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Improved Reliability Models for Mechanical and Electrical Components at Navigation Lock and Dam and Flood Risk Management Facilities

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Final Report

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Abstract

This work developed the use of Expert-Opinion Elicitation (EOE) to help estimate the characteristic life (CL) of mechanical and electrical (ME) components at US Army Corps of Engineers (USACE) navigation projects. This effort developed improved reliability models for the ME components at the USACE navigation facilities. Current USACE ME reliability methods use generic component failure rate data from US Department of Defense (DoD) Military Standard (MIL-STD) 756B, in which failure rate data is processed for components that function in operating environments, failure modes, and maintenance practices different from those at USACE navigation and flood risk management projects. The reliability of the ME system from this data set yields very conservative results, very often overestimating the time-dependent reliability of the entire ME system. EOE will be used to define the CL for a list of critical ME components at USACE navigation and flood risk management projects. These elicited values for CL will form the basis for failure rates to be used with the existing methods for ME system reliability calculations. Additional work on fault trees for ME systems is being completed as part of dam safety and levee risk assessment procedures development.

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Preface

This study was conducted for the US Army Corps of Engineers (USACE) Navigation Systems Research Program and the Reliability Models for Major Rehabilitation Program from Fiscal Year 2006 (FY06) through FY08. The technical monitor was Daniel Casapulla, Headquarters, US Army Corps of Engineers (HQUSACE).

The work was performed by the Geotechnical Section of the Geotechnical/ Water Resources Branch of Engineering and Planning, New England District. At the time the work was done, Anthony Firicano was Chief of the Geotechnical Section and Dr. Raimo Liias was Chief of the Geotechnical/Water Resources Branch. At the time of publication, Jeff Lillycrop was the Technical Director for Navigation.

At the time of publication, COL Kevin Wilson was the Commander and Executive Director of the Engineer Research and Development Center (ERDC), and Dr. Jeffery P. Holland was the Director.

1 Introduction

1.1 Background

The current USACE mechanical and electrical (ME) reliability methods use generic component failure rate data from US Department of Defense Military Standard 756B (DoD MIL-STD-756B) documents. This failure rate data is typically processed for components that function in a different operating environment, different failure modes, and different maintenance practices than at USACE navigation projects. Therefore, the reliability of the ME system from this data set yields very conservative results and very often overestimates the time-dependent reliability of the entire ME system.

This work was undertaken to develop improved reliability models for the ME) components at the US Army Corps of Engineers (USACE) navigation facilities. While efforts are underway to begin collecting such failure rate data from USACE projects, a functional failure rate data set to use in reliability calculations is at least 10 years away. As part of this research effort to assist with improving the existing reliability models, Expert-Opinion Elicitation (EOE) will be used to define the characteristic life (CL) for a list of critical ME components at USACE navigation projects. These elicited values for CL will be the basis for failure rates to be used with the existing methods for ME system reliability calculations. Additional work on fault trees for ME systems (Patev, Putcha, and Foltz 2005) is being completed as part of dam safety and levee risk assessment procedures development.

1.2 EOE

The EOE process is a formal (defined format), heuristic (verbal) process of obtaining information or answers to specific questions. These questions are defined in terms of “issues.” These issues can assist in defining such items as cumulative failure rates, event timing, and percentage for event/fault trees. Ayyub, Blair, and Patev (2000) outline EOE as a process. This process should not really be used in lieu of failure statistics, but should be used where failure statistics are unavailable or too costly to collect. EOE should be performed during a face-to-face meeting of members of an expert panel that is developed specifically for the issues under consideration. The EOE should be conducted after informing the experts of the background information, objectives, list of issues, and anticipated outcome. Ayyub, Blair, and Patev (2000) describe the different components of the EOE process.

1.3 Recent USACE EOE studies

EOE is a technique that uses a panel of individuals with various areas of specialized knowledge for estimating parameters or addressing issues of interest based on their expertise. EOE has been recently applied by the Vicksburg District's study of three different construction alternatives for Lindy C. Boggs Lock and Dam (Ayyub, Blair, and Patev 2002) by the Pittsburgh District for concrete deterioration problems at Emsworth Lock and Dam and by Nashville District for Chickamauga Lock and Dam to determine hazard rates for the cost and closure matrices. Other recent uses of EOE by the USACE include those areas of dam safety, flood damages, and navigation system wide studies such as Ohio River Main Stem Study (ORMSS) and the Great Lakes and St. Lawrence Seaway System Study (GLSLS).

1.4 Characteristic life (CL) of ME components

Abernethy (2009) defines the CL is defined as the age at which 63.2% of the units will have failed, sometimes called the B63.2 life. Assuming that this relationship assumes an exponential distribution (Weibull distribution with $\beta = 1$), the Cumulative Distribution Function (CDF) can be shown mathematically as:

$$F(t) = 1 - e^{-(t/\alpha)\beta} = 1 - (1/e) = 0.632$$

where β is a shape factor and α is the CL.

Figure 1 shows a typical data plot of the slope and Mean Time To Failure (MTTF).

Abernethy (2009) defines the slope of the Weibull plot or beta, (β), which determines the member of the family of Weibull failure distributions that best fits or describes the data. The slope, β, also indicates the class of failure that is present, in which:

$\beta < 1.0$ indicates infant mortality
$\beta = 1.0$ means random failures (independent of age)
$\beta > 1.0$ indicates wear out failures.

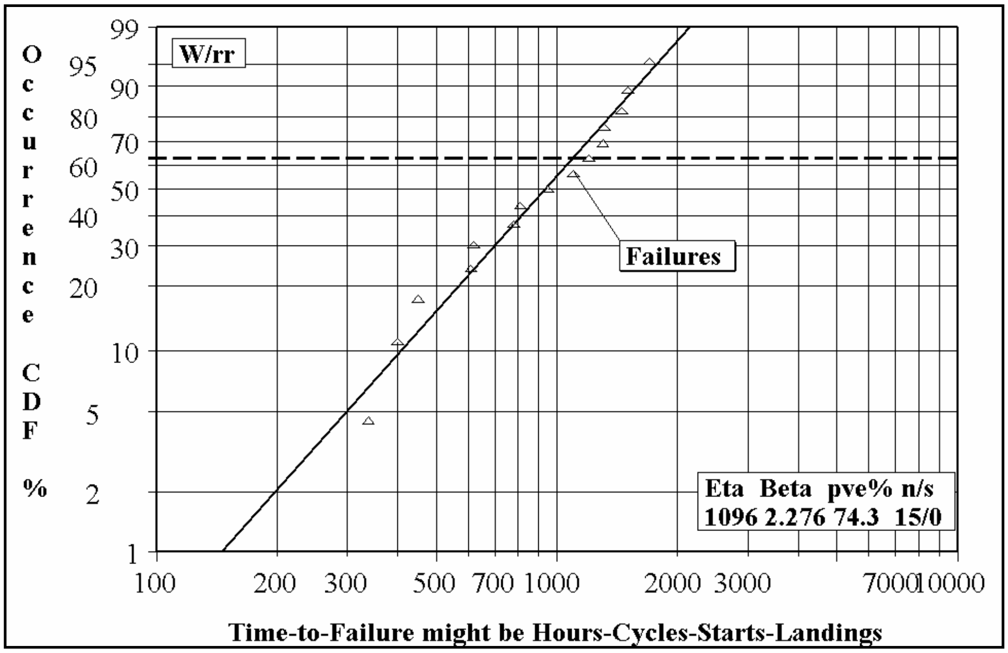

Figure 1. Typical Weibull data plot (Abernethy 2009).

The CL of an ME component is directly related to the MTTF and the failure rate, λ. This relationship is derived as:

$$\text{MTTF} = 1 / \lambda$$
$$\alpha = \text{MTTF}.$$

Note that the relationship between the CL and MTTF is dependent on β. The relationship is dependent on the value of β, in which:

$$\beta = 1, \text{MTTF} = \alpha$$
$$\beta > 1, \text{MTF} < \alpha$$
$$\beta < 1, \text{MTTF} > \alpha$$
$$\beta = 0.5, \text{MTTF} = 2\,(\alpha).$$

Typically, CL is based on such assumptions as:

- The components have similar maintenance practices.
- There is no replacement of smaller internal parts.
- Environmental and operating conditions are consistent or protected.
- All components are composed of materials that were properly selected and designed.

Note that there is uncertainty in defining consistent or proper maintenance and environment. There are no consistent operating conditions within USACE, as loading cycles vary from less than one per year for a dam to more than 10 per day for a lock. This is one of the complications discussed further in Section 1.6.

1.5 Objectives and scope of EOE for CL of ME components

This analysis uses EOE to obtain information relating to the CL of critical components at USACE navigation facilities. The information obtained from this EOE is not readily available in the literature. MIL-STDs are based on failure rates and assume a CL based on a defined Weibull distribution. These data standards are not valid for USACE ME equipment since they typically underestimate (i.e., estimate earlier failures) the CL. Also, failure rate data may be available from some ME equipment manufacturers, but this failure rate data is often proprietary and not available to the USACE.

The overall objective and results from this study are to define CL values for use in future ME reliability modeling of USACE navigation projects. A list of critical components will be defined to pinpoint those pieces of ME equipment that create significant economic consequences such as navigation delays, lock shutdowns, and lock closures. These values for CL will be elicited by bringing together a team of USACE ME experts from around the nation. The use of nationwide ME experts will permit the inclusion of a wide range of experience and operation of these critical components. Chapter 2 discusses the selection of the experts.

1.6 Estimating CL

As mentioned previously, the CL is dependent on consistent or proper maintenance, environment, and operating conditions. These factors are not uniform across USACE. Maintenance profiles vary significantly. Environment may include any combination of heat, cold, ice, ultraviolet (UV) light, saltwater, oxygenated water or protection from all such extremes. Operating conditions range from frequent use each day for a navigation lock, to use less than once per year for a flood control dam; the loading during use will also vary. Other non-uniform physical properties include design, water head, and component size. These are only a small portion of the parameters that make it a challenge to estimate an average CL for a particular project. Table 1 lists some factors that may be used to adjust the CL.

Table 1. Factors affecting estimation of CL.

Type	Factor
Environmental	Temperature (heat and cold)
	Humidity (high or low)
	Wind
	Frequency of wetting
	Ice
	UV
	Oxygenated water
	Protected from environment
	Climate controlled environment
Operational	Quality of lubrication
	Quality of paint protection
	Frequency of load cycles
	Load history versus design loads
	Variation in dominate failure mode across inventory
	Era of component manufacture

The experts elicited in this study represented a wide range of USACE ME equipment throughout the entire United States. Their consensus was based on their knowledge and experience representing their operating, environment, and maintenance practices. The experts agreed that using the "k-factors" adjustments defined in Engineer Circular (EC) 1110-2-6062 (HQUSACE 2011) and in Military Standards (MIL-STDs) would be sufficient to refine each of the CL for their equipment. This technique has been successfully adopted in the USACE practice and provides reasonable and quantifiable results. Therefore, when experts apply past experience of component maintenance, environment, and operating conditions to estimate CL, they need to consider how each parameter or property varies from normal and how that might have lead to an earlier or later failure than the estimated CL.

1.7 Selection of critical ME components for navigation projects

The list of critical component was complied and screened by the facilitator and four ME engineers from Pittsburgh District, Rock Island District, and Headquarters prior to the EOE. One of the primary criteria for screening the ME components was the number of hours of navigation delay it would take to temporarily repair or replace the component. The components were screened based on a minimum of 4 hours of navigation delay to repair or replace the component. This value was based on the availability of the failed component (most are not at lock site) and the availability of District staff to inspect and repair the component.

The final list of critical components was sent to the panel of experts as part of the read-ahead package prior to the elicitation. This was to gain their inputs and agreements to the list of components that would be elicited during the EOE. In the read-ahead package sent to the experts, the panel was only informed of the issues and not given any of the questions that would be elicited. The list was reviewed again as the part of startup to the EOE to ensure that no questions or issues lingered with any of the components that were screened.

This list of components was broken into disciplines (i.e., mechanical and electrical [ME]) and by subcategories as well. The list of the mechanical components was broken into the following categories: mechanical drive systems (Table 2), hydraulic drive systems (Table 3), miscellaneous gate-valve systems, and other systems.

The list of electrical components was broken into the following categories: Power (Table 4), Motor Control, Sensors and Switches, and electromechanical (EM) Control.

Table 2. Mechanical drive systems component list.

Type	Component
Bearings	
	Rolling element
	Sleeve (self lubricated)
	Bronze sleeve
Couplings	
	Flexible
Shafts	Rigid
Pins	
Gear reducers	
	Worm
	Parallel
	Right angle
Open gearing	

Type	Component
	Spur
	Helical
	Bevel
	Rack
Brake	Electromechanical
Clutch	Slip
Wire ropes	
	Spiral plate
	Single/multiple sheave(s)
	Single Drum
	Round
	Flat
Wire rope drums	
Wire rope sheaves	
Chains	Roller
	Link
Chain sprocket	
Miter gates	
	Sector arms
	Strut arms - buffered
	Strut arms - rigid
	Support roller
	Rack support beam
Valves	
	Bellcranks
	Crosshead/guide
	Strut
	Butterfly
	Ball
	Slide
	Knife
	Jet

Table 3. Hydraulic drive systems component list.

Type	Component
Vertical Lift	
Control Valves	
	Check
	Relief
	Directional
	Manual
	Solenoid
	Proportional/throttle
Pumps	
	Fixed
	Variable
Hydraulic Motors	
	Fixed
	Variable
Piping	
Hose	
Misc Gate/Filling Emptying Valves	
Wheel assembly	
Pintles/bushings	
Gudgeon pin/bushings	
Trunnion pin/bushings	
Strut spindle pin	
Other Systems	
Tow haulage	
	Hydraulic
	Mechanical
Emptying filling	
	Butterfly
	Vertical lift
Gate connection (pins, cable, chain)	
Grease/lube system	
Actuators (screw type, limit torque)	

Table 4. Power.

Type	Component
Power	
Power utility	
Power receptacle	
Service transformer	
Transfer switches	
	Automatic
	Manual
Switchgear	
Circuit breakers	
Power panelboard	
Cables	
	Buried/submerged
	Duct/cable tray
	Portable/flexible
	Twisted
	Coax
	Fiber optic
Bus duct (electronic	
Switchboards	
Motor control centers	
Motor Control	
Motor starters	
	Full voltage
	Reduced/variable
	Variable Frequency Drive (VFD)
Programmable Logic Controller (PLC) systems	
Sensors and Switches	
Selsyn motor	
Traveling nut limit switch	
Rotating cam	
Encoder resolver	
Hydraulic cylinder position sensor	
Rotating limit switches	
Proximity switch (mag/photo)	
Mechanical proximity plunger switch	
Linear displacement transducer	
Pressure switch (hydraulic systems)	

Type	Component
Water level transducer (all types)	
Inclinometer	
Relay-based control panel	
Supervisory Control And Data Acquisition (SCADA)	
Electromechanical Drives	
Electric motors (new and rebuilt)	
Standby generator sets	
DC rectifier (brakes)	

2 Selection of Experts

2.1 Requirements

The size of the expert panel should be large enough to achieve a needed diversity of opinion and credibility that will lead to resultant CL with minimal bias and robustness. Depending on the topics of interest, it is recommended to have five to seven paneled experts for this type of study and analysis. This EOE will have six experts for each discipline, mechanical and electrical. A nomination process was first used to establish a list of candidates who could contribute best to the elicitation. From this list, formal nominations and a selection process was established to define the candidates with the best background that closely fit the topics at hand. The panel members were defined based on a comprehensive combined knowledge of:

- design of ME system for navigation structures
- construction of ME systems for navigation structures
- operating and maintenance of ME systems navigation structures
- knowledge of state-of-the-art mechanical/electrical equipment used at USACE and external navigation projects
- knowledge and experience with reliability calculations.

Observers also need to be invited to participate in the elicitation process. The observers can contribute to the discussion, but not to the expert judgment and results. The observers can include:

- One or two observers from the USACE offices with detailed experience and knowledge of ME systems for navigation projects including planned construction, and operations and maintenance.
- One or two people with expertise in probabilistic analysis, probabilistic computations, consequence computations and assessment, and expert elicitation. This observer can be the technical facilitator or the technical integrator and facilitator.

2.2 Lists of experts

Tables 5–8 list and give brief biographical statements for all identified experts.

Table 5. The expert panel.

Name	Affiliation
Jim Hay, P.E.	Operations Division, McNairy Lock and Dam, Walla Walla District USACE
Ross Woodbury, P.E.	Operations Division, Louisville District, USACE
David Buccini	Mechanical Engineer, Mechanical/Electrical Section, Pittsburgh District, USACE
Bryan Radkte, P.E.	Electrical Engineer, Mechanical/Electrical Section, Rock Island District, USACE
John Nites, P.E.	Electrical Engineer, Mechanical/Electrical Section, Pittsburgh District, USACE
Todd Jennings, P.E.	Civil Engineer, General Engineering Section, Huntington District, USACE
Chuck Palmer	Operations Division, Walla Walls District, USACE
Tim Paulus	Mechanical Engineer, St. Paul District, USACE
Russ Whitten	Chief Electrical/Mechanical Division, Huntington District (Ret.)

Table 6. Mechanical panel members.

Name	Affiliation
Jim Hay, P.E.	Operations Division, Walla Walla District USACE
Chuck Palmer, P.E.	Mechanical Engineer, Mechanical/Electrical Section, Walla Walls District, USACE
Tim Paulus, P.E.	Mechanical Engineer, Mechanical/Electrical Section, St. Paul District, USACE
Ross Woodbury, P.E.	Operations Division, Louisville District, USACE
Todd Jennings, P.E.	Civil Engineer, General Engineering Section, Huntington District, USACE
Russ Whitten, P.E.	Chief, Mechanical/Electrical Section, Huntington District, USACE

Table 7. Electrical panel members.

Name	Affiliation
Jim Hay, P.E.	Operations Division, McNairy Lock and Dam, Walla Walla District USACE
Ross Woodbury, P.E.	Operations Division, Louisville District, USACE
David Buccini	Mechanical Engineer, Mechanical/Electrical Section, Pittsburgh District, USACE
Bryan Radkte, P.E.	Electrical Engineer, Mechanical/Electrical Section, Rock Island District, USACE
John Nites, P.E.	Electrical Engineer, Mechanical/Electrical Section, Pittsburgh District, USACE
Todd Jennings, P.E.	Civil Engineer, General Engineering Section, Huntington District, USACE

Table 8. Observers.

Name	Affiliation
James Bartek, P.E.	Chief of the Mechanical/Electrical Section in Engineering Division, Rock Island District, USACE
David Buccini	Regional Technical Specialist – Mechanical Engineering for the Great Lakes and Ohio River Division (LRD), USACE
Dan Casapulla, P.E.	Lead Mechanical Engineer at HQUSACE
Stuart D. Foltz	Research civil engineer at the Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL)
Brendan McKinley	Regional Technical Specialist – Mechanical Engineering for Lakes and Rivers Division (LRD), USACE
Richard W. Schultz, P.E.	Chief of the Mechanical/Electrical Section in Engineering Division, Louisville District, USACE

The technical integrator and facilitator was Robert C. Patev, the USACE North Atlantic Division Regional Technical Specialist for Navigation Design and a structural/geotechnical engineer with the US Army Corps of Engineer, New England District in Concord, MA. Mr. Patev was more recently a research civil engineer at the Engineer Research and Development Center, Information Technology Laboratory (ERDC-ITL). For the past 15 years, Mr. Patev has focused his work in the areas of risk assessment and engineering reliability. He has worked in directing the risk and reliability research arena for the Corps and has worked with Corps Districts on the application of time-dependent reliability procedures to many navigation projects. Mr. Patev's background is diverse; he has bachelor's and master's degrees in geology, geotechnical engineering, and structural engineering. He has published a variety of journal and conference papers on risk assessment and engineering reliability and has contributed technical chapters to a variety of textbooks.

3 Expert-Opinion Elicitation

3.1 Background

The elicitation process of opinions is a formal process that is performed systematically for each issue according to the following steps:

- Issue familiarization of experts and review of critical component list.
- Train experts in elicitation process using two examples.
- Experts discuss and come to agreement on assumptions for each issue.
- Facilitate the first elicitation and collection of opinions.
- Collect and present results to experts.
- The group discusses its first response.
- Facilitate the second elicitation and collection of opinions.
- Make the final presentation of experts' opinions.
- Solicit the experts' confidence of final response.
- Return to Step 3 and repeat for all components.

The issues consist of groups of similar questions concerning the CL of critical ME components at navigation projects. The issues also include the experts' confidence level in the final value that was obtained after the second elicitation. Assumptions made and defined by the experts with each issue will be documented with the final results. These final tabulated responses define a CL for the components that will be used in the system reliability analysis of ME equipment at USACE navigation projects.

3.2 Selected issues

The issues for the experts were developed from the critical ME list that the experts reviewed in their read-ahead package. The issues were only focused on the normal deterioration and wear on the ME systems at navigation projects. Since the goal of the elicitation was to only estimate CL, the issues to address in this EOE are less difficult than typical EOE for navigation reliability.

3.2.1 Mechanical system issues

3.2.1.1 Description of problem

The mechanical system consists of four major categories: (1) mechanical drive systems, (2) hydraulic drive systems, (3) misc. gate/filling/emptying valves, and (4) other systems. The components in each of these categories are subjected to deterioration due to wear, corrosion, overstress, and fatigue from normal operational and environmental conditions at lock and dam facilities.

3.2.1.2 Potential failure mode(s)

The failure modes for these components were limited to any potential internal failure mechanism that could occur during normal operation of the lock and dam system. Individual failure modes were not identified for each component since it would be difficult to identify and elicit CL estimates for each failure mode with a high level of confidence.

3.2.1.3 Potential consequences/repair scenarios

The CL for the mechanical components was defined as the time until the component caused a navigation delay or closure greater than 4 hours. Partial or temporary repair scenarios were not considered for the mechanical system other than a replacement or rehabilitation of the entire system at a particular life cycle.

3.2.1.4 Issue definition for questions

Questions were defined for each critical mechanical component to determine the CL of that component and their confidence in that final elicited value. No assumptions were given to the experts as to the life of a navigation project.

3.2.2 Electrical system issues

3.2.2.1 Description of problem

The electrical system consists of four major categories: (1) power, (2) motor control, (3) motor and switches, and (4) electromechanical drives. The components in each of these categories are subjected to deterioration due to wear and fatigue from normal operational and environmental conditions at lock and dam facilities.

3.2.2.2 Potential failure mode(s)

The failure modes for these components were limited to any potential internal failure mechanism that could occur during normal operation of the lock and dam system. Individual failure modes were not identified for each component since it would be difficult to identify and elicit CL estimates for each failure mode with a high level of confidence.

3.2.2.3 Potential consequences/repair scenarios

The CL for the mechanical components was defined as the time until the component caused a navigation delay or closure greater than 4 hours. Partial or temporary repair scenarios were not considered for the mechanical system other than a replacement or rehabilitation of the entire system at a particular life cycle.

3.2.2.4 Event definition for questions

Questions were defined for each critical electrical component to determine the CL of that component and their confidence in that final elicited value. No assumptions were given to the experts as to the life of a navigation project.

3.3 Elicitation and aggregation of expert opinions

The panel of experts, observers and the facilitator convened at the Louisville District offices in Louisville, KY for the period of 2 days to discuss and address the issues shown above. The following protocol was followed in the deliberation of the issues:

- Training of the experts on probabilities and the elicitation process was conducted using two different elicitation examples. This training was conducted to familiarize the experts with the type of questions that were forthcoming, and to focus the experts on how to discuss and answer the issues that were forthcoming. The experts felt this training was very helpful in understanding and making them more comfortable with their elicitation and gained their confidence for discussion with other panel members.

- After presenting an issue and question, discussion of the issue was encouraged to ensure that all experts clearly understood the questions and event before answering. The participants also listed and agreed to the assumptions. For each issue, experts were given a general form to record their evaluation or input. The experts' judgment along with their supportive reasoning was recorded for the issues. The experts were also advised that the CL can only be answered in a whole number.
- The collected assessments from the experts were analyzed and aggregated quickly to obtain the first response from the experts about the issue. The medians and percentiles for the issue were computed in real time, and were discussed as they were being shown on a computer projection unit. Discussions then ensued among the experts to develop a consensus and agreement among the experts toward their first responses. The experts were given the opportunity to revise their assessments of the individual issues at the end of discussion. Also, the experts were asked to state the rationale for their statements and revisions. The revised assessments of the experts were collected for aggregation and analysis. Any additional assumptions made by the experts were documented as well.
- The experts were then asked for their second responses after discussion was formally closed. The collected assessments from the experts were analyzed and aggregated quickly for review by the experts. This last assessment was shown to the experts, but no changes were made to these results. The median of the final expert estimates was used as the final value. The experts were also asked to give a qualitative response to their confidence in the final medians for the CL estimate from the second response. This response was requested as high (±5 years), medium (±10 years), or low (±15 years). These medians are documented in this report for initial and final responses.
- In addition, a comprehensive documentation of this process is essential to ensure acceptance and credibility of the elicitation results. This document includes complete descriptions of both the first and second responses and the confidence of the experts in the final median response. The summarized results for each issue are provided in Section 3.6. Appendix A includes the actual elicited results in Microsoft Excel spreadsheets form.

3.4 Sample questions used for issues

The elicitation questions defined for each issue were developed based on defining the CL for the ME components. The following section gives an example elicitation question for “Mechanical Drive System – Bearings – Roller” issue. For each question, Appendix A includes the Excel spreadsheet used to record the results and the expert panel responses for each issue.

3.5 Example question for mechanical drive system issue – bearings – rolling element

3.5.1 Event name

Bearing (rolling element) fail in the mechanical drive system during normal operation.

3.5.2 Question

What is the CL (in years) for a rolling element type bearing?

3.6 Summary of results from elicitation

This section discusses an aggregated summary of the results from the elicitation. The results in this section are shown as the ***median*** of each (first and second) response. The minimums and maximums are included to show the variation in the expert’s responses. Also included with these results are the assumptions made and agreed to by the experts as shown for each response and the confidence each expert had in each of the final median response to the question. The confidence levels were solicited only in three categories: high (±5 years), medium (±10 years), or low (±15 years). Appendix A contains more detailed results from the elicitation, including the non-aggregated results, which contain the minimum, maximum, and various percentiles for each question. The non-aggregated results also show individual responses for each expert.

Note that, in all cases, experts’ confidence was established using “low,” “medium,” and “high” categories. The confidence results are expressed for each question based on the median for the second response.

3.6.1 Mechanical system – mechanical drive systems

3.6.1.1 Assumptions made by experts for mechanical drive systems

The experts made and agreed to the following assumptions:

- CL is the expected life until failure.
- Normal maintenance is done; there is no replacement.
- Operations are assumed to be “normal,” i.e., there is no increase in future traffic.
- CL is expressed in years (no fractions).
- The general purpose environment is “good.”
- The typical lock and dam does not go underwater.
- All materials are properly selected and designed.

3.6.1.2 Bearings-rolling element

What is the estimated CL (in years) for a rolling element type bearing?

	1st response	2nd response
Minimum	40	40
Median	40	**40**
Maximum	45	40

	Median	Low	Med	High
Final value(s)	40	0	1	5

3.6.1.3 Bearing sleeve (self lubricated)

What is the estimated CL (in years) for a sleeve (self lubricated) bearing?

	1st response	2nd response
Minimum	20	20
Median	28	**25**
Maximum	40	35

	Median	Low	Med	High
Final value(s)	25	1	4	1

3.6.1.4 Bearing – bronze sleeve

What is the estimated CL (in years) for a bronze sleeve bearing?

	1st response	2nd response
Minimum	30	20
Median	40	**25**
Maximum	45	35

	Median	Low	Med	High
Final value(s)	25	1	4	1

3.6.1.5 Couplings-flexible

What is the estimated CL (in years) for flexible couplings?

	1st response	2nd response
Minimum	30	20
Median	40	**25**
Maximum	45	35

	Median	Low	Med	High
Final value(s)	25	1	4	1

3.6.1.6 Couplings-rigid

What is the estimated CL (in years) for flexible couplings?

	1st response	2nd response
Minimum	40	45
Median	50	**50**
Maximum	80	70

	Median	Low	Med	High
Final value(s)	50	0	0	6

3.6.1.7 Shafts

What is the estimated CL (in years) for shafts?

	1st response	2nd response
Minimum	50	50
Median	50	**50**
Maximum	80	60

	Median	Low	Med	High
Final value(s)	50	0	0	6

3.6.1.8 Pins

What is the estimated CL (in years) for pins?

	1st response	2nd response
Minimum	25	30
Median	33	**35**
Maximum	40	35

	Median	Low	Med	High
Final value(s)	35	0	1	5

3.6.1.9 Gear reducers – worm

What is the estimated CL (in years) for worm gear reducers?

	1st response	2nd response
Minimum	25	25
Median	28	**25**
Maximum	40	30

	Median	Low	Med	High
Median Final value(s)	25	0	3	3

3.6.1.10 Gear reducers – parallel

What is the estimated CL (in years) for parallel gear reducers?

	1st response	2nd response
Minimum	30	40
Median	40	**40**
Maximum	50	45

	Median	Low	Med	High
Final value(s)	40	0	1	5

3.6.1.11 Gear reducers – right angle

What is the estimated CL (in years) for right angle gear reducers?

	1st response	2nd response
Minimum	30	35
Median	40	**38**
Maximum	45	45

	Median	Low	Med	High
Final value(s)	38	0	4	2

3.6.1.12 Open gearing –spur

What is the estimated CL (in years) for spur open gearing?

	1st response	2nd response
Minimum	35	45
Median	48	**50**
Maximum	60	60

	Median	Low	Med	High
Final value(s)	50	0	1	5

3.6.1.13 Open gearing –helical

What is the estimated CL (in years) for helical open gearing?

	1st response	2nd response
Minimum	30	35
Median	38	**38**
Maximum	50	40

	Median	Low	Med	High
Final value(s)	38	0	6	0

3.6.1.14 Open gearing-bevel

What is the estimated CL (in years) for bevel open gearing?

	1st response	2nd response
Minimum	30	35
Median	38	**40**
Maximum	40	40

	Median	Low	Med	High
Final value(s)	40	0	6	0

3.6.1.15 Open gearing –rack

What is the estimated CL (in years) for rack open gearing?

	1st response	2nd response
Minimum	35	40
Median	45	**50**
Maximum	60	60

	Median	Low	Med	High
Final value(s)	50	0	4	2

3.6.1.16 Brake – electromechanical

What is the estimated CL (in years) for electromechanical brake?

	1st response	2nd response
Minimum	35	40
Median	43	**45**
Maximum	45	45

	Median	Low	Med	High
Final value(s)	45	0	0	6

3.6.1.17 Clutch

What is the estimated CL (in years) for the clutch?

	1st response	2nd response
Minimum	20	20
Median	30	**30**
Maximum	35	35

	Median	Low	Med	High
Final value(s)	30	2	4	0

3.6.1.18 Wire ropes-spiral

What is the estimated CL (in years) for spiral wire ropes?

	1st response	2nd response
Minimum	3	3
Median	5	**5**
Maximum	40	20

	Median	Low	Med	High
Final value(s)	5	2	0	4

3.6.1.19 Wire ropes-single sheave

What is the estimated CL (in years) for single sheave wire ropes?

	1st response	2nd response
Minimum	12	15
Median	20	**20**
Maximum	40	25

	Median	Low	Med	High
Final value(s)	20	0	4	2

3.6.1.20 Wire ropes-single drum

What is the estimated CL (in years) for single drum wire ropes?

	1st response	2nd response
Minimum	10	25
Median	25	**28**
Maximum	30	30

	Median	Low	Med	High
Final value(s)	28	0	3	3

3.6.1.21 Wire ropes drums

What is the estimated CL (in years) for wire ropes drums?

	1st response	2nd response
Minimum	40	50
Median	50	**50**
Maximum	60	60

	Median	Low	Med	High
Final value(s)	50	0	0	6

3.6.1.22 Wire ropes sheaves

What is the estimated CL (in years) for wire ropes sheaves?

	1st response	2nd response
Minimum	20	25
Median	30	**33**
Maximum	40	40

	Median	Low	Med	High
Final value(s)	33	0	4	2

3.6.1.23 Chains

What is the estimated CL (in years) for chains?

	1st response	2nd response
Minimum	20	25
Median	28	**40**
Maximum	60	45

	Median	Low	Med	High
Final value(s)	40	2	3	1

3.6.1.24 Chain sprockets

What is the estimated CL (in years) for chain sprockets?

	1st response	2nd response
Minimum	40	50
Median	48	**60**
Maximum	60	60

	Median	Low	Med	High
Final value(s)	40	2	3	1

3.6.1.25 Miter gate sector arms

What is the estimated CL (in years) miter gate sector arms?

	1st response	2nd response
Minimum	50	50
Median	68	**73**
Maximum	120	75

	Median	Low	Med	High
Final value(s)	73	1	1	4

3.6.1.26 Miter gate strut arms (buffered)

What is the estimated CL (in years) miter gate strut (buffered) arms?

	1st response	2nd response
Minimum	30	30
Median	40	**35**
Maximum	75	40

	Median	Low	Med	High
Final value(s)	35	0	3	3

3.6.1.27 Miter gate arms – strut (rigid)

What is the estimated CL (in years) miter gate strut (rigid) arms?

	1st response	2nd response
Minimum	20	30
Median	43	**40**
Maximum	120	75

	Median	Low	Med	High
Final value(s)	40	0	6	0

3.6.1.28 Miter gate support roller

What is the estimated CL (in years) miter gate support roller?

	1st response	2nd response
Minimum	30	30
Median	43	**43**
Maximum	50	50

	Median	Low	Med	High
Final value(s)	43	0	5	1

3.6.1.29 Miter gate rack support beam

What is the estimated CL (in years) miter gate rack support beam?

	1st response	2nd response
Minimum	50	50
Median	60	**60**
Maximum	80	80

	Median	Low	Med	High
Final value(s)	60	0	5	1

3.6.1.30 Valves – bellcranks

What is the estimated CL (in years) for the valve bellcranks?

	1st response	2nd response
Minimum	50	70
Median	75	**78**
Maximum	100	100

	Median	Low	Med	High
Final value(s)	78	0	3	3

3.6.1.31 Valves – crossheads/guides

What is the estimated CL (in years) for valve crossheads/guides?

	1st response	2nd response
Minimum	45	55
Median	63	**73**
Maximum	80	80

	Median	Low	Med	High
Final value(s)	73	0	4	2

3.6.1.32 Valves –struts

What is the estimated CL (in years) for the valve struts?

	1st response	2nd response
Minimum	35	35
Median	45	**43**
Maximum	60	60

	Median	Low	Med	High
Final value(s)	43	0	2	4

3.6.2 Mechanical system – hydraulic drive systems

3.6.2.1 Assumptions made by experts for hydraulic drive systems

The experts made and agreed to the following assumptions:

- CL is the expected life until failure.
- Normal maintenance is done; there is no replacement.
- Operations are assumed to be "normal," i.e., there is no increase in future traffic.
- CL is expressed in years (no fractions).
- The general purpose environment is "good."
- The typical lock and dam does not go underwater.
- All materials are properly selected and designed.
- All materials are properly selected and designed.

3.6.2.2 Hydraulic cylinders

What is the estimated CL (in years) for the hydraulic cylinders?

	1st response	2nd response
Minimum	50	55
Median	60	**60**
Maximum	70	70

	Median	Low	Med	High
Final value(s)	60	0	0	6

3.6.2.3 Control valves –check

What is the estimated CL (in years) for check valves?

	1st response	2nd response
Minimum	30	40
Median	50	**45**
Maximum	60	50

	Median	Low	Med	High
Final value(s)	45	0	2	4

3.6.2.4 Control valves –relief

What is the estimated CL (in years) for relief valves?

	1st response	2nd response
Minimum	30	30
Median	45	**40**
Maximum	60	50

	Median	Low	Med	High
Final value(s)	40	0	2	4

3.6.2.5 Control valves –manual

What is the estimated CL (in years) for manual valves?

	1st response	2nd response
Minimum	50	60
Median	60	**60**
Maximum	70	70

	Median	Low	Med	High
Final value(s)	60	0	1	5

3.6.2.6 Control valves –solenoid

What is the estimated CL (in years) for solenoid valves?

	1st response	2nd response
Minimum	30	30
Median	45	**40**
Maximum	60	50

	Median	Low	Med	High
Final value(s)	40	0	5	1

3.6.2.7 Control valves – proportional/throttle

What is the estimated CL (in years) for proportional/throttle valves?

	1st response	2nd response
Minimum	30	30
Median	40	**40**
Maximum	50	50

	Median	Low	Med	High
Final value(s)	40	0	5	1

3.6.2.8 Pumps –fixed

What is the estimated CL (in years) for fixed drive pumps?

	1st response	2nd response
Minimum	45	50
Median	50	**50**
Maximum	80	60

	Median	Low	Med	High
Final value(s)	50	0	0	6

3.6.2.9 Pumps –variable

What is the estimated CL (in years) for variable drive pumps?

	1st response	2nd response
Minimum	25	25
Median	45	**30**
Maximum	60	45

	Median	Low	Med	High
Final value(s)	30	0	1	5

3.6.2.10 Piping

What is the estimated CL (in years) for variable drive pumps?

	1st response	2nd response
Minimum	40	40
Median	40	**40**
Maximum	50	50

	Median	Low	Med	High
Final value(s)	60	0	3	3

3.6.3 Mechanical system – misc. gate/filling and emptying valves and other systems

3.6.3.1 Assumptions made by experts for misc. gate/filling and emptying valves

The experts made and agreed to the following assumptions:

- CL is the expected life until failure.
- Normal maintenance is done; there is no replacement.
- Operations are assumed to be “normal,” i.e., there is no increase in future traffic.
- CL is expressed in years (no fractions).
- The general purpose environment is “good.”
- The typical lock and dam does not go underwater.
- All materials are properly selected and designed.

3.6.3.2 Wheel assembly (rollers)

What is the estimated CL (in years) for the wheel assembly (rollers)?

	1st response	2nd response
Minimum	10	40
Median	40	**40**
Maximum	50	40

	Median	Low	Med	High
Final value(s)	40	0	3	3

3.6.3.3 Pintles/bushings

What is the estimated CL (in years) for the pintle/bushings?

	1st response	2nd response
Minimum	25	30
Median	30	**30**
Maximum	75	60

	Median	Low	Med	High
Final value(s)	30	0	2	4

3.6.3.4 Gudgeon pin/bushings

What is the estimated CL (in years) for the gudgeon pin/bushings?

	1st response	2nd response
Minimum	30	35
Median	48	**43**
Maximum	50	50

	Median	Low	Med	High
Final value(s)	43	0	4	2

3.6.3.5 Trunnion pin/bushings

What is the estimated CL (in years) for the trunnion pin/bushings?

	1st response	2nd response
Minimum	15	25
Median	35	**38**
Maximum	45	40

	Median	Low	Med	High
Final value(s)	38	0	1	5

3.6.3.6 Trunnion pin/bushings

What is the estimated CL (in years) for the trunnion pin/bushings?

	1st response	2nd response
Minimum	15	25
Median	35	**38**
Maximum	45	40

	Median	Low	Med	High
Final value(s)	38	0	1	5

3.6.3.7 Strut spindle pin

What is the estimated CL (in years) for the strut spindle pin?

	1st response	2nd response
Minimum	20	20
Median	25	**25**
Maximum	40	25

	Median	Low	Med	High
Final value(s)	25	0	0	6

3.6.3.8 Tow haulage –hydraulic

What is the estimated CL (in years) for a hydraulic tow haulage unit?

	1st response	2nd response
Minimum	20	25
Median	35	**30**
Maximum	50	35

	Median	Low	Med	High
Final value(s)	30	0	6	0

3.6.3.9 Tow haulage –mechanical

What is the estimated CL (in years) for a hydraulic tow haulage unit?

	1st response	2nd response
Minimum	20	30
Median	43	**48**
Maximum	60	60

	Median	Low	Med	High
Final value(s)	48	1	3	2

3.6.3.10 Butterfly valves

What is the estimated CL (in years) for butterfly valves?

	1st response	2nd response
Minimum	40	40
Median	45	**50**
Maximum	60	60

	Median	Low	Med	High
Final value(s)	50	0	6	0

3.6.3.11 Vertical lift valves

What is the estimated CL (in years) for vertical lift valves?

	1st response	2nd response
Minimum	30	40
Median	45	**50**
Maximum	50	50

	Median	Low	Med	High
Final value(s)	50	0	4	2

3.6.4 Electrical system issues

The experts for electrical system issues made the following assumptions:

- CL is the expected life until failure.
- Normal maintenance is done; there is no replacement.
- Operations are assumed to be “normal,” i.e., there is no increase in future traffic.
- CL is expressed in years (no fractions).
- The general purpose environment is “good.”
- The typical lock and dam does not go underwater.
- The equipment has been in service for 50-60 years.
- All materials are properly selected and designed.
- A power outage of 4 hours or more is assumed.
- Environmental factors could be used for site specific conditions.

3.6.4.1 Power utility

What is the estimated CL (in years) for power utility (commercial) power?

	1st response	2nd response
Minimum	1	1
Median	5	**4**
Maximum	10	10

	Median	Low	Med	High
Final value(s)	50	4	0	3

3.6.4.2 Service transformer

What are estimated CL (in years) the service transformer?

	1st response	2nd response
Minimum	30	40
Median	45	**55**
Maximum	60	60

	Median	Low	Med	High
Final value(s)	55	0	3	3

3.6.4.3 Transfer switches –automatic

What are estimated CL (in years) automatic transfer switches?

	1st response	2nd response
Minimum	15	20
Median	30	**30**
Maximum	40	40

	Median	Low	Med	High
Final value(s)	30	0	0	6

3.6.4.4 Transfer switches –manual

What are estimated CL (in years) for manual transfer switches?

	1st response	2nd response
Minimum	40	60
Median	60	**65**
Maximum	80	80

	Median	Low	Med	High
Final value(s)	65	0	1	5

3.6.4.5 Switchgear

What is the estimated CL (in years) for the switchgear?

	1st response	2nd response
Minimum	40	70
Median	55	**78**
Maximum	90	90

	Median	Low	Med	High
Final value(s)	78	0	4	2

3.6.4.6 Circuit breakers

What is estimated CL (in years) for circuit breakers?

	1st response	2nd response
Minimum	30	40
Median	45	**63**
Maximum	70	75

	Median	Low	Med	High
Final value(s)	63	0	2	4

3.6.4.7 Power panelboard

What is the estimated CL (in years) for power panelboard?

	1st response	2nd response
Minimum	25	60
Median	65	**78**
Maximum	90	90

	Median	Low	Med	High
Final value(s)	20.0	0	4	2

3.6.4.8 Cables-buried/submerged

What is the estimated CL (in years) for buried/submerged cables?

	1st response	2nd response
Minimum	30	50
Median	55	**60**
Maximum	75	75

	Median	Low	Med	High
Final value(s)	60	0	4	2

3.6.4.9 Cables-duct/cable tray

What is the estimated CL (in years) for buried/submerged cables?

	1st response	2nd response
Minimum	75	75
Median	80	**80**
Maximum	100	100

	Median	Low	Med	High
Final value(s)	80	0	4	2

3.6.4.10 Cables-portable/flexible

What is the estimated CL (in years) for portable/flexible cables?

	1st response	2nd response
Minimum	20	20
Median	28	**38**
Maximum	35	35

	Median	Low	Med	High
Final value(s)	38	1	3	2

3.6.4.11 Bus duct (electronic)

What is the estimated CL (in years) for portable/flexible cables?

	1st response	2nd response
Minimum	75	80
Median	95	**95**
Maximum	150	120

	Median	Low	Med	High
Final value(s)	95	2	1	3

3.6.4.12 Switchboards

What is the CL (in years) for switchboards?

	1st response	2nd response
Minimum	50	75
Median	75	**83**
Maximum	90	90

	Median	Low	Med	High
Final value(s)	83	0	6	0

3.6.4.13 Motor control centers

What is the CL (in years) for motor control centers?

	1st response	2nd response
Minimum	50	75
Median	75	**83**
Maximum	90	90

	Median	Low	Med	High
Final value(s)	83	0	6	0

3.6.4.14 Motor starters – full voltage

What is the CL (in years) for full voltage motor starters?

	1st response	2nd response
Minimum	30	60
Median	60	**63**
Maximum	80	80

	Median	Low	Med	High
Final value(s)	63	0	1	5

3.6.4.15 Motor starters – reduced/variable

What is the CL (in years) for reduced/variable motor starters?

	1st response	2nd response
Minimum	15	50
Median	50	**50**
Maximum	60	60

	Median	Low	Med	High
Final value(s)	50	0	5	1

3.6.4.16 Motor starters – VFD

What is the CL (in years) for VFD motor starters?

	1st response	2nd response
Minimum	15	25
Median	25	**35**
Maximum	40	40

	Median	Low	Med	High
Final value(s)	35	4	2	0

3.6.4.17 PLC systems

What is the CL (in years) for PLC systems?

	1st response	2nd response
Minimum	20	25
Median	25	**25**
Maximum	40	40

	Median	Low	Med	High
Final value(s)	25	0	3	3

3.6.4.18 Selsyn motor

What is the CL (in years) for a Selsyn motor?

	1st response	2nd response
Minimum	30	30
Median	55	**43**
Maximum	100	80

	Median	Low	Med	High
Final value(s)	43	0	6	0

3.6.4.19 Traveling nut limit switch

What is the CL (in years) for a traveling nut limit switch?

	1st response	2nd response
Minimum	30	50
Median	73	**65**
Maximum	105	100

	Median	Low	Med	High
Final value(s)	65	0	6	0

3.6.4.20 Electric motors (new and rebuilt)

What is the CL (in years) for new or rebuilt electric motors?

	1st response	2nd response
Minimum	50	60
Median	65	**68**
Maximum	85	80

	Median	Low	Med	High
Final value(s)	68	0	6	0

3.6.4.21 Standby generator set

What is the CL (in years) for a standby generator set?

	1st response	2nd response
Minimum	25	40
Median	50	**50**
Maximum	75	70

	Median	Low	Med	High
Final value(s)	50	0	2	4

3.6.4.22 Direct current (DC) rectifier (brakes)

What is the CL (in years) for a standby generator set?

	1st response	2nd response
Minimum	10	25
Median	35	**35**
Maximum	50	45

	Median	Low	Med	High
Final value(s)	35	1	1	4

4 Conclusions

The CL data collected as part of this study will be useful in evaluation of the reliability of ME systems at USACE navigation projects. The results documented in this report are estimates of the characteristic lives of the typical navigation project across the country. The results for the CL presented here may be modified if more detailed information on performance is known for a site specific project. This data collected from this elicitation can be used in Weibull models to predict the reliability of ME components. Weibull models are recommended for use with fault tree methods for analysis of ME system reliability (Patev, Putcha, and Foltz 2005).

Tables 9 and 10 summarize all the median elicitation values for the mechanical system and electrical system at navigation projects. Reference is made to Appendices A and B for the actual response values, and the elicitation and confidence results for each component.

Table 9. CL for navigation mechanical components.

Component		Life (in years)
	Mechanical drive systems	
Characteristic shafts pins gear reducers		
Bearings	Rolling element	40
	Sleeve (self lubricated)	25
	Bronze sleeve	40
Couplings	Flexible	35
	Rigid	50
		35
	Worm	25
	Parallel	40
	Right angle	38
	Spur	50
	Helical	38
Open Gearing	Bevel	40
	Rack	50
	Electromechanical	45
	Slip	30
	Spiral Plate	5
	Single Sheave(s)	20

Component		Life (in years)
Brake Clutch Wire ropes	Single Drum	28
		50
		33
Wire rope drums Wire rope	Roller	40
		60
	Sector arms	73
	Strut arms - buffered	35
	Strut arms - rigid	40
	Support roller	43
	Rack support beam	60
	Bellcranks	78
Valves	Crosshead/Guide	73
	Strut	43
	Worm	25
	Parallel	40
	Right angle	38
Hydraulic Drive Systems		
Hydraulic cylinder		60
Control Valves		
Check		45
Relief		40
Directional		
Manual		60
Solenoid		40
Proportional/Throttle		40
Pumps		
Fixed		50
Variable		30
Hydraulic Motors	Fixed	50
	Variable	30
Piping		40
Selsyn motor		43
Traveling nut limit switch		65
ElectroMechanical Drives		
Electric Motors (new and rebuilt)		68
Standby generator sets		50
DC Rectifier (brakes)		35
Tow Haulage	Hydraulic	30

Component		Life (in years)
	Mechanical	48
Emptying Filling	Butterfly	50
	Vertical Lift	50
	Misc Gate/Filling Emptying Valves	
Wheel assembly		40
Pintles/Bushings		30
Gudgeon pin/bushings		43
Trunnion pin/bushings		38
Strut spindle pin		25

Table 10. CL for navigation electrical components characteristic power life (in years).

Component		Life (in years)
Service transformer		4
Transfer switches		55
	Automatic	
	Manual	30
Switchgear		65
Circuit breakers		78
Power Panelboard		63
Cables		78
	Buried Submerged	
	Duct/Cable Tray	60
	Portable/Flexible	80
Bus duct		28
Switchboards		95
Motor control centers		83
Motor control		83
Motor Starters		
	Full Voltage	
	Reduced/Variable	63
	VFD	50
PLC systems		35
Service transformer		25

Acronyms, Abbreviations, and Technical Terms

Acronyms and Abbreviations

Term	Definition
CDF	Cumulative Distribution Function
CERL	Construction Engineering Research Laboratory
CL	Characteristic Life
DC	Direct Current
DoD	US Department of Defense
EC	Engineer Circular
EM	ElectroMechanical
EOE	Expert-Opinion Elicitation (EOE)
ERDC	Engineer Research and Development Center
GLSLS	Great Lakes and St. Lawrence Seaway System Study
HQUSACE	Headquarters, US Army Corps of Engineers
ITL	Information Technology Laboratory
LRD	Great Lakes and Ohio River Division
ME	Mechanical and Electrical
MTTF	Mean Time To Failure
OMB	Office of Management and Budget
ORMSS	Ohio River Main Stem Study
PLC	Programmable Logic Controller
TF	Technical Facilitator
TI	Technical Integrator
TIF	Technical Integrator and Facilitator
TR	Technical Report
US	United States
USACE	US Army Corps of Engineers
UV	Ultraviolet
VFD	Variable Frequency Drive

Technical Terms

Term	Definition
Average	A central tendency measure that is computed as the sum of values divided by their count.
Evaluators	Evaluators consider available data, become familiar with the views of proponents and other evaluators, question the technical bases of data, and challenge the views of proponents.
Expert	A person with related or unique experience to an issue or question of interest for the process.
Expert elicitation	A formal process of obtaining information or answers to specific questions about certain issues.
Expert-Opinion Elicitation (EOE) process	A formal, heuristic process of gathering informing and data or answering questions on issues or problems of concern.
Leader of EOE process	An entity having managerial and technical responsibility for organizing and executing the project, overseeing all participants, and intellectually owning the results.
Mean	Refer to average.
Median value	The point that divides the data into two equal parts, i.e., 50% of the data are above it and 50% are below it.
Observers	Observers can contribute to the discussion, but cannot provide expert opinion that enters in the aggregated opinion of the experts.
Peer reviewers	Experts that can provide an unbiased assessment and critical review of an Expert-Opinion Elicitation process, its technical issues, and results.
p-percentile value	The value of the parameter such that p% of the data is less or equal to this value.
Probability	Measured by dividing the number of occurrences by the total number of repetitions.
Proponents	Proponents are experts who advocate a particular hypothesis or technical position. In science, a proponent evaluates experimental data and professionally offers a hypothesis that would be challenges by the proponent's peers until proven correct or wrong.
Resource experts	Resource experts are technical experts with detailed and deep knowledge of particular data, issue aspects, particular methodologies, or use of evaluators.
Technical Facilitator (TF)	An entity responsible for structuring and facilitating the discussions and interactions of experts in the EOE process; staging effective interactions among experts; ensuring equity in presented views; eliciting formal evaluations from each expert; and creating conditions for direct, non-controversial integration of expert opinions.
Technical integrator (TI)	An entity responsible for developing the composite representation of issues based on informed members and/or sources of related technical communities and experts; explaining and defending composite results to experts and outside experts, peer reviewers, regulators, and policy makers; and obtaining feedback and revising composite results.

Term	Definition
Technical Integrator and Facilitator (TIF)	An entity responsible for both functions of TI and TF.
Uncertainty	The doubt (or the lack of sureness) about the outcomes (in number or magnitude) of a system.
Failure event	Any event that will have an adverse impact on lock performance is defined a failure event.
Failure rate	The probability of failure per unit time or a unit of operation, such as cycle, revolution, rotation, startup, etc.
Variance	Measure of dispersion.

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Appendix A: Expert Elicitation Spreadsheets – Mechanical System Components

Table A1. Mechanical system – bearings.

Event Name	Full Description of Issue	Expert-opinion elicitation						Confidence		
		First Response			Second Response					
		Rolling Element	Sleeve (self lubricated)	Bronze Sleeve	Rolling Element	Sleeve (self lubricated)	Bronze Sleeve	Rolling Element	Sleeve (self lubricated)	Bronze Sleeve
Bearings fail in the mechanical drive system during normal operation	What is the expected characterisitic life for the different bearings identified?									
	Expert #1	40	40	40	40	30	40	high	high	high
	Expert #2	40	30	40	40	25	40	med	med	med
	Expert #3	40	25	40	40	25	40	high	med	high
	Expert #4	40	20	30	40	20	40	high	med	high
	Expert #5	40	40	40	40	35	35	high	low	low
	Expert #6	45	20	45	40	20	40	high	med	high
Summary Table	**Minimum =**	40	20	30	40	20	35			
	25 Percentile =	40	21	40	40	21	40			
	Median =	40	28	40	40	25	40			
	75 Percentile =	40	38	40	40	29	40			
	Maximum =	45	40	45	40	35	40			

Table A1. (Cont'd).

Event Name	Full Description of Issue	Expert-opinion elicitation					
		First Response		Second Response		Confidence	
Couplings fail in the mechanical drive system during normal operation	What is the expected characterisitic life for the different couplings identified?	Flexible	Rigid	Flexible	Rigid	Flexible	Rigid
	Expert #1	30	40	30	50	high	high
	Expert #2	35	50	35	50	high	high
	Expert #3	30	40	30	45	high	high
	Expert #4	30	50	35	60	high	high
	Expert #5	35	50	35	50	high	high
	Expert #6	40	80	35	70	high	high
Summary Table	**Minimum =**	30	40	30	45		
	25 Percentile =	30	43	31	50		
	Median =	33	50	35	50		
	75 Percentile =	35	50	35	58		
	Maximum =	40	80	35	70		

Table A2. Mechanical system - shafts

Event Name	**Full Description of Issue**	**Expert-opinion elicitation**		
		First Response	**Second Response**	**Confidence**
Shafts fail in the mechanical drive system during normal operation	What is the expected characterisitic life for the shafts identified?	Shafts	Shafts	Shafts
	Expert #1	50	50	high
	Expert #2	80	60	high
	Expert #3	50	50	high
	Expert #4	50	50	high
	Expert #5	50	50	high
	Expert #6	50	50	high
Summary Table	**Minimum =**	50	50	
	25 Percentile =	50	50	
	Median =	50	50	
	75 Percentile =	50	50	
	Maximum =	80	60	

Table A3. Mechanical system – pins.

Event Name	Full Description of Issue	Expert-opinion elicitation		
		First Response	Second Response	Confidence
Pins fail in the mechanical drive system during normal operation	What is the expected characterisitic life for the pins identified?			
		Pins	Pins	Pins
	Expert #1	25	35	high
	Expert #2	40	35	med
	Expert #3	40	35	high
	Expert #4	30	30	high
	Expert #5	35	35	high
	Expert #6	30	30	high
Summary Table	**Minimum =**	25	30	
	25 Percentile =	30	31	
	Median =	33	35	
	75 Percentile =	39	35	
	Maximum =	40	35	

Table A4. Mechanical system – gear reducers.

Event Name	Full Description of Issue	Expert-opinion elicitation								
		First Response			Second Response			Confidence		
Gear reducers fail in the mechanical drive system during normal operation	What is the expected characterisitic life for the gear reducers identified?	Worm	Parallel	Right Angle	Worm	Parallel	Right Angle	Worm	Parallel	Right Angle
	Expert #1	40	40	40	30	45	45	med	high	high
	Expert #2	30	50	45	25	45	40	med	high	med
	Expert #3	25	30	30	25	40	35	med	high	high
	Expert #4	25	40	40	25	40	40	high	high	med
	Expert #5	35	50	45	25	40	35	med	med	med
	Expert #6	25	40	30	25	40	35	high	high	med
Summary Table	**Minimum =**	25	30	30	25	40	35			
	25 Percentile =	25	40	33	25	40	35			
	Median =	28	40	40	25	40	38			
	75 Percentile =	34	48	44	25	44	40			
	Maximum =	40	50	45	30	45	45			

Table A5. Mechanical system – open gearing.

Event Name	Full Description of Issue	Expert-opinion elicitation											
		First Response				Second Response				Confidence			
Open gearing fails in the mechanical drive system during normal operation	What is the expected characterisitic life for the different open gearing identified?	Spur	Helical	Bevel	Rack	Spur	Helical	Bevel	Rack	Spur	Helical	Bevel	Rack
	Expert #1	50	40	40	50	50	40	40	50	high	med	med	high
	Expert #2	40	30	30	40	50	35	35	45	high	med	med	med
	Expert #3	45	35	35	35	45	35	35	40	high	med	med	high
	Expert #4	60	40	40	60	60	40	40	60	high	med	med	high
	Expert #5	35	30	35	35	50	40	40	50	med	med	med	med
	Expert #6	60	50	40	50	55	35	40	55	high	med	med	high
Summary Table	**Minimum =**	35	30	30	35	45	35	35	40				
	25 Percentile =	41	31	35	36	50	35	36	46				
	Median =	48	38	38	45	50	38	40	50				
	75 Percentile =	58	40	40	50	54	40	40	54				
	Maximum =	60	50	40	60	60	40	40	60				

Table A6. Mechanical system – electromechanical brakes,

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Brakes fail in the mechanical drive system during normal operation	What is the characterisitic life for the different brakes identified?	Electromechanical (magnetic and torque)	Electromechanical (magnetic and torque)	Electromechanical (magnetic and torque)
	Expert #1	45	45	high
	Expert #2	45	45	high
	Expert #3	35	40	high
	Expert #4	40	45	high
	Expert #5	45	45	high
	Expert #6	40	40	high
Summary Table	**Minimum =**	35	40	
	25 Percentile =	40	41	
	Median =	43	45	
	75 Percentile =	45	45	
	Maximum =	45	45	

Table A7. Mechanical system – slip brakes.

Event Name	Full Description of Issue	Expert-opinion elicitation		
		First Response	Second Response	Confidence
Brakes fail in the mechanical drive system during normal operation	What is the characterisitic life for the different brakes identified?	Slip	Slip	Slip
	Expert #1	30	30	med
	Expert #2	30	30	med
	Expert #3	35	35	med
	Expert #4	30	30	med
	Expert #5	35	35	low
	Expert #6	20	20	low
Summary Table	**Minimum =**	20	20	
	25 Percentile =	30	30	
	Median =	30	30	
	75 Percentile =	34	34	
	Maximum =	35	35	

Table A8. Mechanical system – wire ropes.

Event Name	Full Description of Issue	Expert-opinion elicitation								
		First Response			Second Response			Confidence		
Wire ropes fail in the mechanical drive system during normal operation	What is the expected characterisitic life for the wire ropes identified?	Spiral Plate	Single Sheave(s)	Single Drum	Spiral Plate	Single/Multiple Sheave	Single Drum	Spiral Plate	Single/Multiple Sheave	Single Drum
	Expert #1	3	20	30	3	20	30	high	med	med
	Expert #2	5	12	20	5	20	25	high	med	med
	Expert #3	20	25	20	20	25	25	low	med	high
	Expert #4	40	40	30	20	20	30	low	med	high
	Expert #5	3	15	10	3	15	25	high	high	med
	Expert #6	5	20	30	5	20	30	high	high	high
Summary Table	**Minimum =**	3	12	10	3	15	25			
	25 Percentile =	4	16	20	4	20	25			
	Median =	5	20	25	5	20	28			
	75 Percentile =	16	24	30	16	20	30			
	Maximum =	40	40	30	20	25	30			

Table A8. (Cont'd).

Event Name	Full Description of Issue	Expert-opinion elicitation					
		First Response		Second Response		Confidence	
Wire rope drums and sheaves fail in the mechanical drive system during normal operation	What is the characterisitic life for the wire rope drums and sheaves identified?	Drums	Sheaves	Drums	Sheaves	Drums	Sheaves
	Expert #1	50	25	50	40	high	med
	Expert #2	60	40	60	35	high	med
	Expert #3	45	40	50	40	high	med
	Expert #4	50	30	50	30	high	high
	Expert #5	50	20	50	25	high	med
	Expert #6	50	30	50	30	high	high
Summary Table	**Minimum =**	45	20	50	25		
	25 Percentile =	50	26	50	30		
	Median =	50	30	50	33		
	75 Percentile =	50	38	50	39		
	Maximum =	60	40	60	40		

Table A9. Mechanical system – chains.

Event Name	Full Description of Issue	Expert-opinion elicitation		
		First Response	Second Response	Confidence
Chains fail in the mechanical drive system during normal operation	What is the estimated characterisitic life for the different chains identified?	Roller	Roller	Roller
	Expert #1	20	40	med
	Expert #2	20	40	low
	Expert #3	45	45	high
	Expert #4	30	40	med
	Expert #5	25	25	med
	Expert #6	60	30	low
Summary Table	**Minimum =**	20	25	
	25 Percentile =	21	33	
	Median =	28	40	
	75 Percentile =	41	40	
	Maximum =	60	45	

Table A10. Mechanical system – chain sprocket.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Chain sprocket fails in the mechanical drive system during normal operation	What is the estimated characterisitic life for the different chain sprocket identified?	Chain Sprocket	Chain Sprocket	Chain Sprocket
	Expert #1	40	50	med
	Expert #2	45	60	med
	Expert #3	60	60	high
	Expert #4	40	60	med
	Expert #5	50	50	low
	Expert #6	60	60	low
Summary Table	Minimum =	40	50	
	25 Percentile =	41	53	
	Median =	48	60	
	75 Percentile =	58	60	
	Maximum =	60	60	

Table A11. Mechanical system – strut arms.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response: Sector arms	First Response: Strut arms - buffered	First Response: Strut arms - rigid	Second Response: Sector arms	Second Response: Strut arms - buffered	Second Response: Strut arms - rigid	Confidence: Sector arms	Confidence: Strut arms - buffered	Confidence: Strut arms - rigid
Sector or strut arms fail in the mechanical drive system during normal operation	What is the expected characterisitic life for the sector and strut arms identified?									
	Expert #1	75	75	75	75	40	40	high	med	med
	Expert #2	120	50	120	75	35	75	med	med	med
	Expert #3	60	40	50	60	35	50	high	high	med
	Expert #4	75	30	30	75	30	30	high	high	med
	Expert #5	50	40	35	50	40	40	low	med	med
	Expert #6	60	30	20	70	30	30	high	high	med
Summary Table	**Minimum =**	50	30	20	50	30	30			
	25 Percentile =	60	33	31	63	31	33			
	Median =	68	40	43	73	35	40			
	75 Percentile =	75	48	69	75	39	48			
	Maximum =	120	75	120	75	40	75			

Table A12. Mechanical system – support roller.

Event Name	Full Description of Issue	Expert-opinion elicitation				Confidence	
		First Response		Second Response			
		Support Roller	Rack Support Beam	Support Roller	Rack Support Beam	Support Roller	Rack Support Beam
Support roller fails during normal operation	What is the expected characterisitic life for support rollers and beams identified?						
	Expert #1	50	70	50	70	med	med
	Expert #2	30	60	30	60	high	high
	Expert #3	45	50	45	50	med	med
	Expert #4	40	50	40	60	med	med
	Expert #5	50	80	50	80	med	med
	Expert #6	40	60	40	60	med	med
Summary Table	**Minimum =**	30	50	30	50		
	25 Percentile =	40	53	40	60		
	Median =	43	60	43	60		
	75 Percentile =	49	68	49	68		
	Maximum =	50	80	50	80		

Table A13. Mechanical system – valves.

Event Name	Full Description of Issue	Expert-opinion elicitation								
		First Response			Second Response			Confidence		
Valve componens fails during normal operation	What is the expected characterisitic life for the valve components identified?	Bellcrank	Crosshead/Guide	Strut	Bellcrank	Crosshead/Guide	Strut	Bellcrank	Crosshead/Guide	Strut
	Expert #1	75	75	60	75	75	60	med	med	high
	Expert #2	100	80	40	100	80	40	high	high	high
	Expert #3	50	50	35	70	70	35	med	med	med
	Expert #4	75	75	40	75	75	40	high	high	high
	Expert #5	60	50	50	80	55	45	high	med	high
	Expert #6	90	45	60	90	60	50	med	med	med
Summary Table	**Minimum =**	50	45	35	70	55	35			
	25 Percentile =	64	50	40	75	63	40			
	Median =	75	63	45	78	73	43			
	75 Percentile =	86	75	58	88	75	49			
	Maximum =	100	80	60	100	80	60			

Table A14. Mechanical system – hydraulic cylinder.

Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
What is the expected characterisitic life for the hydraulic cylinder identified?	Hydraulic Cylinder	Hydraulic Cylinder	Hydraulic Cylinder
Expert #1	60	60	high
Expert #2	50	60	high
Expert #3	60	60	high
Expert #4	70	70	high
Expert #5	55	55	high
Expert #6	60	60	high
Minimum =	50	55	
25 Percentile =	56	60	
Median =	60	60	
75 Percentile =	60	60	
Maximum =	70	70	

Table A15. Mechanical system – control valves.

Event Name	Full Description of Issue	Expert-opinion elicitation					
		First Response		Second Response			
Valves fail in the hyraulic drive system during normal operation	What is the expected characterisitic life for the different valves identified?					**Confidence**	
		Check	Relief	Check	Relief	Check	Relief
	Expert #1	50	50	40	50	high	high
	Expert #2	60	60	50	40	high	high
	Expert #3	40	30	40	30	high	high
	Expert #4	50	40	50	40	high	high
	Expert #5	30	30	40	35	med	med
	Expert #6	60	60	50	40	med	med
Summary Table	**Minimum =**	30	30	40	30		
	25 Percentile =	43	33	40	36		
	Median =	50	45	45	40		
	75 Percentile =	58	58	50	40		
	Maximum =	60	60	50	50		

Table A15. (Cont'd).

Event Name	Full Description of Issue	Expert-opinion elicitation								
		First Response			Second Response				Confidence	
Valves fail in the hyraulic drive system during normal operation	What is the expected characterisitic life for the different valves identified?	Manual	Solenoid	Proportional	Manual	Solenoid	Proportional	Manual	Solenoid	Proportional
	Expert #1	70	40	40	70	40	40	high	med	med
	Expert #2	60	40	40	60	40	40	high	med	med
	Expert #3	60	30	40	60	35	40	high	high	high
	Expert #4	60	50	30	60	45	30	high	med	med
	Expert #5	50	25	50	60	40	50	high	med	med
	Expert #6	50	40	30	60	40	30	med	med	med
Summary Table	**Minimum =**	50	25	30	60	35	30			
	25 Percentile =	53	33	33	60	40	33			
	Median =	60	40	40	60	40	40			
	75 Percentile =	60	40	40	60	40	40			
	Maximum =	70	50	50	70	45	50			

Table A16. Mechanical system – pumps.

Event Name	Full Description of Issue	Expert-opinion elicitation					
		First Response		Second Response		Confidence	
Pump fail in the hyraulic drive system during normal operation	What is the expected characterisitic life for the different pumps identified?	Fixed	Variable	Fixed	Variable	Fixed	Variable
	Expert #1	50	45	50	45	high	high
	Expert #2	75	40	60	30	high	high
	Expert #3	45	45	50	40	high	med
	Expert #4	50	25	50	25	high	high
	Expert #5	50	45	50	30	high	high
	Expert #6	80	60	50	25	high	high
Summary Table	**Minimum =**	45	25	50	25		
	25 Percentile =	50	41	50	26		
	Median =	50	45	50	30		
	75 Percentile =	69	45	50	38		
	Maximum =	80	60	60	45		

Table A17. Mechanical system – hydraulic motors.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response – Fixed	First Response – Variable	Second Response – Fixed	Second Response – Variable	Confidence – Fixed	Confidence – Variable
Hydraulic motor fails in the hydraulic drive system during normal operation	What is the expected characterisitic life for the hydraulic motor identified?						
	Expert #1	40	40	40	40	high	med
	Expert #2	40	30	40	30	high	med
	Expert #3	50	35	50	35	high	med
	Expert #4	50	25	50	25	high	high
	Expert #5	50	30	50	30	high	high
	Expert #6	50	25	50	25	high	high
Summary Table	**Minimum =**	40	25	40	25		
	25 Percentile =	43	26	43	26		
	Median =	50	30	50	30		
	75 Percentile =	50	34	50	34		
	Maximum =	50	40	50	40		

Table A18. Mechanical system – piping.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Piping fails in the hydraulic drive system during normal operation	What is the expected characterisitic life for the piping identified?	Piping	Piping	Piping
	Expert #1	50	50	med
	Expert #2	40	40	high
	Expert #3	40	40	high
	Expert #4	40	40	high
	Expert #5	50	50	med
	Expert #6	40	40	med
Summary Table	**Minimum =**	40	40	
	25 Percentile =	40	40	
	Median =	40	40	
	75 Percentile =	48	48	
	Maximum =	50	50	

Table A19. Mechanical system – wheel assembly (rollers).

Event Name	Full Description of Issue	Expert-opinion elicitation		
		First Response	Second Response	Confidence
Wheel Assembly fails during normal operation	What is the expected characterisitic life for the wheel assembly identified?	Wheel Assembly	Wheel Assembly	Wheel Assembly
	Expert #1	10	40	high
	Expert #2	40	40	high
	Expert #3	40	40	med
	Expert #4	50	40	med
	Expert #5	40	40	high
	Expert #6	40	40	med
Summary Table	**Minimum =**	10	40	
	25 Percentile =	40	40	
	Median =	40	40	
	75 Percentile =	40	40	
	Maximum =	50	40	

Table A20. Mechanical system – pintles/bushings.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Pintles or Gudgeon/Trunnion pins fail during normal operation	What is the expected characterisitic life for the Pintles/Bushings identified?			
		Pintles/Bushings	Pintles/Bushings	Pintles/Bushings
	Expert #1	75	60	med
	Expert #2	30	30	high
	Expert #3	30	30	high
	Expert #4	25	30	high
	Expert #5	40	40	med
	Expert #6	30	30	high
Summary Table	**Minimum =**	25	30	
	25 Percentile =	30	30	
	Median =	30	30	
	75 Percentile =	38	38	
	Maximum =	75	60	

Table A21. Mechanical system – gudgeon/trunnion.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Pintles or Gudgeon/Trunnion pins fail during normal operation	What is the expected characterisitic life for the Gudgeon/Bushings identified?			
		Gudgeon/Bushings	Gudgeon/Bushings	Gudgeon/Bushings
	Expert #1	50	50	med
	Expert #2	50	40	high
	Expert #3	40	40	high
	Expert #4	30	35	med
	Expert #5	45	50	med
	Expert #6	50	45	med
Summary Table	**Minimum =**	30	35	
	25 Percentile =	41	40	
	Median =	48	43	
	75 Percentile =	50	49	
	Maximum =	50	50	

Table A22. Mechanical system – trunnion pin/bushings.

Event Name	Full Description of Issue	Expert-opinion elicitation		
		First Response	Second Response	Confidence
Pintles or Gudgeon/Trunnion pins fail during normal operation	What is the expected characterisitic life for the Trunnion Pin/Bushings identified?	Trunnion Pin/Bushings	Trunnion Pin/Bushings	Trunnion Pin/Bushings
	Expert #1	15	25	med
	Expert #2	25	30	high
	Expert #3	40	40	high
	Expert #4	45	40	high
	Expert #5	35	35	high
	Expert #6	35	40	high
Summary Table	**Minimum =**	15	25	
	25 Percentile =	28	31	
	Median =	35	38	
	75 Percentile =	39	40	
	Maximum =	45	40	

Table A23. Mechanical system – strut spindle pin.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Gate connection fails during normal operation	What is the expected characterisitic life for the strut spindle pin identified?			
		Strut Spindle Pin	Strut Spindle Pin	Strut Spindle Pin
	Expert #1	25	25	high
	Expert #2	20	25	high
	Expert #3	40	25	high
	Expert #4	20	20	high
	Expert #5	40	25	high
	Expert #6	25	25	high
Summary Table	**Minimum =**	20	20	
	25 Percentile =	21	25	
	Median =	25	25	
	75 Percentile =	36	25	
	Maximum =	40	25	

Table A24. Mechanical system – tow haulage system.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response – Hydraulic	First Response – Mechanical	Second Response – Hydraulic	Second Response – Mechanical	Confidence – Hydraulic	Confidence – Mechanical
Tow Haulage system fails during normal operation	What is the expected characterisitic life for the tow haulauge system identified?						
	Expert #1	35	40	35	50	med	high
	Expert #2	40	40	30	40	med	med
	Expert #3	35	45	35	45	med	high
	Expert #4	20	20	30	30	med	med
	Expert #5	50	60	30	60	med	med
	Expert #6	25	50	25	50	med	low
Summary Table	**Minimum =**	20	20	25	30		
	25 Percentile =	28	40	30	41		
	Median =	35	43	30	48		
	75 Percentile =	39	49	34	50		
	Maximum =	50	60	35	60		

Table A25. Mechanical system – emptying/filling systems.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response – Butterfly	First Response – Vertical Lift	Second Response – Butterfly	Second Response – Vertical Lift	Confidence – Butterfly	Confidence – Vertical Lift
Emptying or filling system fails during normal operation	What is the expected characterisitic life for the different emptying and filling systems identified?						
	Expert #1	40	35	40	40	med	med
	Expert #2	50	30	50	50	med	med
	Expert #3	40	50	40	50	med	high
	Expert #4	60	50	60	50	med	high
	Expert #5	50	40	50	50	med	med
	Expert #6	40	50	50	50	med	med
Summary Table	**Minimum =**	40	30	40	40		
	25 Percentile =	40	36	43	50		
	Median =	45	45	50	50		
	75 Percentile =	50	50	50	50		
	Maximum =	60	50	60	50		

Appendix B: Expert Elicitation Spreadsheets – Electrical System Components

Table B1. Electrical system – power utility.

Event Name	**Full Description of Issue**	**Expert-opinion elicitation**		
		First Response	**Second Response**	**Confidence**
Power utility (commercial) fails during normal operation	What is the expected characterisitic life for the power utility (commercial) identified?	Power Utility	Power Utility	Power Utility
	Expert #1	10	10	high
	Expert #2	1	1	med
	Expert #3	5	3	med
	Expert #4	5	3	high
	Expert #5	5	5	high
	Expert #6	10	5	med
Summary Table	**Minimum =**	1	1	
	25 Percentile =	5	3	
	Median =	5	4	
	75 Percentile =	9	5	
	Maximum =	10	10	

Table B2. Electrical system – service transformer.

Event Name	Full Description of Issue	Expert-opinion elicitation		
		First Response	Second Response	Confidence
Service transformer fails in the electrical power system during normal operation	What is the expected characterisitic life for the service transformer identified?	Service Transformer	Service Transformer	Service Transformer
	Expert #1	30	50	med
	Expert #2	40	40	med
	Expert #3	60	60	med
	Expert #4	50	60	high
	Expert #5	50	60	high
	Expert #6	40	50	high
Summary Table	**Minimum =**	30	40	
	25 Percentile =	40	50	
	Median =	45	55	
	75 Percentile =	50	60	
	Maximum =	60	60	

Table B3. Electrical system – transfer switch.

Event Name	Full Description of Issue	Expert-opinion elicitation					
		First Response		Second Response		Confidence	
		Automatic	Manual	Automatic	Manual	Automatic	Manual
Transfer switch fails in the electrical power system during normal operation	What is the expected characterisitic life for the transfer switches identified?						
	Expert #1	30	40	40	70	high	high
	Expert #2	40	60	30	60	high	high
	Expert #3	40	70	30	75	high	high
	Expert #4	20	80	25	80	high	med
	Expert #5	15	40	20	60	high	high
	Expert #6	30	60	30	60	high	high
Summary Table	**Minimum =**	15	40	20	60		
	25 Percentile =	23	45	26	60		
	Median =	30	60	30	65		
	75 Percentile =	38	68	30	74		
	Maximum =	40	80	40	80		

Table B4. Electrical system – switchgear.

Event Name	**Full Description of Issue**	**Expert-opinion elicitation**		
		First Response	**Second Response**	**Confidence**
Switchgear fails in the electrical power system during normal operation	What is the expected characterisitic life for the switchgear identified?	Switchgear	Switchgear	Switchgear
	Expert #1	50	75	med
	Expert #2	50	70	med
	Expert #3	90	90	med
	Expert #4	65	85	high
	Expert #5	40	70	high
	Expert #6	60	80	med
Summary Table	**Minimum =**	40	70	
	25 Percentile =	50	71	
	Median =	55	78	
	75 Percentile =	64	84	
	Maximum =	90	90	

Table B5. Electrical system – circuit breakers.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Circuit breakers fails in the electrical power system during normal operation	What is the expected characterisitic life for the circuit breakers identified?			
		Circuit Breaker	Circuit Breaker	Circuit Breaker
	Expert #1	40	50	high
	Expert #2	30	40	med
	Expert #3	40	70	high
	Expert #4	70	75	high
	Expert #5	50	70	high
	Expert #6	55	55	med
Summary Table	**Minimum =**	30	40	
	25 Percentile =	40	51	
	Median =	45	63	
	75 Percentile =	54	70	
	Maximum =	70	75	

Table B6. Electrical system – power panelboard.

Event Name	Full Description of Issue	Expert-opinion elicitation		
		First Response	**Second Response**	**Confidence**
Circuit breakers fails in the electrical power system during normal operation	What is the expected characterisitic life for the power panelboard identified?	Power Panelboard	Power Panelboard	Power Panelboard
	Expert #1	25	75	med
	Expert #2	40	60	med
	Expert #3	60	90	med
	Expert #4	90	80	high
	Expert #5	80	80	high
	Expert #6	70	70	med
Summary Table	**Minimum =**	25	60	
	25 Percentile =	45	71	
	Median =	65	78	
	75 Percentile =	78	80	
	Maximum =	90	90	

Table B7. Electrical system – cables.

Event Name	Full Description of Issue	Expert-opinion elicitation					
		First Response		Second Response		Confidence	
Cables fails in the electrical power system during normal operation	What is the expected characterisitic life for the cables identified?	Buried/Submerged	Duct/Cable Tray	Buried/Submerged	Duct/Cable Tray	Buried/Submerged	Duct/Cable Tray
	Expert #1	75	75	75	75	med	med
	Expert #2	50	80	50	80	med	med
	Expert #3	70	100	70	100	med	med
	Expert #4	30	80	60	80	high	high
	Expert #5	40	75	60	80	high	high
	Expert #6	60	100	60	80	med	med
Summary Table	**Minimum =**	30	75	50	75		
	25 Percentile =	43	76	60	80		
	Median =	55	80	60	80		
	75 Percentile =	68	95	68	80		
	Maximum =	75	100	75	100		

Table B7. (Cont'd).

Event Name	Full Description of Issue	Expert-opinion elicitation		
		First Response	Second Response	Confidence
Cables fails in the electrical power system during normal operation	What is the expected characterisitic life for the cables identified?			
		Portable/Flexible	Portable/Flexible	Portable/Flexible
	Expert #1	30	30	low
	Expert #2	30	30	med
	Expert #3	25	25	high
	Expert #4	20	20	high
	Expert #5	20	25	high
	Expert #6	35	35	med
Summary Table	**Minimum =**	20	20	
	25 Percentile =	21	25	
	Median =	28	28	
	75 Percentile =	30	30	
	Maximum =	35	35	

Table B8. Electrical system – bus duct.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Bus duct fails in the electrical power system during normal operation	What is the expected characterisitic life for the bus duct identified?			
		Electronic	Electronic	Electronic
	Expert #1	75	90	high
	Expert #2	100	100	high
	Expert #3	150	120	high
	Expert #4	90	85	low
	Expert #5	80	80	med
	Expert #6	100	100	low
Summary Table	**Minimum =**	75	80	
	25 Percentile =	83	86	
	Median =	95	95	
	75 Percentile =	100	100	
	Maximum =	150	120	

Table B9. Electrical system – switchboards.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Switchboard fails in the electrical power system during normal operation	What is the expected characterisitic life for the switchboards identified?			
		Switchboards	Switchboards	Switchboards
	Expert #1	50	80	med
	Expert #2	60	75	med
	Expert #3	90	90	med
	Expert #4	90	85	med
	Expert #5	60	75	med
	Expert #6	90	90	med
Summary Table	**Minimum =**	50	75	
	25 Percentile =	60	76	
	Median =	75	83	
	75 Percentile =	90	89	
	Maximum =	90	90	

Table B10. Electrical system – motor control center.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Bus duct fails in the electrical power system during normal operation	What is the expected characterisitic life for the motor control center identified?			
		MCC	MCC	MCC
	Expert #1	50	80	med
	Expert #2	60	75	med
	Expert #3	90	90	med
	Expert #4	90	85	med
	Expert #5	60	75	med
	Expert #6	90	90	med
Summary Table	**Minimum =**	50	75	
	25 Percentile =	60	76	
	Median =	75	83	
	75 Percentile =	90	89	
	Maximum =	90	90	

Table B11. Electrical system – motor starters.

Event Name	Full Description of Issue	Expert-opinion elicitation								
		First Response			Second Response				Confidence	
		Full Voltage	Reduced/Variable	VFDs	Full Voltage	Reduced/Variable	VFDS	Full Voltage	Reduced/Variable	VFDS
Motor starter fails in the electrical motor control system during normal operation	What is the expected characterisitic life for the motor starters identified?									
	Expert #1	30	15	15	60	50	40	high	med	med
	Expert #2	40	30	20	60	50	40	high	med	med
	Expert #3	80	60	40	80	60	40	high	med	low
	Expert #4	70	50	40	65	50	30	high	med	low
	Expert #5	60	60	25	65	60	25	high	high	low
	Expert #6	60	50	25	60	50	25	med	med	low
Summary Table	**Minimum =**	30	15	15	60	50	25			
	25 Percentile =	45	35	21	60	50	26			
	Median =	60	50	25	63	50	35			
	75 Percentile =	68	58	36	65	58	40			
	Maximum =	80	60	40	80	60	40			

Table B12. Electrical system – PLC systems.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
PLC system fails in the electrical motor control system during normal operation	What is the expected characterisitic life for the PLC system identified?	PLC System	PLC System	PLC System
	Expert #1	25	25	med
	Expert #2	20	20	med
	Expert #3	40	40	med
	Expert #4	25	25	high
	Expert #5	25	25	high
	Expert #6	25	25	high
				7.5
Summary Table	**Minimum =**	20	20	
	25 Percentile =	25	25	
	Median =	25	25	
	75 Percentile =	25	25	
	Maximum =	40	40	

Table B13. Electrical system – sensors and switches.

Event Name	Full Description of Issue	Expert-opinion elicitation					
		First Response		Second Response		Confidence	
Sensors and switches fails in the electrical motor control system during normal operation	What is the expected characterisitic life for the sensors and switches identified?	Selsyn Motor	Travelling nut limit switch	Selsyn Motor	Travelling nut limit switch	Selsyn Motor	Travelling nut limit switch
	Expert #1	30	50	30	50	med	high
	Expert #2	30	30	30	60	med	high
	Expert #3	90	70	80	70	med	med
	Expert #4	100	105	45	100	med	high
	Expert #5	70	80	60	80	med	med
	Expert #6	40	75	40	50	med	low
Summary Table	**Minimum =**	30	30	30	50		
	25 Percentile =	33	55	33	53		
	Median =	55	73	43	65		
	75 Percentile =	85	79	56	78		
	Maximum =	100	105	80	100		

Table B14. Electrical system – electric motors.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Electric motors fails during normal operation	What is the expected characterisitic life for the electric motors identified?	Electric Motors	Electric Motors	Electric Motors
	Expert #1	55	60	med
	Expert #2	50	60	med
	Expert #3	70	80	med
	Expert #4	80	80	med
	Expert #5	85	75	med
	Expert #6	60	60	med
Summary Table	**Minimum =**	50	60	
	25 Percentile =	56	60	
	Median =	65	68	
	75 Percentile =	78	79	
	Maximum =	85	80	

Table B15. Electrical system – standby generator set.

Event Name	Full Description of Issue	Expert-opinion elicitation: First Response	Expert-opinion elicitation: Second Response	Confidence
Standby generator (diesel or natural gas) fails during normal operation	What is the expected characterisitic life for the standby generator system identified?			
		Standby Generator Set	Standby Generator Set	Standby Generator Set
	Expert #1	25	40	med
	Expert #2	40	40	high
	Expert #3	50	50	high
	Expert #4	70	70	med
	Expert #5	50	50	high
	Expert #6	50	50	high
Summary Table	**Minimum =**	25	40	
	25 Percentile =	43	43	
	Median =	50	50	
	75 Percentile =	50	50	
	Maximum =	70	70	

Table B16. Electrical system – DC rectifier.

Event Name	Full Description of Issue	Expert-opinion elicitation		
		First Response	Second Response	Confidence
Brake system fails during normal operation	What is the expected characterisitic life for the DC rectifier identified?	DC Rectifier	DC Rectifier	DC Rectifier
	Expert #1	25	30	high
	Expert #2	40	40	high
	Expert #3	30	30	high
	Expert #4	10	25	low
	Expert #5	50	40	high
	Expert #6	45	45	med
Summary Table	**Minimum =**	10	25	
	25 Percentile =	26	30	
	Median =	35	35	
	75 Percentile =	44	40	
	Maximum =	50	45	

Appendix C: Results from Flood Risk Management ME Expert-Opinion Elicitation

An additional study was conducted using the same experts to elicit the characteristic lives of ME equipment at flood control projects. The values reflect the operation, maintenance, and environment to which they are exposed, and the consensus of the experts to a national standard that could be adjusted using k-factors as discussed in EC 1110-2-6062 (HQUSACE 2011).

Tables C1 and C2 list the final results, which provide the basis to compare the characteristic lives of the similar navigation ME components.

Table C1. Flood risk management ME expert-opinion results for mechanical components for navigation and dam projects (mechanical drive systems).

Type	Component	Navigation Components CL (years)	Flood Reduction Components CL (years)
Bearings			
	Rolling element	40	60
	Sleeve (self lubricated)	25	20
	Bronze sleeve	40	60
Couplings			
	Flexible	35	40
	Rigid	50	60
Shafts		80	100
Pins		35	70
Gear reducers			
	Worm	25	40
	Parallel	40	60
	Right angle	38	40
Open gearing			
	Spur	60	100
	Helical	38	100
	Bevel	40	50
	Rack	60	80
Brake	Electromechanical	45	60
Clutch	Slip	30	—
	Jaw	—	70
Wire ropes			

Type	Component	Navigation Components CL (years)	Flood Reduction Components CL (years)
	Spiral plate	5	—
	Single/multiple sheave(s)	20	—
	Single Drum	28	—
	Round	—	50
	Flat	—	20
Wire rope drums		75	100
Wire rope sheaves		33	50
Chains	Roller	40	60
	Link	—	40
Chain sprocket		60	75
Miter gates			
	Sector arms	73	—
	Strut arms - buffered	35	—
	Strut arms - rigid	50	—
	Support roller	43	—
	Rack support beam	60	—
Valves			
	Bellcranks	78	—
	Crosshead/guide	73	—
	Strut	43	—
	Butterfly	—	50
	Ball	—	50
	Slide	—	50
	Knife	—	50
	Jet	—	50

Table C2. Flood risk management ME expert-opinion results for mechanical components for navigation and dam projects.

Type	Component	Navigation Components CL (years)	Flood Reduction Components CL (years)
Hydraulic cylinder		60	60
Control valves			
	Check	45	40
	Relief	40	40
	Directional		
	Manual	60	60
	Solenoid	40	40
	Proportional/throttle	40	40
Pumps			
	Fixed	50	60
	Variable	30	35
Hydraulic Motors			
	Fixed	50	—
	Variable	30	—
Piping		40	40
Hose		—	25
Misc Gate/Filling Emptying Valves			
Wheel assembly (rollers)		40	50
Pintles/bushings		30	—
Gudgeon pin/bushings		43	—
Trunnion pin/bushings		38	60
Strut spindle pin		25	—
Other Systems			
Tow haulage			
	Hydraulic	30	—
	Mechanical	48	—
Emptying filling			
	Butterfly	50	—
	Vertical lift	50	—
Gate connection (pins, cable, chain)		—	50
Grease/lube system		—	30
Actuators (screw type, limit torque)		—	50

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14. ABSTRACT
This work developed the use of Expert-Opinion Elicitation (EOE) to help estimate the characteristic life (CL) of mechanical and electrical (ME) components at US Army Corps of Engineers (USACE) navigation projects. This effort developed improved reliability models for the ME components at the USACE navigation facilities. Current USACE ME reliability methods use generic component failure rate data from US Department of Defense (DoD) Military Standard (MIL-STD) 756B, in which failure rate data is processed for components that function in operating environments, failure modes, and maintenance practices different from those at USACE navigation and flood risk management projects. The reliability of the ME system from this data set yields very conservative results, very often overestimating the time-dependent reliability of the entire ME system. EOE will be used to define the CL for a list of critical ME components at USACE navigation and flood risk management projects. These elicited values for CL will form the basis for failure rates to be used with the existing methods for ME system reliability calculations. Additional work on fault trees for ME systems is being completed as part of dam safety and levee risk assessment procedures development.

15. SUBJECT TERMS
characteristic life, Delphi method, electrical failures, Expert-Opinion Elicitation, flood control dams, flood risk management

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