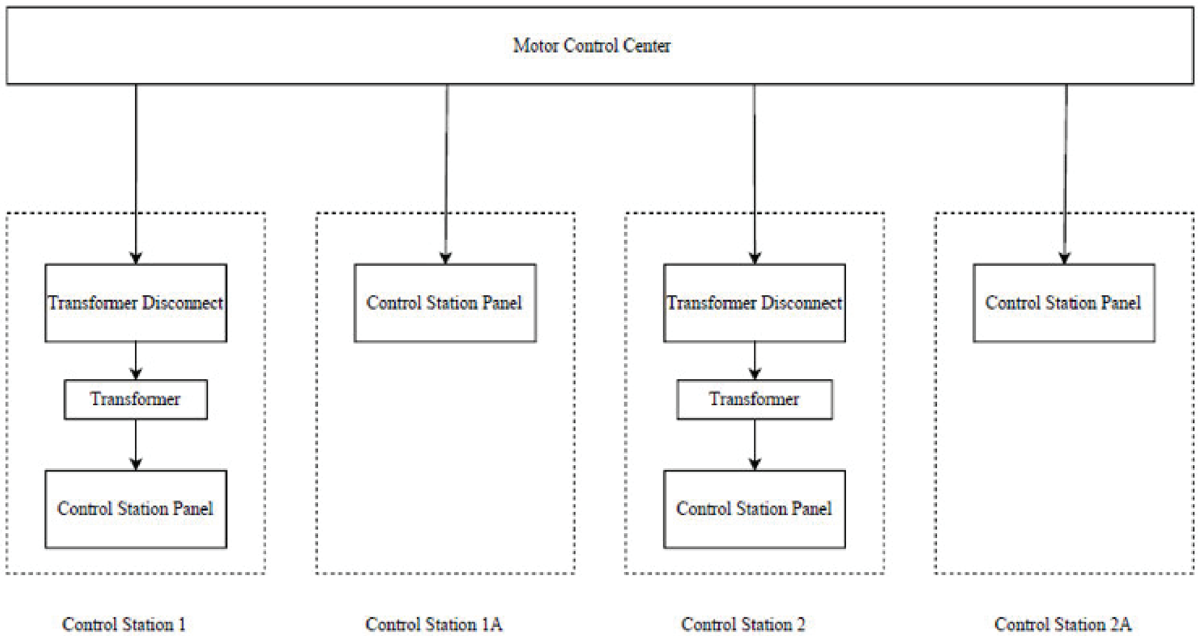

Figure 8- Lock and Dam-Lock

4.2. Implementation of Methodology

Cranes and air compressors were excluded from this work. Air compressors were excluded because they were not considered pertinent. Cranes were excluded because the cranes are inspected by the manufacturer. Controls were also excluded because small components of controls can be replaced within minutes of them failing. Hand tools that would be needed to complete the preventative maintenance were not investigated.

Isograph Availably Workbench-Reliability Centered Maintenance (RCM) Module determines optimized maintenance strategies based on techniques such as Failure Mode Effects and Criticality Analysis (FMECA). The program uses a failure mode and effects analysis (FMEA) to find the critical failure modes. Then the program examines each critical failure mode to determine the best maintenance strategy to reduce the effects of each failure. The maintenance strategy considers cost, safety, environmental and operational consequences. The program minimizes costs, while meeting safety, environmental and operational goals. [63] The dormant Weibull function cannot be entered into the isograph availability workbench. The Weibull function was used. Based on the data software, the program does meet the requirements for validating the framework, but it does have limitations. The program needs to be set up in a series of tasks. They are listed below.

- To define system boundaries the equipment to be analyzed needs to be selected which was done in Chapter 1.
- A location hierarchy needs to be built. A location hierarchy is the system, subsystem and failure modes which include functions of equipment and functional failures of equipment which was done in Chapter 2.
- The effects of each failure need to be defined. The effects considered in this work are major loss of operating gates, intermediate loss of operating gates, damaged equipment, and flooding.
- The failure distribution needs to be defined and in this work the Weibull function was used.
- The maintenance actions that can be performed needs to be specified which was done in Chapter 2.
- Finally, perform simulations on each maintenance action to determine what is the optimum strategy. [64]

4.3. Planned Maintenance

Planned maintenance refers to scheduled tasks that extend the life of components and prevent failure. For the planned maintenance tasks, there are multiple variables of concern. The task duration is the time it takes to do maintenance on the equipment. The operational cost is any cost that is not included the labor, equipment, and spare cost. This does not include equipment delays or logistic delays. The resources include labor categories, equipment and spares that are required to complete the planned maintenance. The task enabled is the planned maintenance that has been enabled for the routine planned maintenance. The task group is what group the planned maintenance has been assigned. [64]

4.4. Corrective Maintenance

Corrective maintenance is done after a component has failed; specifically in the case of this study, to replace a failed component. For the corrective maintenance tasks there are multiple costs that need to be considered. The operational cost is any cost that are not included the labor, equipment, and spare cost. The task duration is the time it takes to repair the equipment. This does not include equipment delays or logistic delays. The resources include labor categories, equipment and spares that are required to complete the corrective maintenance. The corrective action that was considered in this work was to replace each piece of equipment that failed. [64]

CHAPTER 5-RESULTS & RECOMMENDED FRAMEWORK

In this chapter, the results from evaluating the data from the two previously detailed projects will be discussed, as well as the implementation of the framework and details the results. Asset management requires performance prediction, risk analysis, and data interpretation. The data and models from the previous chapters must be entered into a computational framework.

5.1. Implementation of Model Framework

The original framework included a MATLAB and Microsoft Excel code to evaluate the strategies and maintenance costs using the previously detailed methods. Upon further investigation, the Isograph Reliability Workbench was recommended from an USACE engineer who studies reliability and maintenance. The program was thoroughly researched to ensure that it could be used to validate the framework in this work. The program included everything that is required to be implemented in the code. The inputs for the software were the data that was detailed in Chapter 3. The inputs included task duration, operational cost, labor, equipment, spare cost, and effects which are detailed in section 5.2.1. Once the strategies were analyzed, the task groups, which are detailed in section 5.4, were eligible to be optimized; optimizing maintenance strategies is a direct application of this research. The preventative maintenance tasks include interval durations that could occur weekly, monthly, quarterly, or annually, which the software selects based on minimizing cost which is detailed later. The software takes the equipment criticality into account. The cost of the strategies was analyzed in the Availability Workbench and taken into consideration during optimizing the maintenance strategy and task groups. The resources such as labor, equipment costs, and time were also added into the program and taken into consideration when optimizing the maintenance strategies and task groups. The program also performs a cost comparison, which was another crucial calculation that needed to be included in the previous code. The calculation was needed to allow for scenario analyses to be conducted. It was found that the Isograph Availability Workbench RCM Module has everything that was needed to validate the framework presented in this work. The dormant Weibull function was not able to be implemented into this software. The Weibull function was analyzed instead.

5.2. Simulation Results Explanation

The mean unavailability is the expected fractional time the equipment will be out-of-service over its lifetime, or the total time it is out-of-service divided by the total project lifetime. The number of failures is the total number of failures of the equipment over the project's lifetime. The number of PMs is the total number of preventative maintenance tasks preformed of the equipment over the project's lifetime. The total failure down time is the down time of the equipment due to failures. The total PM down time is when the total down time includes down time caused by planned maintenance. The number of inspections is the total number of inspection tasks performed on the equipment over the project's lifetime. The total inspection down time is when the total down time includes down time caused by inspection. The cost benefit ratio is:

$$CBR = \frac{Cost\ with\ specified\ tasks\ and\ alarms}{Costs\ without\ specified\ tasks\ and\ alarms}$$

Equation 4-Cost Benefit Ratio

The cost in the cost benefit ratio includes labor cost, equipment cost, and effect cost over the project's lifetime. A cost benefit ratio less than 1 means that the tasks/planned maintenance for that specific cause is worthwhile from a cost viewpoint. [64]

5.2.1. Effects

The effect prediction data is available once a project simulation has been completed. The data includes the length of the effect due to corrective and planned maintenance associated with all the causes as well as cost data.

The total cost over the lifetime for effects is given by the equation below.

$$C = (C_R * T) + (C_0 * N)$$

Equation 5-Effect Total Cost

Where,

C: effect cost over the lifetime
C_R: effect cost rate. The cost rate designates the estimated cost per unit time due to the occurrence of the effect.
C_0 = effect cost per occurrence
(Cost can be assigned for each effect per occurrence in the effect task. Effect costs were not assigned because USACE is not a production plant.)
T: effect duration over the lifetime
N: number of occurrences of the effect over the lifetime

5.2.2. Labor Cost

Labor categories are used to determine the contribution of labor to life cycle costs. The labor category prediction data is available once a project simulation has been completed. The data includes the active time due to corrective and planned maintenance as well as labor costs. The number of tasks performed using the labor category over the project's lifetime is also predicted.

The labor cost includes the corrective call-out rate, scheduled call-out cost, and the cost rate. The corrective call-out cost is the cost when each time one member of the labor category is called to preform corrective maintenance task. The scheduled call-out rate is the cost each time a member of the labor category is called to perform a schedule maintenance task. The cost rate is the cost per unit time when paying one member of the labor category to perform a maintenance task. [64]

5.2.3. Equipment

The individual equipment prediction data is available once a project simulation has been completed. The data includes the time it takes to do corrective and scheduled maintenance as well as equipment usage costs. The number of tasks associated with the equipment over the system lifetime is also predicted.

The equipment cost includes the corrective cost, planned cost, and inspection cost. The total cost is the cost associated with the selected equipment over the project's lifetime. The corrective cost is associated with the number of times the equipment fails and using the selected equipment for corrective tasks over the project's lifetime. The planned cost is associated with the tasks selected for the selected equipment for planned tasks over the project's lifetime. The inspection cost is associated with choosing the selected equipment for inspection tasks over the project's lifetime. [64]

5.2.4. Life Costs

The life costs are defined as the sum of all costs associated with maintaining the dam or lock and dam over its lifetime. Life costs are determined from all the causes in the location hierarchy. The software is used to summarize the lifetime cost parameters, which includes total labor costs, total spare purchase costs, total effects cost, total operational cost and total costs. Total labor costs include total corrective labor costs, total planed labor cost, total inspection labor cost, total equipment labor cost, total corrective equipment costs, total planned equipment costs, and total inspection equipment costs. Total spare purchase costs include total effects cost, corrective spare purchase costs, and planned spare purchase costs. Total effect costs include corrective effect cost, planned effect cost, and inspection effect cost. Total operational costs include corrective operation costs, planned operational costs and inspection operational costs. Total costs include safety criticality, operational criticality, and environmental criticality. [64]

5.3. Optimizing Strategies

The optimum maintenance strategies were determined for each component by the cost benefit ratio detailed in section 5.2. Since there are multiple components at the project, the weighted average of the cost benefit ratios for each strategy was calculated to get the strategy cost benefit ratio. The strategy was chosen by the lowest cost benefit ratio. If there were two cost benefit ratios that were the same, then the strategy was chosen based on engineering judgement. If there were multiple strategies for a component, the one with the most (multiple) lowest cost benefit ratio was chosen.

The optimized maintenance strategies from the dam are listed in **Table 2**. All the preventative maintenance tasks have a CBR less than one except for motors. This means that it is more cost effective to let a motor run until failure than do preventative maintenance on the motor. The reason for this may be there are only three motors on the spillway and the time it takes to do the maintenance is too long and costly compared to the effects. For the other components listed, it is more cost beneficial to do preventative maintenance on them.

Equipment Type	Cost Benefit Ratio (CBR)	Strategy[i]
Cables	0.97	Inspection
Circuit breakers	0.19	2-NFPA 70B
Motor Starters	0.16	2-Indusrty
Traveling Nut Limit Switch	0.98	2-Industry
Generators	0.27	3-Industry
Motor Control Center	0.44	2-NFPA 70B
Electric Motors	5.94	2-General Electric
Brakes	0.98	2-Industry

Table 2-Dam Optimized Maintenance Strategies

The optimized maintenance strategies from the lock and dam are listed in **Table 3**. All the preventative maintenance tasks have a CBR less than one except for motor control center. Similar to the dam, this means that it is more cost effective to let a motor control center run until failure than do preventative maintenance on the motor. The reason for this may be that the maintenance time is too long and costly compared to the effects of the failure. For the other components listed, it is cost beneficial to do preventative maintenance on them.

Equipment Type	Cost Benefit Ratio (CBR)	Strategy[ii]
Cables	0.98	Inspection
Automatic Transfer Switch	0.25	2- NEMA Standard KS 3
Circuit breakers	0.29	2- NFPA 70B
Motor Starters	0.16	2-Industry
Traveling Nut Limit Switch	0.16	2- Industry
Generators	0.88	3- Industry
Motor Control Center	1.29	2- NFPA 70B
Power Panelboard	0.19	3- Schneider Electric
Electric Motors	0.64	2-General Electric
Brakes	0.99	2- Industry

Table 3-Lock and Dam Strategy Optimization

The dam and the lock and dam were analyzed as two separate projects. The two projects were analyzed separately because they are designed to do different functions. The cost of certain equipment is higher for a lock and dam because, for larger items, a boat is required to move equipment to the middle lock wall where the operations building is located. The lock and dam also cost more money to manage annually than a dam which is detailed in the next sections. For the components that the projects have in common all the optimized strategies were the same strategy. The reason that it is cost effective to preform maintenance on motors for the lock and dam is that the quantity of the motors and the effects that the motors have on the project are large.

5.4. Optimizing Task Groups

Once the optimum strategies were defined the strategies were then separated into task groups to find the optimized task group. The strategies were separated into three different groups: component group, interval group, and location group. The component group was separated by different components for example, all breakers were grouped together and so on. The interval group was separated by intervals, for example the components with tasks every 1460 hours were put together. The location group was separated by the location; for the lock and dam it was separated between lock, dam, and operations. The lock group included components on the lock while the dam group included components on the dam. The operations group included generator, utility, and motor control center. The location group was separated by the location, and for the dam it was separated between spillway, intake structure, and operations. The spillway group included components on the spillway while the intake group included components in the intake. The operations group included generator and utility.

The location group for both a dam and a lock and dam were the optimum maintenance task group. This is due to the intervals of each location and criticality. The components on the dam have similar criticalities. The components on the locks have similar criticality and the operations groups have similar criticality. Each location group also has similar effects if the components fail. If the lock components fail, then operations are lost of the lock. If the dam components fail, then the effects are flooding and damaged equipment along with loss of operations. The operations group effects are the loss of operations. Since these properties of the components are similar it is more cost effective to do each location together in the same interval.

5.4.1. Optimizing Task Groups-Lock and Dam

The location group for the dam and a lock and dam was the optimum maintenance task group. This is due to the intervals of each location and criticality. The components on the dam have similar criticalities. The components on the locks have similar criticality and the operations groups have similar criticality. Each location group also has similar effects if the components fail. If the lock components fail, then operations of the lock are lost. If the dam components fail, then the effects are flooding and damaged equipment along with the loss of operations of the dam. The operations group effects are the loss of operations of power distribution and motor control. Since these properties of the components are similar, it is more cost effective to do each location together in the same interval.

During a meeting with an assistant lock master ([redacted] personal communication, March 10, 2021), [redacted] confirmed it cost USACE $2,800,000.00 in 2020 to manage the lock and dam. It costs roughly $80,000 every two weeks in labor. In **Table 3**, the optimized task group for the lock and dam is shown. The estimated lifetime is 100,000 hours which is 11.42 years. The corrective labor is $2,471,000.00 over the lifetime which is the labor for replacing or repairing the failures of the project. Over a year the corrective labor is $216,374.78. The equipment and spare costs are the cost of replacing and repairing the equipment for the corrective maintenance. The cost of the equipment over the lifetime is $945,356,300.00. The equipment cost over a year would be $82,780,761.82. The planned labor and inspection are the cost of the preventative maintenance, which, over the lifetime the total is $321,900.00. For a year the cost of preventative maintenance is $28,187.39. The effect cost is the total effect cost because of the effects that were set with each failure mode. For example, a failure could lead to damaged equipment. The effect cost over the lifetime is $11,150,800.00. The effect cost per year is $976,427.32. This cost is the effects of the failures per year. This cost can be lowered or eliminated by doing preventative maintenance tasks which are much lower in cost to the project.

Lifetime	Corrective Labor	Planned Labor	Inspection	Equipment/Spare Costs	Effect Costs	Total
100,000 hours	$2,471,000	$303,700	$18,200	$945,356,300	$11,150,800	$959,300,000

Table 4-Optimized Task Group for Lock and Dam

5.4.2. Optimizing Task Groups-Dam

The location group for the dam was the optimum maintenance task group. This is due to the intervals of each location and criticality. The components on the spillway have similar criticalities. Each location group also has similar effects if the components fail. If the spillway components fail, then the effects are flooding and damaged equipment along with loss of operations. The operations group effects are the loss of operations. Since these properties of the components are similar it is more cost effective to do preventative maintenance on each location together in the same interval.

An email with a USACE staff member confirmed that the facility spent $991,000.00 to manage the dam in 2020. ([redacted] personal communication, March 10, 2021) In **Table 4**, the optimized task group for the lock and dam is shown. The estimated lifetime is 100,000 hours which is 11.42 years. The corrective labor is $411,700.00 over the lifetime which is the labor for replacing or repairing the failures of the project. Over a year the corrective labor is $36,050.79. The equipment and spare costs are the cost of replacing and repairing the equipment for the corrective maintenance. The cost of the equipment over the lifetime is $341,023,000.00. The equipment cost over a year would be $2,986,190.00. The planned labor and inspection are the cost of the preventative maintenance, which, over the lifetime the total is $78,380.00. For a year the cost of preventative maintenance is $6,863.40. The effect cost is the total effect cost because of the effects that were set with each failure mode. For example, a failure could lead to damaged equipment. The effect cost over the lifetime is $1,195,000.00. The effect cost per year is $104,640.98. This cost is the effects of the failures per year. This cost can be lowered or eliminated by doing preventative maintenance tasks which are much lower in cost to the project.

Lifetime	Corrective Labor	Planned Labor	Inspection	Equipment/Spare Costs	Effect Costs	Total
100,000 hours	$411,700	$74,750	$3,630	$341,123	$1,195,000	$342,700,000

Table 5-Optimized Task Group for Dam

5.5. Sensitivity Analysis

A sensitivity analysis was performed to the dam to ensure the results of the optimized maintenance strategies from the framework were robust. The strategies need to work for all situations and all types of project.

The first sensitivity analysis was conducted on labor cost to evaluate whether the recommended strategy is changed. The electrician's cost was changed from $10 an hour to $15 an hour. To calculate the cost benefit ratio, the weighted average was used. The cost benefit ratio is slightly different for the components in result to the cost of the labor being increased. However, the strategies that were optimized were the same as the strategies optimized in the simulation with the labor as $10 an hour.

The next sensitivity analysis was conducted on the age of each component to evaluate whether the recommended strategy is changed. The life of each component was changed from what it is to one year. This assumes all components are new and recently installed. The cost benefit ratio is slightly different for the components in result to the age being altered and the lifetime failures of each component being different. However, the strategies that were deemed optimal were the same as the strategies deemed optimal in the simulation when the age is what the actual age of each component is.

Equipment Type	Cost Benefit Ratio (CBR)	Cost Benefit Ratio (CBR) Lifetime Changed	Cost Benefit Ratio (CBR) Labor Cost Increased
Cables	0.97	0.98	0.98
Circuit breakers	0.19	0.20	0.18
Motor Starters	0.16	0.01	0.17
Traveling Nut Limit Switch	0.98	1.01	1.09
Generators	0.27	1.09	0.32
Motor Control Center	0.44	0.41	0.55
Electric Motors	0.78	0.75	0.79
Brakes	0.98	1.0	1

Table 6-Sensitivity Analysis Results

The sensitivity analysis show that the cost benefit ratios between all three scenarios are similar. They are slightly different since the cost changed for the labor and the life changed adding failures to the project's lifetime. The cost benefit ratio for the lifetime changed is the highest out of the three scenarios. This is due to the failures being reduced since the equipment is considered new and in good condition. Even though the cost benefit ratios are slightly different the sensitivity analysis still shows that the optimized strategies are robust and can be used in multiple scenarios.

5.6. Framework

Figure 9, shows the recommended framework developed in this project.

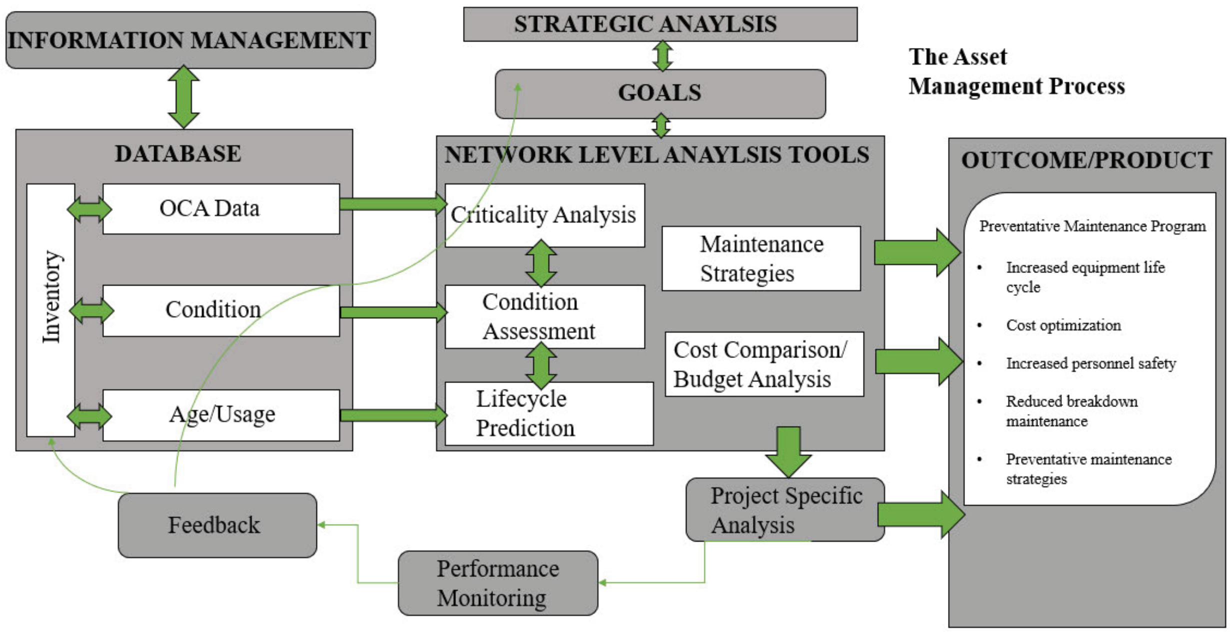

Figure 9-The Asset Management Process

The framework was designed to fit USACE electrical equipment asset management. The framework needed to include a database that directly linked into the analysis. The framework also needed to be at the network level and then be able to be used for specific projects. The performance measures were implemented at the project specific level to give feedback on the framework. For the reasons listed, the framework that was developed was based off American Association of State Highway and Transportation Officials (AASHTO) Asset Management framework. [65] AASHTOs framework best fit the needs of electrical equipment asset framework.

The framework includes a database which is developed from data from USACE, and then this data is used to assess the condition, the criticality of components and predict the lifecycle of the equipment. Also included in the network level analysis is the different maintenance strategies that were optimized by using Isograph Availability Workbench RCM Module. The cost comparison and budget analysis were also completed by using Isograph Availability Workbench RCM Module. This gave us the desired outcome, which is cost optimized preventative maintenance schedule. This framework was then tested by analyzing two separate projects and validated from the results of the project specific analysis and by evaluating the performance measures. The framework presented in this thesis is a general framework that can be potentially implemented into every project USACE-LRH has. The framework was completed step by step and tested on two separate projects for project specific analysis. The framework was tested on a dam, and a lock and dam, which are two of the main types of projects USACE operates.

In the methodology, step 1 was completed in Chapters 1-3 by researching and defining performance measures that would be evaluated in this work. The performance measures that are used are resources needed for each strategy, the life extension period of the component, and cost of each strategy. Step 2 was completed in Chapters 1-3 by researching and using the critical component list defined by USACE experts. Step 3 was completed in Chapters 1-3 by collecting data on the different electrical components. Step 4 was completed in Chapter 4 by collecting data and implementing it into the Isograph Availability Workbench RCM Module. Step 5 was completed by optimizing maintenance strategies. Step 6 was completed by optimizing maintenance groups and comparing the costs against the corrective maintenance costs.

CHAPTER 6-DISCUSSION, CONCLUSION, & RECOMENDATIONS

6.1. Discussion

This work presented the concept of asset management and designed a framework to manage the electrical assets at USACE. Performance measures were developed and evaluated. The critical components that were evaluated were presented as well as the significance of each component. The literature reviewed detailed the failure mechanisms of each component and the preventative maintenance strategies used to prevent failures. Based on the failure mechanisms of the critical components and strategies that were presented, a methodology was developed and was tested by using the data that is detailed in Chapter 3. The methodology was tested by using the Isograph Availability Workbench detailed in Chapter 4. The results in Chapter 5 validated the framework proposed in this thesis.

The limitations of this thesis were due to certain components not being investigated. The dormant Weibull function could not be implemented into the software that was used. However, the Weibull function was used instead and validates the framework presented. The framework was validated by the strategies being individually optimized, then being optimized into groups to decrease the cost of the preventative maintenance. A sensitivity analysis was performed to ensure the recommended strategies were robust. The results of the sensitivity analysis was that the same strategies were optimized, and the cost benefit ratio was similar, which validates that the framework can be used for multiple scenarios.

6.2. Conclusion

The framework presented in this work is a general framework that can be implemented into every project USACE has. The framework was completed step by step and tested on two separate projects for project specific analysis. The framework was tested on a dam and a lock and dam which are two of the main types of projects USACE operates. With the framework being tested on two separate projects and the results being the same optimized strategies, this shows that the framework is robust and can be implemented into each project and provide an effective preventive maintenance program for the electrical components. The results of the sensitivity analysis also show how the framework is robust and can be implemented into projects across Huntington district. While the dormant Weibull function could not be implemented, the Weibull function used in the failure distribution still considered how the components fail over time. To validate the framework, the Weibull function is considered sufficient. As stated previously, there is not an electrical preventative maintenance program at USACE, and by implementing a program at all USACE's projects, it would add up to significant savings. For example, if one project must replace an entire control cabinet due to there being no maintenance and that the cabinet was corroded and letting weather elements reach the internal components which failed the cabinet. This could have been prevented by a program instead of paying the cost to replace all of them at the said project.

Real word data was used in this thesis to validate the framework. The results have shown that an electrical preventative maintenance program is cost beneficial and should be implemented at USACE. The research that was performed in this work was able to help minimize expenses for the USACE by optimizing the best maintenance strategy task group and comparing the cost to what USACE is currently doing. The secondary objective was to recommend a concise readily implementable preventative maintenance procedure. The readily implementable preventive maintenance procedures are listed in Appendix B-D.

6.3. Recommendations

It is recommended that USACE should implement the framework presented in this thesis. The framework was validated through the data that was collected from USACE. It is significantly cost beneficial to implement a preventative maintenance program rather than continuing with the current “fix-as-fails”/corrective strategy. For a year the cost of preventative maintenance for a dam is $6,863.40, while the corrective labor is $36,050.79, which is not including the equipment costs for the current “fix-as-fails” strategy. For a year the cost of preventative maintenance for a lock and dam is $28,187.39, while the corrective labor is $216,374.78, which is not including the equipment costs for the current “fix-as-fails” strategy. These costs show that the preventative maintenance is more cost beneficial than the current strategy.

For continuing work, an implementation plan should be investigated. The strategies in this work can be used as a basepoint. The readily implementable preventive maintenance procedures that are listed in Appendix B-D should be entered into FEMs or a work order should be created for them. The components that were excluded could also be investigated further to see if preventative maintenance would extend the life and be cost beneficial.

The dormant Weibull function should be considered in future research as well. One problem with applying the traditional Weibull formula to locks and dams is that it does not consider durations for time when electrical components are not in use. For example, some dam gates are only operated once a month or once a year. USACE has researched how long electrical components have lasted in real world applications at the dams and identified the dormant Weibull function as a promising alternative to the traditional Weibull function. The dormant Weibull function will give a more accurate cost and failure rate for the projects USACE operates.

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[i] 2.8 Preventative Maintenance Strategies

[ii] 2.8 Preventative Maintenance Strategies

APPENDICIES

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APPENDIX A-APPROVAL LETTER

MARSHALL UNIVERSITY®

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Office of Research Integrity

October 26, 2020

Megan Bates
910 Mossman Circle
Point Pleasant, WV 25550

Dear Ms. Bates:

This letter is in response to the submitted thesis abstract entitled *"Asset Management Framework for Army Corps of Engineers Lock and Dam Electrical Equipment."* After assessing the abstract, it has been deemed not to be human subject research and therefore exempt from oversight of the Marshall University Institutional Review Board (IRB). The Code of Federal Regulations (45CFR46) has set forth the criteria utilized in making this determination. Since the information in this study does not involve human subjects as defined in the above referenced instruction, it is not considered human subject research. If there are any changes to the abstract you provided then you would need to resubmit that information to the Office of Research Integrity for review and a determination.

I appreciate your willingness to submit the abstract for determination. Please feel free to contact the Office of Research Integrity if you have any questions regarding future protocols that may require IRB review.

Sincerely,

Bruce F. Day

Bruce F. Day, ThD, CIP
Director

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APPENDIX B-MAINTENANCE STRATEGEIES OPTIMIZED FROM THESIS

B.1. <u>Cables- NFPA 70B 2016 Edition.</u>

1. The cable insulation should be visually inspected for damage.
2. The cables should also be insulation resistance tested or dc over-potential tested annually. Records should be kept so the records can be compared year to year.
3. According to USACE LRH Insulation and Resistance Testing Program, feeders should be evaluated in a pass/fail test. The minimum insulation resistance (in Megohms) for cables was determined from the following IEEE formula:

$$[(Rated\ voltage\ of\ cable\ in\ kV) + 1] * \frac{1000}{length\ of\ cable\ (ft)}$$

Equation 1-minimum insulation resistance (in Megohms)

4. If a cable reading (in Megohms) falls below the minimum resistance calculated for the specific cable, then it is suggested that the cable have failed the insulation resistance test and be replaced.

B.2. <u>Automatic Transfer Switch- NEMA Standard KS 3.</u>

1. Examine the switch for dust, dirt, soot, or moisture.
   a. If there are signs of these then the switch should be cleaned by using a lint free dry cloth, brush, or vacuum cleaner.
   b. Do not blow into the switch.
   c. The containments should be eliminated.
2. A proper enclosure should be used that is appropriate for the environment the switch is in.
3. The switch and terminators need to be examined for signs of overheating.
   a. If there are signs of overheating, then the terminal and connecting straps can be cleaned.
4. A mechanical operating test should be done to ensure the switch mechanism is operating freely.
   a. The switch should be operated ON or OFF 2-3 times.
      i. The handle should operate smoothly without binding.
      ii. If there is a mechanical trip provision the trip provision should be operated within manufactures instructions.
5. An insulation resistance test can be done to determine the adequacy of the insulation.
6. The switch must be repaired or replaced if the contacts are not open with the switch in the OFF position, the contacts are not closed with the switch in the ON position, the switch does not reset, or the mechanical trip provisions (if provided) do not trip the switch.

B.3. <u>Molded Case Circuit Breakers-NFPA 70B 2016 Edition.</u>

1. The molded case circuit breaker should be visually inspected for damage.
2. The MCCB should be kept clean of external contamination.
3. The case of the breaker should be inspected for cracks.
4. The connections should be checked for tightness and signs of overheating.

5. The circuit breaker should be operated manually to keep the contacts clean and lubrication performing properly.
    a. If there is a trip to test button, then that should also be manually operated.

B.4. <u>Motor Starters- existing industry electrical preventative maintenance program.</u>

1. The contactors in the starter panel should be inspected and cleaned.
    a. The panel should be cleaned by a smooth cloth or a very fine emery paper.
2. The entire panel should be cleaned with a wet cloth and brush should be used when hand cannot reach.
    a. A vacuum should be used to remove dust.
3. The connections should be checked.
    a. If there are any loose connections tighten by using a screwdriver.
    b. If the wires are loose, reconnect them.
4. The terminal box on the motor should be inspected for loose connections.
    a. If there are loose connections use the correct size spanner to tighten the connections.
5. The overall condition of the starter panel should be visually inspected.

B.5. <u>Traveling Nut Limit Switch-existing industry electrical preventative maintenance program.</u>

1. The roller lever should be checked for loose lever mounting screws, improper roller rotation, other problems, or damage.
2. The head should be checked to make sure the head mounting screws are tightly fastened and the exterior of the head is not damaged.
3. The cover should be checked to make sure the head mounting screws are tightly fastened and the exterior of the head is not damaged.
4. The housing should be checked for exterior damage.
    a. To address this issue, replace the limit switch.
5. The terminal box should be checked for electrical continuity, proper insulation, loose terminal screws, cracking and any corrosion.
    a. To address these items, replace the limit switch.
6. The operation of the limit switch should be checked.
    a. The over-travel should be checked, and the roller lever should be manually operated to ensure it operates smoothly.
        i. To address these, readjust the over-travel and replace the limit switch if the roller lever does not operate smoothly.

B.6. <u>Generator-existing industry electrical preventative maintenance program for generators and large motors.</u>

NOTE. According to the NFPA 70B, 20-17.5 motors should be infrared scanned annually. According to FIST Volume 3-4, 2.2 motors should be meggered annually.

1. The concrete foundation should be checked for cracks. The base should be checked for broken, lose or weakened parts.

2. The anchor bolts should be checked and tightened.
3. The base should be checked for sound absorbing adequacy.
4. The frame should be checked for cracks and loos or broken parts.
    a. Clean and repaint the frame as necessary.
    b. The frame ground connection should also be checked.
5. The laminations should be inspected for looseness and the clamping bolts should be tightened.
    a. If the laminations vibrate and cannot be stopped by tightening the clamping bolts the put varnish between the loose laminations.
    b. Check for damaged laminations at the air gap.
6. Squirrel cage rotor bars need checked for loose or broken bars or end connections.
    a. The filed circuit connections need to be checked and tighten if necessary.
    b. The voltage drop should be checked at each pole by applying alternating current at the collector rings.
7. The overall rotor resistance should be checked.
8. The air gap should be checked at the four quadrature positions and recenter the rotor if needed.
    a. If the machine is horizontal the bearings might need replaced if that bottom air gap is smaller than the top.
9. The rotor air fans should be inspected for cracks. The holding bolts should be inspected and tightened.
10. The windings should be inspected for damaged insulation, dirt, oil, and moisture.
    a. If there is dust the dust should be blown out with clean dry air pressure not exceeding 40 lbs. per square inch.
11. The exposed parts of the windings should be cleaned thoroughly with a nonflammable solvent.
12. The windings should be revarnished if the insulation is brittle, hard, or dull.
13. The insulation should be checked for separation, cracking, brittleness, or corona.
14. The wire and string banding on direct current armature windings should be checked.
15. The end-turn lashing of alternating current stator coils should be checked.
    a. If end turns vibrate excessively then apply lashing.
16. The slot wedges should be checked if they are loose, they need to be replaced.
    a. If the coils in slots are loose tighten them be rewedging.
17. The collection rings and brush operation should be checked daily.
    a. If needed wipe the collector rings. If the brushes are short, then replace them.
    b. If the collector rings have a good polish, then they should be left alone.
18. The brush spring tension and brush fit should be checked. The brush holders can be reset if not properly spaced.
19. The brush neutral position needs to be checked. If there is carbon or metallic dust, then it needs cleaned. Replace and sand in new brushes if needed.
20. The bearings should be checked daily for temperature, lubrication and oil level should be checked.
    a. The oil should be checked for dirt, sludge, and acidity.

    b. Filter or replace the oil as needed.
21. The end play should be checked on horizontal machines. If bearings are rough, then they should be replaced or refinished.
22. The bearing oil piping and cooling water piping should be inspected for leaks.
23. The shaft should be inspected for wobbling and alignment.
24. The insulated bearings insulation should be inspected.
25. The oil film resistance should be checked occasionally.
26. The keys, setscrews, and coupling bolts should be tight.
27. The flexible parts of the couplings need to be checked for wear and fatigue.
28. The belt or silent chain tension needs adjusted.
29. The grease in the gear box should be flushed out and renewed.
30. The chains, belts and gears need inspected. The alignment between driving and driven machine should be checked.
31. The bearing cooling coils, and surface air coolers should be checked for leaks.
32. The cooling water flow should be checked.
33. The external supply and piping need to be check for leaks.
34. The cooling coils should be flushed out with air and water.
    a. Then test the bearing coils for leaks by applying air pressure to coils.
    b. Look for air bubbles rising in the oil and a drop in air pressure.
35. The indicators, gauges, and relays should be checked for correct operation and sticking, dirty contacts.
36. The calibration should be checked if there is doubt.
    a. Detailed records should be kept tracking armature temperature against the generator load.
    b. If the temperature readings begin to rise over 5 degrees Centigrade for the same loading conditions, then there could be a problem and further investigation should take place.

B.7. <u>Motor Control Center-NFPA 70B Standard.</u>

NOTE: Motor control equipment should be inspected and repaired at the same time as the motors it controls.

1. Enclosures in a poor environment should be inspected for dust, dirt and corrosive conditions.
    a. If there is dust and dirt, then it should be removed with a vacuum cleaner.
    b. Enclosures that are badly corroded should be clean and refurbished or replaced.
    c. Foreign material such as dirt, debris or hardware should be removed from the outside top surfaces, so it doesn't fall into the enclosure.
2. The equipment inside the enclosure should be inspected for dust, dirt, moisture or other contaminant.
    a. If any of these are found the cause should be eliminated.

3. The ventilation passages should be checked for obstructions, if there are obstructions remove them.
    a. If a cooling or heating system is installed to maintain a safe environment, then the system need to be inspected to make sure it is working properly.
4. The bus bar and terminal connections should be inspected for tightness.
    a. If there are lose connections, they should be tightened to the manufacture's recommendations.
5. The bus bar support insulators and barriers should be inspected to make sure they are free of debris.
6. The insulators should also be checked for signs of cracking.
    a. If there is debris, it should be cleaned/removed.
7. The power and control wiring should be inspected for signs of overheating.
    a. If there are damaged conductors, they should be replaced.
8. Disconnects should be examined on the line and load side. If there is excessive debris on the disconnect, it should be cleaned.
    a. If there is mechanical operation, then the mechanical mechanisms should be operated manually to make sure they operate smoothly.
9. The thermal element should be operating correctly.
    a. If not, the cause should be identified and corrected.
10. The thermal element should be replaced if necessary.
11. Push buttons, selector switches, indicating lights, timers, and auxiliary relays are on motor starters.
    a. To inspect them check for loose connections, proper mechanical operation of operators and contact blocks.
    b. Inspection of exposed contacts, signs of overheating, and replacement of pilot lamps, if necessary.
12. If there are mechanical interlocks, they should be examined to ensure they are free to operate smoothly.
    a. If there are signs of excessive wear or deformation, then they should be replaced.

B.8. <u>Power Panelboard- Schneider Electric Switchboard preventative maintenance.</u>

1. In the electrical room the fixed part and level of support need to be inspected.
2. In the enclosure the interlocking device, cover panel, general appearance, dedusting need to be inspected.
3. If there are indicating lights or mechanical indicators they need to be inspected.
4. An inspection of heating, power connections, busbars, terminations, busbar supports, downstream power connections, the grounding of the switchgear, and cable connections should be done.
5. The switchgear needs dusted and cleaned.
6. The switchgear needs to be operated to ensure it is working correctly.
7. A visual inspection of the switchgear should be done to inspect the wearing parts, main contacts, and arcing chamber.

B.9. <u>Electric Motors-General Electric electrical preventative maintenance program.</u>

1. Included in the visual inspection should include at least the following,
    a. Check that the holding-down bolts are tight
    b. Check all visible fixings and bolts, including those holding the cover to the baseplate, the cooler to the cover (if any).
    c. Inspect the terminal cubicle, bus bar for any insulation failure due to overheating,
    d. Check for any corrosion of metal parts inside the panels, check for any dust accumulation or foreign matter,
    e. Look for leakage of oil from the bearings along the shaft,
    f. Clean around the bearing area, and if the machine has cartridge-mounted bearings, clean around the bearing insulation at the cartridge feet, and ensure all covers fitted.
2. Standard cleaning includes clean the stand-off insulators with a clean dry cloth, use a vacuum cleaner to remove dust and dirt from wiring and electrical components.
    a. Inspect cabinet air filters.
3. The filters can be vacuumed or replaced as required.
    a. After cleaning, look at the parts for pitting or signs of metal deposits, if they are pitted do not reuse parts.
4. The exterior of the motor needs cleaned as well.
    a. If there are air filters they should be replaced or cleaned and reconditioned.
    b. If the motor is open ventilated the screen should be cleaned of any buildup.

B.10. <u>Brakes- industry electrical preventative maintenance program.</u>

1. The brake condition should be checked monthly for condition of brake airline filters and lubricators.
2. The brake shoe thickness and brake ring condition need to be checked once a year.
3. The brake cylinders should be operated to check for binding and sticking.
    a. If they are sticking disassemble and repair.
4. The hydraulic lines should be checked for leaks.
5. The brake lining should be checked for wear and oil contamination.
6. The brake drums should be checked for scoring and smooth drums or uneven wear patterns.
7. The brakes need to be verified that they will hold with a loss of power.
8. The dust and dirt should be cleaned from brakes.
9. The springs should be inspected for damaged springs.

APPENDIX C-DAM STRATEGIES

C.1. OPERATIONS TASK GROUP

C.1.1. Cables- NFPA 70B 2016 Edition.

1. The cable insulation should be visually inspected for damage.
2. The cables should also be insulation resistance tested or dc over-potential tested annually. Records should be kept so the records can be compared year to year.
3. According to USACE LRH Insulation and Resistance Testing Program, feeders should be evaluated in a pass/fail test. The minimum insulation resistance (in Megohms) for cables was determined from the following IEEE formula:

$$[(Rated\ voltage\ of\ cable\ in\ kV) + 1] * \frac{1000}{length\ of\ cable\ (ft)}$$

Equation 2-minimum insulation resistance (in Megohms)

4. If a cable reading (in Megohms) falls below the minimum resistance calculated for the specific cable, then it is suggested that the cable have failed the insulation resistance test and be replaced.

C.1.2. Molded Case Circuit Breakers-NFPA 70B 2016 Edition.

1. The molded case circuit breaker should be visually inspected for damage.
2. The MCCB should be kept clean of external contamination.
3. The case of the breaker should be inspected for cracks.
4. The connections should be checked for tightness and signs of overheating.
5. The circuit breaker should be operated manually to keep the contacts clean and lubrication performing properly.
    a. If there is a trip to test button, then that should also be manually operated.

C.1.3. Generator-existing industry electrical preventative maintenance program for generators and large motors.

1. According to the NFPA 70B, 20-17.5 motors should be infrared scanned annually. According to FIST Volume 3-4, 2.2 motors should be meggered annually.
2. The concrete foundation should be checked for cracks. The base should be checked for broken, lose or weakened parts.
3. The anchor bolts should be checked and tightened.
4. The base should be checked for sound absorbing adequacy.
5. The frame should be checked for cracks and loos or broken parts.
    a. Clean and repaint the frame as necessary.
    b. The frame ground connection should also be checked.
6. The laminations should be inspected for looseness and the clamping bolts should be tightened.
    a. If the laminations vibrate and cannot be stopped by tightening the clamping bolts the put varnish between the loose laminations.
    b. Check for damaged laminations at the air gap.

7. Squirrel cage rotor bars need checked for loose or broken bars or end connections.
    a. The filed circuit connections need to be checked and tighten if necessary.
    b. The voltage drop should be checked at each pole by applying alternating current at the collector rings.
8. The overall rotor resistance should be checked.
9. The air gap should be checked at the four quadrature positions and recenter the rotor if needed.
    a. If the machine is horizontal the bearings might need replaced if that bottom air gap is smaller than the top.
10. The rotor air fans should be inspected for cracks. The holding bolts should be inspected and tightened.
11. The windings should be inspected for damaged insulation, dirt, oil, and moisture.
    a. If there is dust the dust should be blown out with clean dry air pressure not exceeding 40 lbs. per square inch.
12. The exposed parts of the windings should be cleaned thoroughly with a nonflammable solvent.
13. The windings should be revarnished if the insulation is brittle, hard, or dull.
14. The insulation should be checked for separation, cracking, brittleness, or corona.
15. The wire and string banding on direct current armature windings should be checked.
16. The end-turn lashing of alternating current stator coils should be checked.
    a. If end turns vibrate excessively then apply lashing.
17. The slot wedges should be checked if they are loose, they need to be replaced.
    a. If the coils in slots are loose tighten them be rewedging.
18. The collection rings and brush operation should be checked daily.
    a. If needed wipe the collector rings. If the brushes are short, then replace them.
    b. If the collector rings have a good polish, then they should be left alone.
19. The brush spring tension and brush fit should be checked. The brush holders can be reset if not properly spaced.
20. The brush neutral position needs to be checked. If there is carbon or metallic dust, then it needs cleaned. Replace and sand in new brushes if needed.
21. The bearings should be checked daily for temperature, lubrication and oil level should be checked.
    a. The oil should be checked for dirt, sludge, and acidity.
    b. Filter or replace the oil as needed.
22. The end play should be checked on horizontal machines. If bearings are rough, then they should be replaced or refinished.
23. The bearing oil piping and cooling water piping should be inspected for leaks.
24. The shaft should be inspected for wobbling and alignment.
25. The insulated bearings insulation should be inspected.
26. The oil film resistance should be checked occasionally.
27. The keys, setscrews, and coupling bolts should be tight.
28. The flexible parts of the couplings need to be checked for wear and fatigue.
29. The belt or silent chain tension needs adjusted.

30. The grease in the gear box should be flushed out and renewed.
31. The chains, belts and gears need inspected. The alignment between driving and driven machine should be checked.
32. The bearing cooling coils, and surface air coolers should be checked for leaks.
33. The cooling water flow should be checked.
34. The external supply and piping need to be check for leaks.
35. The cooling coils should be flushed out with air and water.
    a. Then test the bearing coils for leaks by applying air pressure to coils.
    b. Look for air bubbles rising in the oil and a drop in air pressure.
36. The indicators, gauges, and relays should be checked for correct operation and sticking, dirty contacts.
37. The calibration should be checked if there is doubt.
    a. Detailed records should be kept tracking armature temperature against the generator load.
    b. If the temperature readings begin to rise over 5 degrees Centigrade for the same loading conditions, then there could be a problem and further investigation should take place.

C.2. SPILLWAY TASK GROUP

C.2.1. Cables- NFPA 70B 2016 Edition.

1. The cable insulation should be visually inspected for damage.
2. The cables should also be insulation resistance tested or dc over-potential tested annually. Records should be kept so the records can be compared year to year.
3. According to USACE LRH Insulation and Resistance Testing Program, feeders should be evaluated in a pass/fail test. The minimum insulation resistance (in Megohms) for cables was determined from the following IEEE formula:

$$[(Rated\ voltage\ of\ cable\ in\ kV) + 1] * \frac{1000}{length\ of\ cable\ (ft)}$$

Equation 3-minimum insulation resistance (in Megohms)

4. If a cable reading (in Megohms) falls below the minimum resistance calculated for the specific cable, then it is suggested that the cable have failed the insulation resistance test and be replaced.

C.2.2. Molded Case Circuit Breakers-NFPA 70B 2016 Edition.

6. The molded case circuit breaker should be visually inspected for damage.
7. The MCCB should be kept clean of external contamination.
8. The case of the breaker should be inspected for cracks.

9. The connections should be checked for tightness and signs of overheating.
10. The circuit breaker should be operated manually to keep the contacts clean and lubrication performing properly.
    a. If there is a trip to test button, then that should also be manually operated.

C.2.3. <u>Motor Starters- existing industry electrical preventative maintenance program.</u>

1. The contactors in the starter panel should be inspected and cleaned.
    a. The panel should be cleaned by a smooth cloth or a very fine emery paper.
2. The entire panel should be cleaned with a wet cloth and brush should be used when hand cannot reach.
    a. A vacuum should be used to remove dust.
3. The connections should be checked.
    a. If there are any loose connections tighten by using a screwdriver.
    b. If the wires are loose, reconnect them.
4. The terminal box on the motor should be inspected for loose connections.
    a. If there are loose connections use the correct size spanner to tighten the connections.
5. The overall condition of the starter panel should be visually inspected.

C.2.4. <u>Traveling Nut Limit Switch-existing industry electrical preventative maintenance program.</u>

1. The roller lever should be checked for loose lever mounting screws, improper roller rotation, other problems or damage.
2. The head should be checked to make sure the head mounting screws are tightly fastened and the exterior of the head is not damaged.
3. The cover should be checked to make sure the head mounting screws are tightly fastened and the exterior of the head is not damaged.
4. The housing should be checked for exterior damage.
    a. To address this issue, replace the limit switch.
5. The terminal box should be checked for electrical continuity, proper insulation, loose terminal screws, cracking and any corrosion.
    a. To address these items, replace the limit switch.
6. The operation of the limit switch should be checked.
    a. The over-travel should be checked, and the roller lever should be manually operated to ensure it operates smoothly.
        i. To address these, readjust the over-travel and replace the limit switch if the roller lever does not operate smoothly.

C.2.5. <u>Brakes- industry electrical preventative maintenance program.</u>

1. The brake condition should be checked monthly for condition of brake airline filters and lubricators.
2. The brake shoe thickness and brake ring condition need to be checked once a year.
3. The brake cylinders should be operated to check for binding and sticking.
    a. If they are sticking disassemble and repair.
4. The hydraulic lines should be checked for leaks.
5. The brake lining should be checked for wear and oil contamination.
6. The brake drums should be checked for scoring and smooth drums or uneven wear patterns.
7. The brakes need to be verified that they will hold with a loss of power.
8. The dust and dirt should be cleaned from brakes.
9. The springs should be inspected for damaged springs.

C.2.6. <u>Electric Motors-General Electric electrical preventative maintenance program.</u>

1. Included in the visual inspection should include at least the following,
    a. Check that the holding-down bolts are tight
    b. Check all visible fixings and bolts, including those holding the cover to the baseplate, the cooler to the cover (if any).
    c. Inspect the terminal cubicle, bus bar for any insulation failure due to overheating,
    d. Check for any corrosion of metal parts inside the panels, check for any dust accumulation or foreign matter,
    e. Look for leakage of oil from the bearings along the shaft,
    f. Clean around the bearing area, and if the machine has cartridge-mounted bearings, clean around the bearing insulation at the cartridge feet, and ensure all covers fitted.
2. Standard cleaning includes clean the stand-off insulators with a clean dry cloth, use a vacuum cleaner to remove dust and dirt from wiring and electrical components.
    a. Inspect cabinet air filters.
3. The filters can be vacuumed or replaced as required.
    a. After cleaning, look at the parts for pitting or signs of metal deposits, if they are pitted do not reuse parts.
4. The exterior of the motor needs cleaned as well.
    a. If there are air filters they should be replaced or cleaned and reconditioned.
    b. If the motor is open ventilated the screen should be cleaned of any buildup.
    c. If the motor is open ventilated the screen should be cleaned of any buildup.

C.3. INTAKE TASK GROUP

C.3.1. Cables- NFPA 70B 2016 Edition.

1. The cable insulation should be visually inspected for damage.
2. The cables should also be insulation resistance tested or dc over-potential tested annually. Records should be kept so the records can be compared year to year.
3. According to USACE LRH Insulation and Resistance Testing Program, feeders should be evaluated in a pass/fail test. The minimum insulation resistance (in Megohms) for cables was determined from the following IEEE formula:

$$[(Rated\ voltage\ of\ cable\ in\ kV) + 1] * \frac{1000}{length\ of\ cable\ (ft)}$$

Equation 4-minimum insulation resistance (in Megohms)

4. If a cable reading (in Megohms) falls below the minimum resistance calculated for the specific cable, then it is suggested that the cable have failed the insulation resistance test and be replaced.

C.3.2. Molded Case Circuit Breakers-NFPA 70B 2016 Edition.

11. The molded case circuit breaker should be visually inspected for damage.
12. The MCCB should be kept clean of external contamination.
13. The case of the breaker should be inspected for cracks.
14. The connections should be checked for tightness and signs of overheating.
15. The circuit breaker should be operated manually to keep the contacts clean and lubrication performing properly.
    a. If there is a trip to test button, then that should also be manually operated.

C.3.3. Motor Control Center-NFPA 70B Standard.

NOTE: Motor control equipment should be inspected and repaired at the same time as the motors it controls.

1. Enclosures in a poor environment should be inspected for dust, dirt and corrosive conditions.
    a. If there is dust and dirt, then it should be removed with a vacuum cleaner.
    b. Enclosures that are badly corroded should be clean and refurbished or replaced.
    c. Foreign material such as dirt, debris or hardware should be removed from the outside top surfaces, so it doesn't fall into the enclosure.
2. The equipment inside the enclosure should be inspected for dust, dirt, moisture or other contaminant.
    a. If any of these are found the cause should be eliminated.
3. The ventilation passages should be checked for obstructions

    a. If there are obstructions remove them.
    b. If a cooling or heating system is installed to maintain a safe environment, then the system need to be inspected to make sure it is working properly.
4. The bus bar and terminal connections should be inspected for tightness.
    a. If there are lose connections, they should be tightened to the manufacture's recommendations.
5. The bus bar support insulators and barriers should be inspected to make sure they are free of debris.
6. The insulators should also be checked for signs of cracking.
    a. If there is debris, it should be cleaned/removed.
7. The power and control wiring should be inspected for signs of overheating.
    a. If there are damaged conductors, they should be replaced.
8. Disconnects should be examined on the line and load side. If there is excessive debris on the disconnect, it should be cleaned.
    a. If there is mechanical operation, then the mechanical mechanisms should be operated manually to make sure they operate smoothly.
9. The thermal element should be operating correctly.
    a. If not, the cause should be identified and corrected.
10. The thermal element should be replaced if necessary.
11. Push buttons, selector switches, indicating lights, timers, and auxiliary relays are on motor starters.
    a. To inspect them check for loose connections, proper mechanical operation of operators and contact blocks.
    b. Inspection of exposed contacts, signs of overheating, and replacement of pilot lamps, if necessary.
12. If there are mechanical interlocks, they should be examined to ensure they are free to operate smoothly.
    a. If there are signs of excessive wear or deformation, then they should be replaced.

APPENDIX D-LOCK AND DAM STRATEGIES

D.1. <u>OPERATIONS TASK GROUP</u>

D.1.1. <u>Cables- NFPA 70B 2016 Edition.</u>

1. The cable insulation should be visually inspected for damage.
2. The cables should also be insulation resistance tested or dc over-potential tested annually. Records should be kept so the records can be compared year to year.
3. According to USACE LRH Insulation and Resistance Testing Program, feeders should be evaluated in a pass/fail test. The minimum insulation resistance (in Megohms) for cables was determined from the following IEEE formula:

$$[(Rated\ voltage\ of\ cable\ in\ kV) + 1] * \frac{1000}{length\ of\ cable\ (ft)}$$

Equation 5-minimum insulation resistance (in Megohms)

4. If a cable reading (in Megohms) falls below the minimum resistance calculated for the specific cable, then it is suggested that the cable have failed the insulation resistance test and be replaced.

D.1.2. <u>Automatic Transfer Switch- NEMA Standard KS 3.</u>

1. Examine the switch for dust, dirt, soot, or moisture.
    a. If there are signs of these then the switch should be cleaned by using a lint free dry cloth, brush, or vacuum cleaner.
    b. Do not blow into the switch.
    c. The containments should be eliminated.
2. A proper enclosure should be used that is appropriate for the environment the switch is in.
3. The switch and terminators need to be examined for signs of overheating.
    a. If there are signs of overheating, then the terminal and connecting straps can be cleaned.
4. A mechanical operating test should be done to ensure the switch mechanism is operating freely.
    a. The switch should be operated ON or OFF 2-3 times.
        i. The handle should operate smoothly without binding.
        ii. If there is a mechanical trip provision the trip provision should be operated within manufactures instructions.
5. An insulation resistance test can be done to determine the adequacy of the insulation.
6. The switch must be repaired or replaced if the contacts are not open with the switch in the OFF position, the contacts are not closed with the switch in the ON position, the switch does not reset, or the mechanical trip provisions (if provided) do not trip the switch.

D.1.3. Molded Case Circuit Breakers-NFPA 70B 2016 Edition.

1. The molded case circuit breaker should be visually inspected for damage.
2. The MCCB should be kept clean of external contamination.
3. The case of the breaker should be inspected for cracks.
4. The connections should be checked for tightness and signs of overheating.
5. The circuit breaker should be operated manually to keep the contacts clean and lubrication performing properly.
    a. If there is a trip to test button, then that should also be manually operated.

D.1.4. Motor Control Center-NFPA 70B Standard.

NOTE: Motor control equipment should be inspected and repaired at the same time as the motors it controls.

1. Enclosures in a poor environment should be inspected for dust, dirt and corrosive conditions.
    a. If there is dust and dirt, then it should be removed with a vacuum cleaner.
    b. Enclosures that are badly corroded should be clean and refurbished or replaced.
    c. Foreign material such as dirt, debris or hardware should be removed from the outside top surfaces, so it doesn't fall into the enclosure.
2. The equipment inside the enclosure should be inspected for dust, dirt, moisture or other contaminant.
    a. If any of these are found the cause should be eliminated.
3. The ventilation passages should be checked for obstructions
    a. If there are obstructions remove them.
    b. If a cooling or heating system is installed to maintain a safe environment, then the system need to be inspected to make sure it is working properly.
4. The bus bar and terminal connections should be inspected for tightness.
    a. If there are lose connections, they should be tightened to the manufacture's recommendations.
5. The bus bar support insulators and barriers should be inspected to make sure they are free of debris.
6. The insulators should also be checked for signs of cracking.
    a. If there is debris, it should be cleaned/removed.
7. The power and control wiring should be inspected for signs of overheating.
    a. If there are damaged conductors, they should be replaced.
8. Disconnects should be examined on the line and load side. If there is excessive debris on the disconnect, it should be cleaned.
    a. If there is mechanical operation, then the mechanical mechanisms should be operated manually to make sure they operate smoothly.
9. The thermal element should be operating correctly.
    a. If not, the cause should be identified and corrected.
10. The thermal element should be replaced if necessary.

11. Push buttons, selector switches, indicating lights, timers, and auxiliary relays are on motor starters.
    a. To inspect them check for loose connections, proper mechanical operation of operators and contact blocks.
    b. Inspection of exposed contacts, signs of overheating, and replacement of pilot lamps, if necessary.
12. If there are mechanical interlocks, they should be examined to ensure they are free to operate smoothly.
    a. If there are signs of excessive wear or deformation, then they should be replaced.

D.2. <u>LOCK TASK GROUP</u>

D.2.1. <u>Cables- NFPA 70B 2016 Edition.</u>

1. The cable insulation should be visually inspected for damage.
2. The cables should also be insulation resistance tested or dc over-potential tested annually. Records should be kept so the records can be compared year to year.
3. According to USACE LRH Insulation and Resistance Testing Program, feeders should be evaluated in a pass/fail test. The minimum insulation resistance (in Megohms) for cables was determined from the following IEEE formula:

$$[(Rated\ voltage\ of\ cable\ in\ kV) + 1] * \frac{1000}{length\ of\ cable\ (ft)}$$

Equation 6-minimum insulation resistance (in Megohms)

4. If a cable reading (in Megohms) falls below the minimum resistance calculated for the specific cable, then it is suggested that the cable have failed the insulation resistance test and be replaced.

D.2.2. <u>Molded Case Circuit Breakers-NFPA 70B 2016 Edition.</u>

1. The molded case circuit breaker should be visually inspected for damage.
2. The MCCB should be kept clean of external contamination.
3. The case of the breaker should be inspected for cracks.
4. The connections should be checked for tightness and signs of overheating.
5. The circuit breaker should be operated manually to keep the contacts clean and lubrication performing properly.
    a. If there is a trip to test button, then that should also be manually operated.

D.2.3. <u>Power Panelboard- Schneider Electric Switchboard preventative maintenance.</u>

1. In the electrical room the fixed part and level of support need to be inspected.
2. In the enclosure the interlocking device, cover panel, general appearance, dedusting need to be inspected.
3. If there are indicating lights or mechanical indicators they need to be inspected.

4. An inspection of heating, power connections, busbars, terminations, busbar supports, downstream power connections, the grounding of the switchgear, and cable connections should be done.
5. The switchgear needs dusted and cleaned.
6. The switchgear needs to be operated to ensure it is working correctly.
7. A visual inspection of the switchgear should be done to inspect the wearing parts, main contacts, and arcing chamber.

D.3. <u>DAM TASK GROUP</u>

D.3.1. <u>Cables- NFPA 70B 2016 Edition.</u>

1. The cable insulation should be visually inspected for damage.
2. The cables should also be insulation resistance tested or dc over-potential tested annually. Records should be kept so the records can be compared year to year.
3. According to USACE LRH Insulation and Resistance Testing Program, feeders should be evaluated in a pass/fail test. The minimum insulation resistance (in Megohms) for cables was determined from the following IEEE formula:

$$[(Rated\ voltage\ of\ cable\ in\ kV) + 1] * \frac{1000}{length\ of\ cable\ (ft)}$$

Equation 7-minimum insulation resistance (in Megohms)

4. If a cable reading (in Megohms) falls below the minimum resistance calculated for the specific cable, then it is suggested that the cable have failed the insulation resistance test and be replaced.

D.3.2. <u>Traveling Nut Limit Switch-existing industry electrical preventative maintenance program.</u>

1. The roller lever should be checked for loose lever mounting screws, improper roller rotation, other problems or damage.
2. The head should be checked to make sure the head mounting screws are tightly fastened and the exterior of the head is not damaged.
3. The cover should be checked to make sure the head mounting screws are tightly fastened and the exterior of the head is not damaged.
4. The housing should be checked for exterior damage.
    a. To address this issue, replace the limit switch.
5. The terminal box should be checked for electrical continuity, proper insulation, loose terminal screws, cracking and any corrosion.
    a. To address these items, replace the limit switch.
6. The operation of the limit switch should be checked.
    a. The over-travel should be checked, and the roller lever should be manually operated to ensure it operates smoothly.

i. To address these, readjust the over-travel and replace the limit switch if the roller lever does not operate smoothly.

D.3.3. Brakes- industry electrical preventative maintenance program.

1. The brake condition should be checked monthly for condition of brake airline filters and lubricators.
2. The brake shoe thickness and brake ring condition need to be checked once a year.
3. The brake cylinders should be operated to check for binding and sticking.
    a. If they are sticking disassemble and repair.
4. The hydraulic lines should be checked for leaks.
5. The brake lining should be checked for wear and oil contamination.
6. The brake drums should be checked for scoring and smooth drums or uneven wear patterns.
7. The brakes need to be verified that they will hold with a loss of power.
8. The dust and dirt should be cleaned from brakes.
9. The springs should be inspected for damaged springs.

D.3.4. Power Panelboard- Schneider Electric Switchboard preventative maintenance.

1. In the electrical room the fixed part and level of support need to be inspected.
2. In the enclosure the interlocking device, cover panel, general appearance, dedusting need to be inspected.
3. If there are indicating lights or mechanical indicators they need to be inspected.
4. An inspection of heating, power connections, busbars, terminations, busbar supports, downstream power connections, the grounding of the switchgear, and cable connections should be done.
5. The switchgear needs dusted and cleaned.
6. The switchgear needs to be operated to ensure it is working correctly.
7. A visual inspection of the switchgear should be done to inspect the wearing parts, main contacts, and arcing chamber.

D.3.5. Motor Starters- existing industry electrical preventative maintenance program.

1. The contactors in the starter panel should be inspected and cleaned.
    a. The panel should be cleaned by a smooth cloth or a very fine emery paper.
2. The entire panel should be cleaned with a wet cloth and brush should be used when hand cannot reach.
    a. A vacuum should be used to remove dust.
3. The connections should be checked.
    a. If there are any loose connections tighten by using a screwdriver.
    b. If the wires are loose, reconnect them.
4. The terminal box on the motor should be inspected for loose connections.
    a. If there are loose connections use the correct size spanner to tighten the connections.

5. The overall condition of the starter panel should be visually inspected.

D.3.6. <u>Electric Motors-General Electric electrical preventative maintenance program.</u>

1. Included in the visual inspection should include at least the following,
    a. Check that the holding-down bolts are tight
    b. Check all visible fixings and bolts, including those holding the cover to the baseplate, the cooler to the cover (if any).
    c. Inspect the terminal cubicle, bus bar for any insulation failure due to overheating,
    d. Check for any corrosion of metal parts inside the panels, check for any dust accumulation or foreign matter,
    e. Look for leakage of oil from the bearings along the shaft,
    f. Clean around the bearing area, and if the machine has cartridge-mounted bearings, clean around the bearing insulation at the cartridge feet, and ensure all covers fitted.
2. Standard cleaning includes clean the stand-off insulators with a clean dry cloth, use a vacuum cleaner to remove dust and dirt from wiring and electrical components.
    a. Inspect cabinet air filters.
3. The filters can be vacuumed or replaced as required.
    a. After cleaning, look at the parts for pitting or signs of metal deposits, if they are pitted do not reuse parts.
4. The exterior of the motor needs cleaned as well.
    a. If there are air filters they should be replaced or cleaned and reconditioned.
    b. If the motor is open ventilated the screen should be cleaned of any buildup.

APPENDIX E-REDACTED CONTENT

This work contains redacted content. The content is redacted to protect the nation's critical infrastructure (lock and dams, and dams). The content that was redacted does not compromise the information contained in this thesis.