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Figures

G-4 PROBABILITY OF FAILURE OF MECHANICAL OR ELECTRICAL SYSTEMS ON DAM GATES

G-4.1 Key Concepts

Numerous types of gates are used to release flow from dams. Tainter gates, drum gates vertical lift gates, etc. are just a few of the many being used throughout the world. Each gate has its own operating system which must function when needed. Throughout history man has operated gates to control the flow of water. The early Egyptians diverted water by manually opening and closing wood gates. Although the equipment to perform this task has changed greatly throughout history the final result stays the same. Gates must be operated to perform their intended task. To control operation of gates three things must be provided: Power to move the gates, machinery to operate the gate, and the structural gate itself.

Power can be supplied in numerous ways. Manual power is the oldest and supplest means to operate a gate. Manual power references a means by which a human or animal physically provides the energy to move the object, in this case a gate. Modern types of manual devices which are commonly used to move gate are hand wheel screw actuators. These devices are often mechanized by electric motors which perform the task of providing the power to operate a gate.

The next step up in operation of gates is the electric winch or hoist. These devices are common on gates. Power to operate these types of systems is dependent on electrical service. Almost all dam gates throughout the world rely on some type of electrical service to operate. Because of this, the probability of failure of the electrical system is the first item on any event tree in the potential failure of operation of a gate. Because of the importance of electrical power at any facility the emergency backup generator has become the standard for redundancy to supply power.

The second critical system which must operate is the machinery. Machinery to operate gates varies as much as the types of gates. Typical gates use winches, hoists or hydraulics to operate. Winches and hoists have numerous types of lifting equipment. They can be manually operated or more commonly electrically operated. Some are even hydraulically operated. The types of lifting devices on winches and hoists vary also. Wire ropes and chains are the most common. Each has its advantages.

The latest means to operate gates is by use of hydraulics. A hydraulic system is dependent on not only electrical power but also hydraulic fluid and the means to transfer the fluid.

The third critical component in any system is the gate itself. For this presentation we will restrict the development of calculating the probability of failure of the system to just the mechanical and electrical systems.

All of these systems have a probability of failure. It's this probability that will be addressed in this paper and how it relates to the overall potential of failure of the dam and the risk assessment.

Various means are used to obtain the needed information to determine the reliability of operating system of gates. Two of the most common means are expert elicitation and statistical formulas. This chapter will address how to use statistical formulas to predict probability of failure of gates on dams.

Many dams have multiple gates used for releasing water. Depending upon the flow needed to pass during normal and high flow events determines the criticality of gate operation. If the flow volume needed to pass exceeds the available gate opening capability then, mechanical, and electrical failure of structural gate operation becomes a critical failure mode. If electrical failure at the project occurs all gates are out of service thus creating a critical failure mode for the project. If one or multiple gates are out of service due to mechanical or structural failure, then binomial distribution is used to determine what the probability of "N" out of "M" gates will fail. First one must determine what the probability of an individual gate failure would be and then use binomial distribution to determine how many gates could fail. Therefore, the engineers developing the probability of failure of gates work closely with hydraulic engineers to determine how gate malfunctions affect risk of overtopping or failure of the dam. Failure of gates will alter the hydrographs such that it could potentially result in a normal event turning into an unusual high pool event due to inability to release water.

G-4.2   Probability of Failure of a System

Before one can calculate the probability of failure to operate a gate one must know the various components which make up the system and the probability of each components failure. To determine which components are critical to operation of a gate one must consider all the components from connection to the gate back through the operators and through the electrical power source. If any of the components fail, then the system fails. To calculate the probability of failure of a component statistical formulas are used, one such is the Weibull Distribution formula. The Weibull Distribution was developed in 1937 by Swedish born, Waloddi Weibull and is shown as:

$$R(T) = e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}}$$

Equation G-4-1

Where:

$R(T)$ = *Reliability*
T   = Time
γ = Location Parameter
β = Shape Parameter
η = Characteristic Life

From this, the cumulative distribution function (CDF) or cumulative probability of failure is computed as $F(T) = 1 - R(T)$

The Weibull formula does not take into account time when components are not in use. Operating gates are an example if a machine that can site for long periods of time without being used. Some components tend to corrode or not work after extended periods without operation. Therefore, a modified version of the formula called (Dormant-Weibull Formula) is often used.

G-4.2.1   Dormant-Weibull Formula

The derivation of the Dormant-Weibull formula was provided to the United States Army Corps of Engineers (USACE) by the fault free software developer, Isograph (2008). Also see Reliability and Risk Assessment, equation 4.48 on page 187 (Henley and Kumamoto).

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

Equation G-4-2

Where:

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 Dormant-Weibull model is a new failure model that allows the user to model a component or system that undergoes periodic operation or testing, but is also subject to aging; i.e., the failure rate increases with time. This model also represents a component whose failure will be revealed due to periodic usage during normal operations.

G-4.2.2   Unavailability/Probability of Failure Profile

Figure G-4-1 shows the unavailability profile for a normal, non-repairable Weibull distribution. The Weibull parameters are $\eta = 100$, $\beta = 2$ and $\gamma = 0$, and the lifetime of the component is 100 (all Weibull distributions represented in this document will have these properties, unless stated otherwise). The distribution is a smooth curve that goes asymptotically towards an unavailability of 1.
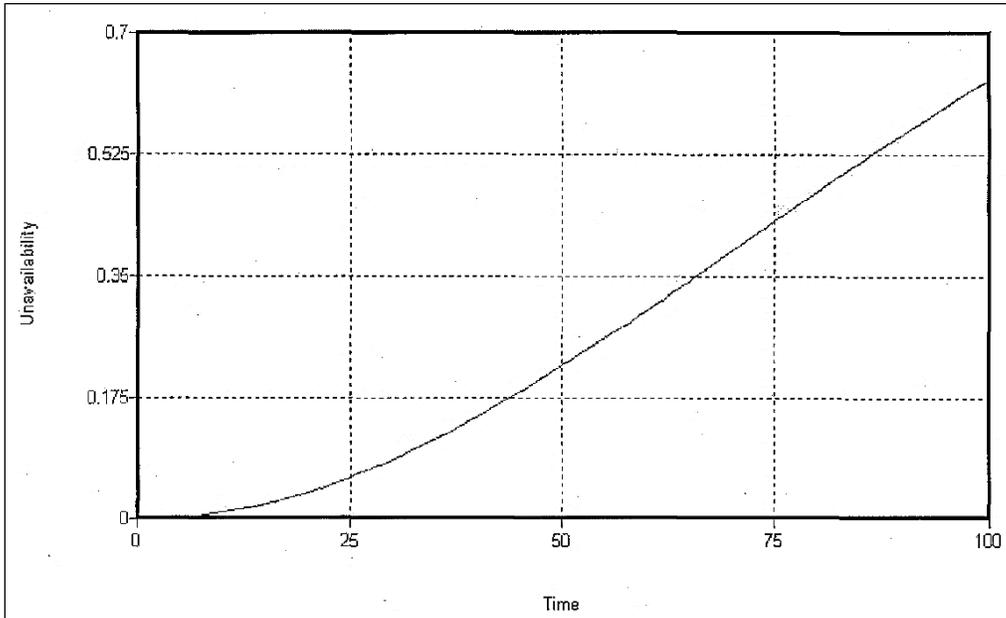
Figure G-4-1.—The unavailability profile for a component modeled using Weibull model.

When using the Dormant-Weibull model, the equation assumes that the component will be functioning after each inspection takes place; i.e., if the inspection reveals a failure it will be repaired. Figure G-4-2 shows the unavailability profile for a component, which ages with a single Weibull distribution. In this case the failures are dormant, and the inspection period is 20 years.

Note that after each inspection the unavailability increases rapidly. This is because even though the component is assumed to be functioning after the inspection, the age of the component is unchanged. Hence the failure rate will increase more rapidly after each inspection, reflecting the increasing age of the component.

Whereas unavailability, $Q(t)$ is defined as the probability of a component being failed at time t, the unreliability, $F(t)$ is the probability that a component has failed
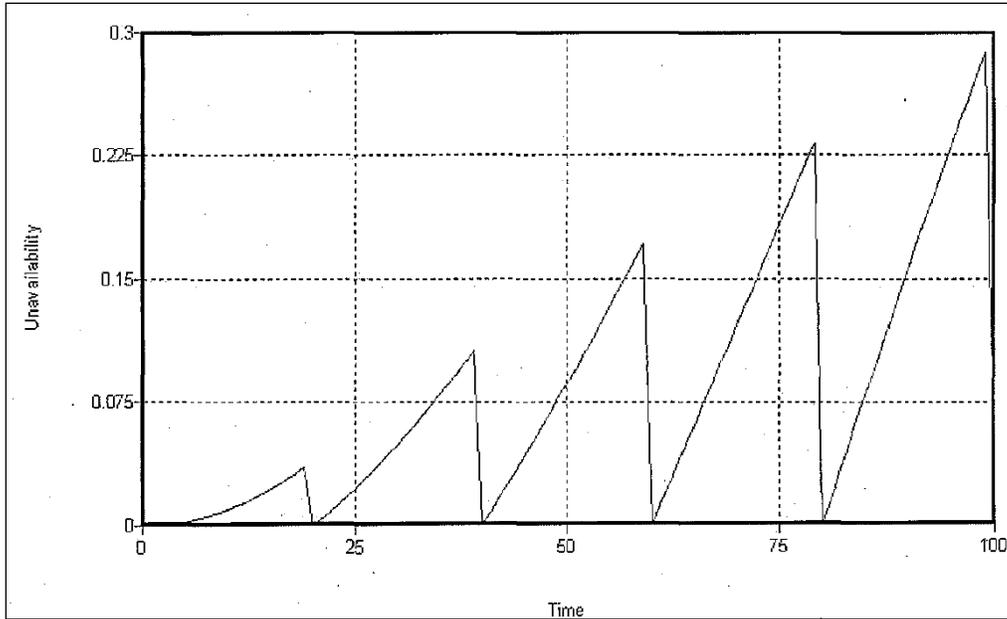
Figure G-4-2.—The unavailability profile for a component modeled using the Dormant-Weibull model.

at some point between time 0 and time t. Put simply, the reliability is the probability of the first failure having occurred by time t, assuming the component was working at time O.

If the age of the component is unaffected by inspections, as is the case in the Dormant-Weibull model, the unreliability profile will be smooth. For this reason,-the shape of the unreliability profile for a component modeled using a Dormant-Weibull model will be smooth, regardless of whether or not inspections take place (figure G-4-3).

G-4.2.3   Software Approximation

In order to get exact point and mean values of unavailability for a component or system modeled using the Dormant-Weibull model, it would be necessary to perform a numerical integration over the unavailability profile. However, such a procedure would be highly intensive and thus not practical from a processing standpoint.

In order to overcome this problem, software programs use an approximation to determine these values. Essentially, the program employs the maximum risk Dormant-Weibull model during each interval between inspections. That is, the maximum value of unavailability at the end of each inspection interval is taken to be the unavailability for that period. This is illustrated on figure G-4-4. This approach is consistent with fault tree analysis standards.
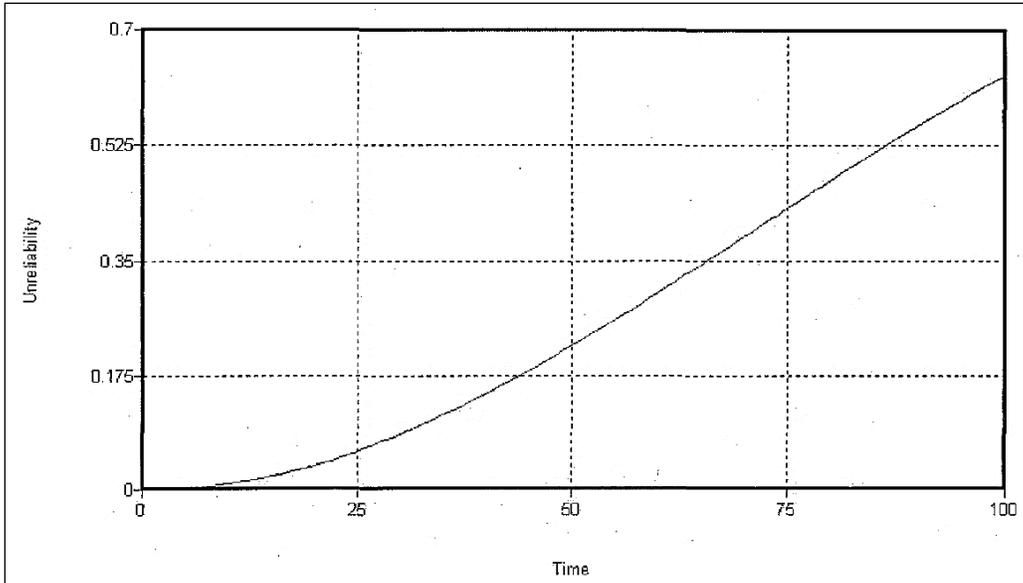
Figure G-4-3.—The unreliability profile for a component modeled using either the Dormant-Weibull model or Weibull model. (Note that the unreliability at 100 years is 63.21% or what is termed the B63.2 life, which is typical for a Weibull distribution).
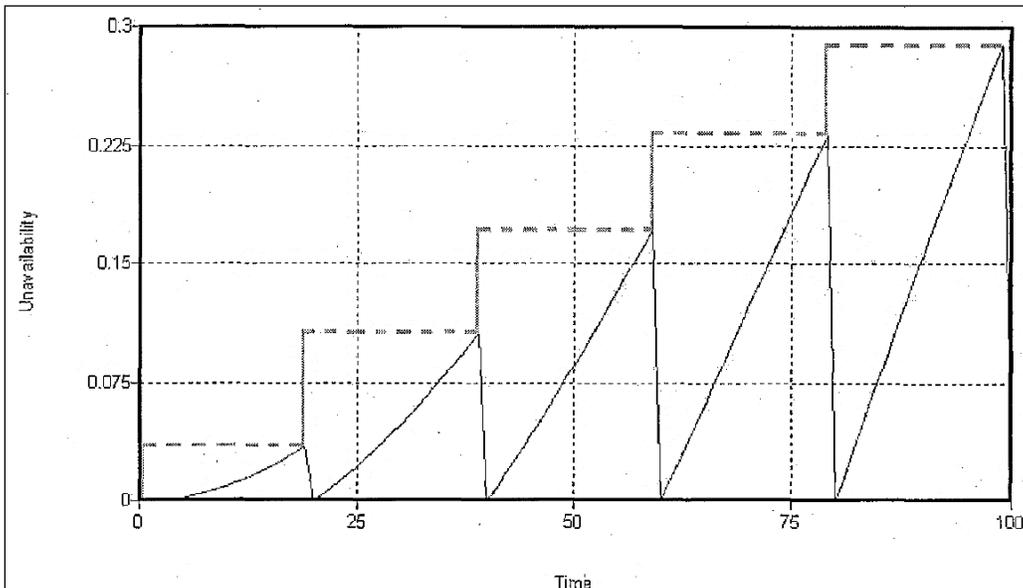
Figure G-4-4.—The unavailability profile for a component modeled using the Dormant-Weibull model. The dotted line represents the value of unavailability used by software for the unavailability during each interval.

G-4.2.4   Results

For any component that is subject to dormant failures, the introduction of
inspections will improve both point and mean values of unavailability. This is
because repairs can only take place after inspections due to the dormant nature of
the failures.

This can be illustrated by comparing figures G-4-1 and G-4-2. Note that both the
point unavailability at the lifetime and the mean unavailability are noticeably less
on figure G-4-2 where an inspection is taking place at regular intervals, compared
to figure G-4-1, which represents a non-repairable component.

Furthermore, more frequent inspections will further reduce the
unavailability/probability of failure of the component. This is illustrated
on figures G-4-5 and G-4-6, which show the unavailability profile for
components with identical Weibull parameters, and inspection intervals of
10 and 50, respectively. Note that the component with inspections 10 apart has
a lower unavailability than that with inspections 50 apart.

**Figure G-4-5.—The unavailability profile for a component modeled using the
Dormant-Weibull model with an inspection interval of 10.**

The unreliability is unaffected by the length of the inspection interval. Again,
this is because the age of the component remains unchanged by an inspection,
regardless of whether a repair is required or not. The only way to change the
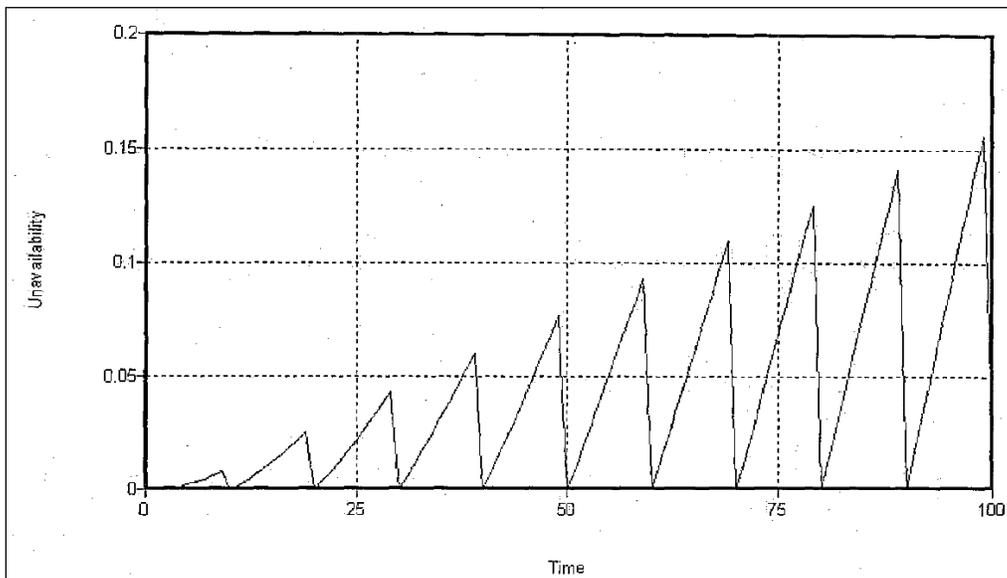unreliability profile for such a component would be to alter the Weibull
parameters.
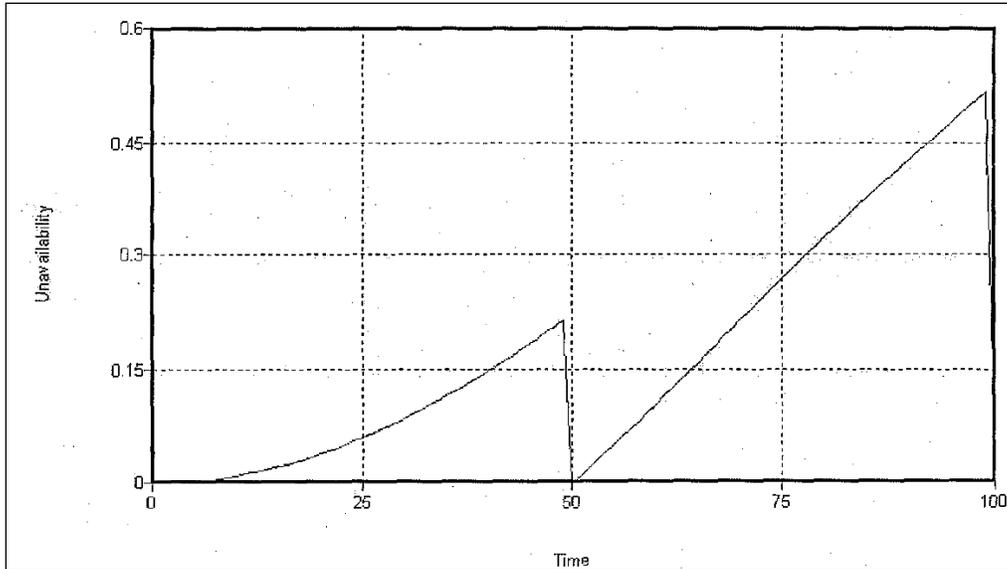
Figure G-4-6.—The unavailability profile for a component modeled using the Dormant-Weibull model with an inspection interval of 50.

G-4.3   Derivation of Unreliability

For an event of failure rate $\lambda(t)$, unreliability $F(t)$ is given by:

$$F(t) = 1 - \exp\left(-\int_{(n-1)\tau}^{n\tau} \lambda(t)dt\right)$$

Equation G-4-3

(See Reliability and Risk Assessment, equation 4.48 on page 187 (Henley and Kumamoto.)

Note that the limits of the integral are nt and (n-1)-T. This represents non-repairable period between inspections with interval τ: The integral in the above expression is solved as follows:

$$\int_{(n-1)\tau}^{n\tau} \lambda(t)dt = \int_{(n-1)\tau}^{n\tau} \frac{\beta(t-\gamma)^{\beta-1}}{\eta^\beta}dt$$

$$= \frac{\beta}{\eta^\beta}\left[\frac{(t-\gamma)^\beta}{\beta}\right]_{(n-1)\tau}^{n\tau}$$

Equation G-4-4

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

Substituting back into the term for the unreliability, $F(t)$, we get the unreliability at the end of an inspection interval, F_n:

$$F_n = 1 - \exp\left(-\frac{(n\tau - \gamma)^\beta}{\eta^\beta} + \frac{((n-1)\tau - \gamma)^\beta}{\eta^\beta}\right)$$

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

Equation G-4-5

For a non-repairable component, F_n is the same as the unavailability (probability of failure on demand), Q_n. Hence, the Dormant-Weibull formula:

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

Equation G-4-6

G-4.4 Key Elements to Using the Weibull/Dormant-Weibull Formula

G-4.4.1 First Key Element in the Weibull Formulas

$$\eta = Characteristic\ life$$

Definition.—The characteristic life is the point in time when we could expect 63.2 percent (%) of the components under study to have failed. This is called the B63.2 life (Abernathy 2009).

Example Its determined that the characteristic life of a component is 25 years, then one would expect to have 63 of 100 components fail by that time in history.

The most accurate means to determining characteristic life of components is to collect data on the number of components which have failed and the length of time the component lasted until failure. In addition, it is also necessary to collect data on the number and length of time for similar components that are still in operation. This is commonly called suspended components.

Characteristic life is traditionally gathered through testing of thousands of samples in a controlled laboratory environment. The USACE has performed and extensive data collection of its mechanical and electrical equipment on flood risk management projects throughout the United States. Example of typical results of the data collection for an electric motor at USACE FRM dams is shown in table G-4-1.

Table G-4-1.—Example of Data Collected on Electric Motors on USACE, Flood Control Dams

Age in Years	Number Replaced or Failed	Age in Years	Number Suspended	Age in Years	Number Suspended
16	2	1	42	43	36
20	1	2	26	44	28
21	2	3	16	45	19
22	2	4	30	46	14
23	1	5	11	47	32
26	1	6	25	48	89
30	2	7	28	49	55
36	6	8	7	50	41
37	5	9	6	51	47
38	7	10	20	52	22
39	22	11	6	53	10
40	8	12	4	54	23
41	16	14	20	55	13
42	14	17	6	56	40
43	26	19	2	57	8
44	3	20	7	58	94
45	4	21	11	59	71
47	2	22	5	60	35
49	1	23	5	61	78
50	3	24	17	62	64
51	22	26	23	63	53
53	8	28	2	64	35
54	4	29	18	65	47
56	2	30	9	68	22
57	9	31	15	69	38
58	10	32	18	70	14
59	10	33	6	71	59
60	7	34	38	72	13
63	3	35	41	74	8
66	2	36	28	75	11
67	2	37	12	76	14
68	1	38	58		
69	2	39	20		
70	7	40	28		
71	5	41	6		
74	3	42	13		

Results from this field data collection for were sent to the University of Maryland Reliability Analysis Center (Mosleh 2013) to determine the characteristic life and beta shape parameters using Bayesian Weibull Analysis. The results of this study are shown in table G-4-2.

Table G-4-2. USACE Data Collection Results for Determining Life Characteristic and Beta Shape Parameters (Source: Mosleh 2013)

Mechanical Components	Characteristic Life	Beta Shape Parameter	Electrical Components	Characteristic Life	Beta Shape Parameter
Air compressor	67	8.94	Brakes (DC rectifier)	81	5.18
Bearings (bronze bushing type)	82	7.29	Control cables (twisted pair)	73	4.36
Bearings (roller type)	129	5.18	Control panel	74	5.57
Brake (springs and pads)	102	3.26	Circuit breaker (fused disconnect)	81	3.23
Butterfly valves	90	3.91	Electric motors	93	3.88
Chain (link type)	63	8.71	Encoders	54	4.32
Chain (roller type)	76	6.37	Generators	50	3.21
Check valves	72	5.05	MCCs	90	3.64
Clutch (jaw)	99	3.26	Motor starter (full voltage)	79	4.4
Couplings (flexible)	78	8.99	Panel board	83	4.95
Couplings (rigid)	142	4.67	Push button switches	88	3.6
Cylinders	111	2.51	Power cable (in conduit)	73	5.08
Enclosed gear reducer-parallel gears	133	4.71	Power cable (buried)	85	3.12
Enclosed worm gearbox gears	92	7.69	Power cable (in duct tray)	73	5.08
Lifting stems	107	2.67	Power cable (overhead)	113	1.84
Manual control valves	89	3.27	Rotating cam switches	91	7.76
Pipes (carbon steel)	105	3.51	Rotating limit switches	82	6.87
Pipes (stainless steel)	94	2.11	Selysn indicator motor	59	3.48
Pressure relief valves	80	5.94	Switchboard	71	5.14
Pumps (fixed disp.)	80	3.93	Switchgear	83	3.83
Pumps (var. disp.)	55	10.15	Transfer switch (automatic)	58	3.63
Right angle gear box	245	2.69	Transfer switch (manual)	71	3.28
Rotating shafts	112	8.68	Transformer	71	3.26
Screw actuator (electric)	84	3.35			
Screw actuator (manual handwheel)	86	3.33			
Sector-bull gears	2119	2.19			
Slide gates	144	3.98			
Solenoid control valve	63	5.11			
Stem nut	153	2.36			
Spur-pinion gears	2119	2.19			
Sprockets	593	1.92			
Sump pumps	66	1.75			
Trunnion pin and bearing	89	5.32			
Wire rope (carbon steel)	80	2.17			
Wire rope (stainless steel)	75	3.04			

An alternative way of demining characteristic life and beta shape Weibull parameters is to plot the failure data of components on Weibull plotting paper (ln-ln paper) to estimate the two parameters for the Weibull distribution. An example of the Weibull plotting for electric motors is shown on figure G-4-7. Figure G-4-8 shows the resulting CDF using the two Weibull parameters for the electric motors.
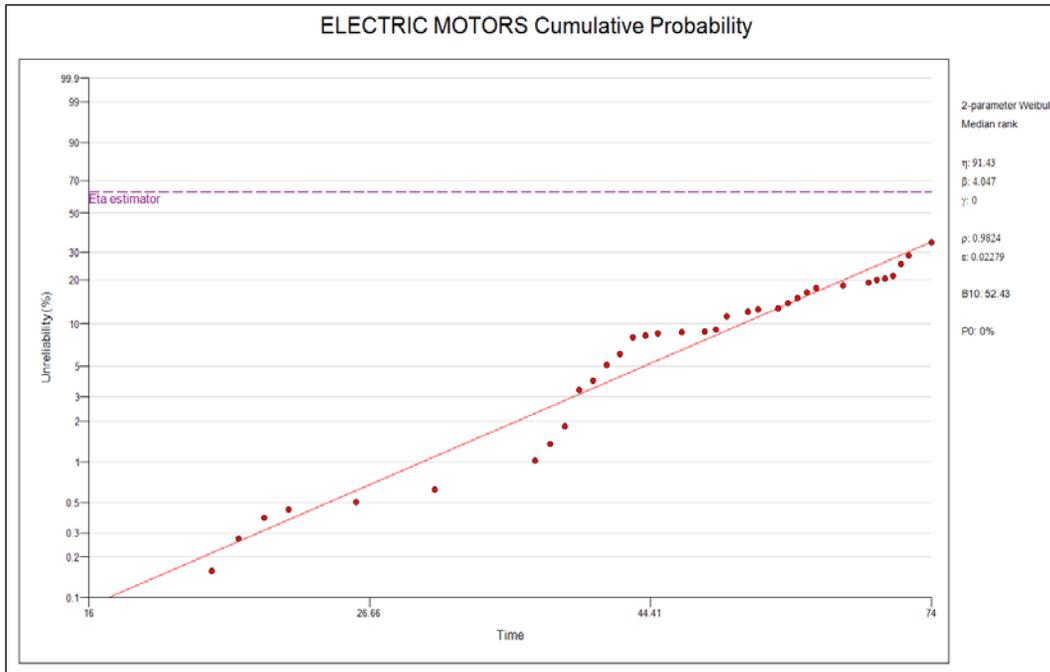

Figure G-4-7.—Typical results of plotted data collected for electric motors. The results are characteristic life is 91 years and the beta shape parameter is 4.05.
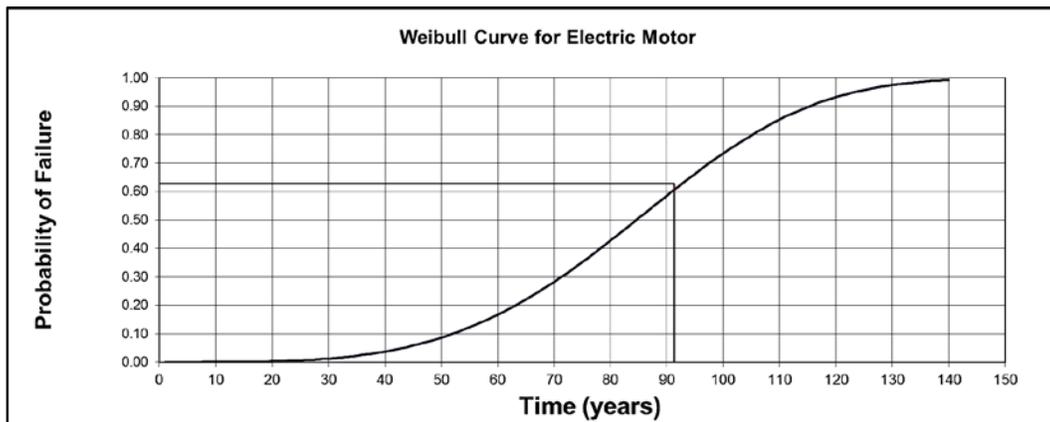

Figure G-4-8.—Typical plotted cumulative probability of failure Weibull curve for an electric motor showing characteristic life of 91 years at a probability of 63.21%.

When the USACE performed its nationwide data collection of its components it collected data from dams over the entire range of projects throughout the United States with average maintenance. In reality, many components have a shorter characteristic life in some environments and conditions than others. Condition is always a factor in determining the probability of failure of a component since it reflects both the maintenance and environmental conditions it is has seen. Inspections of the components may be taken into account to adjust the characteristic life a predetermined adjustment factor depending on its condition rating. In addition, environment, stress levels, and temperature factors are considered and adjustment to the characteristic life predetermined factor (Patev 2005; Patev 2013).

For example, if a component is showing extreme wear or if it is exposed to a harsh salt water environment or heavy silt build up at an early stage of its life then the characteristic life of the component is adjusted down by a predetermined factor.

G-4.4.2   Second Key Element in the Weibull Formulas

β = Shape Parameter

Shape parameters are also calculated from the data which is collected and analyzed and is the slope of the Weibull probability plot line from failure data. The hazard function for the Weibull distribution is sometime referred to as the "bathtub" curve with varying β parameters over time as shown on figure G-4-9.

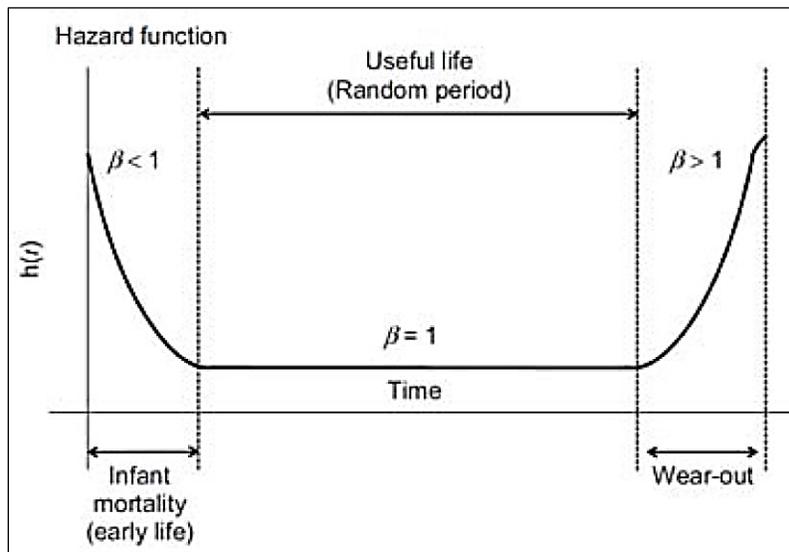**Figure G-4-9.—Typical hazard function "bathtub" curve for Weibull distribution.**

Figure G-4-9 defined the shape parameters as:

$\beta < 1$ Implies quality problems or insufficient "Burn In," usually associated with beginning of a components 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

Figure G-4-10 shows a typical Weibull curve for an electrical motor which has been generated from data which was collect from dams throughout USACE's inventory. It's generated using the Weibull formula and plotted as failure data on figure G-4-7. As defined before the slope of the line represents the shape parameter for the data set. Figure G-4-11 show the how different shape parameters affects the reliability values for the Weibull distribution.
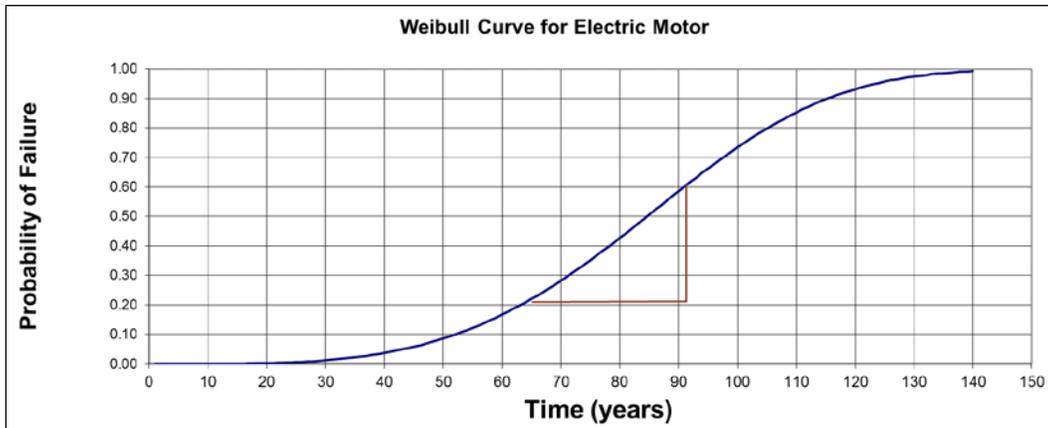

Figure G-4-10.—Typical plotted probability of failure Weibull curve for an electric motor showing beta shape parameter.

G-4.4.3 Third Key Element in the Weibull Formulas

γ = Location or Shift Parameter

The shift or location parameter is used as part of a three parameter Weibull distribution or the Dormant-Weibull distribution. The location or shift parameter is the life period where the component is failure free, i.e., probability density function (pdf) or f(t) is zero. This basically shifts the overall probability of failure curve to represent the actual age of the component where it started to see failures.

Weibull Reliability Plot with 0 < β < 1, β = 1, and β < 1

Figure G-4-11.—Typical reliability values curve showing varying of the shape parameter.

This shift may be used to reflect lack of actuation of a component or if the component may be in a cold or standby mode. The shift parameter is shown on figure G-4-12.

Effect of Location Parameter γ on Weibull *pdf*

Figure G-4-12.—Location or shift parameter on Weibull distribution.

Example.—If a component was originally installed in 1965 as a standby component and did not see activation until 1995 the location parameter of the new component would be equal 30 years. If the component is original, then the location parameter would be equal to 0.

G-4.4.4　　Fourth Key Element in the Dormant-Weibull Formula

$$\tau = \textit{Inspection Interval}$$

τ = **Inspection Interval**.—Time in (years) between when the component was last inspected or operated properly to present.

Example.—A component was last operated 1 month ago and thus the inspection interval is:

$$\tau = 1 \text{ month}/12 \text{ months per year} = .0833$$

G-4.4.5　　Example Using the Dormant-Weibull Formula to Calculate the Probability of Failure of a Wire Rope

For demonstration, a wire rope is 50 years old. The characteristic life of a wire rope is 89 years and the shape parameter is 2.17 from USACE data results. The wire rope operates in a normal environment and was last operated or inspected 1 month ago. On average, the wire wipe operates 12 times a year.

Using the Dormant-Weibull formula:

η　=　characteristic life =89

β　=　Shape Parameter = 2.17

γ　=　Location Parameter = original wire rope = 0

τ　=　Inspection interval or time since last operated in years = 1 month/12 = .08333/year

n　=　Number of times the component operated in its life = 50 years*12 = 672

Unreliability/Unavailability:

$$Q_n = 1 - \left(e^{\left(\frac{(672-1)(.083)-0}{89}\right)^{2.17}} \right) \left(e^{-\left(\frac{672(.083)-0}{89}\right)^{2.17}} \right)$$

$$= .0012 \textit{ this year}$$

Knowing the probability of failure of an individual component in a system is good but the goal is to find the probability of failure of the entire system which operates a gate. The most common way of analyzing an entire system is with a fault tree analysis (FTA) software program.

G-4.5   How a Fault Tree Works

Each individual component's probability of an event happening/probability of failure is calculated by the FTA program using the same Weibull formulas shown earlier (Patev 2005). The FTA program is set up in a logic tree arrangement of the components which make up a system as shown on figure G-4-13. The components combine into what are called gates or faults. The gates represent the probability of those events happening based on those components that make up the fault. There are various types of gates used in FTA but the two most common are AND OR gates. OR gates as shown on figure G-4-14 represents a scenario in which any of the components fails and the entire system fails. AND gates as shown on figure G-4-15 represents systems which have redundancy and all need to fail for the fault or AND gate to fail. An example of an AND gate is three pumps on a hydraulic system in which all three pumps would need to fail for the entire hydraulic system to fail to operate.
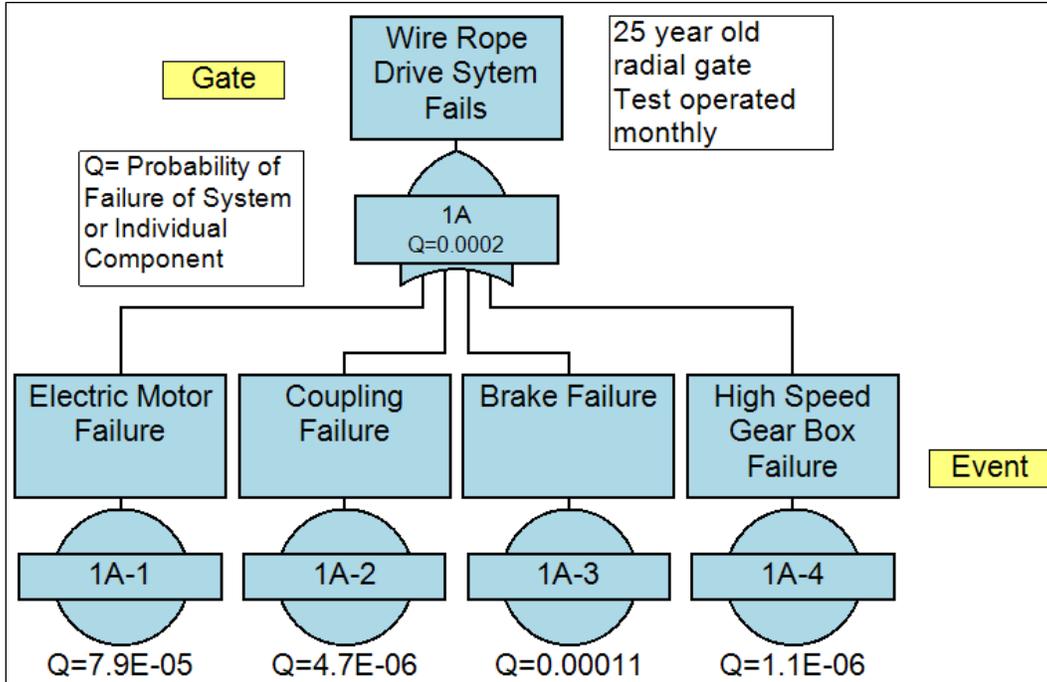
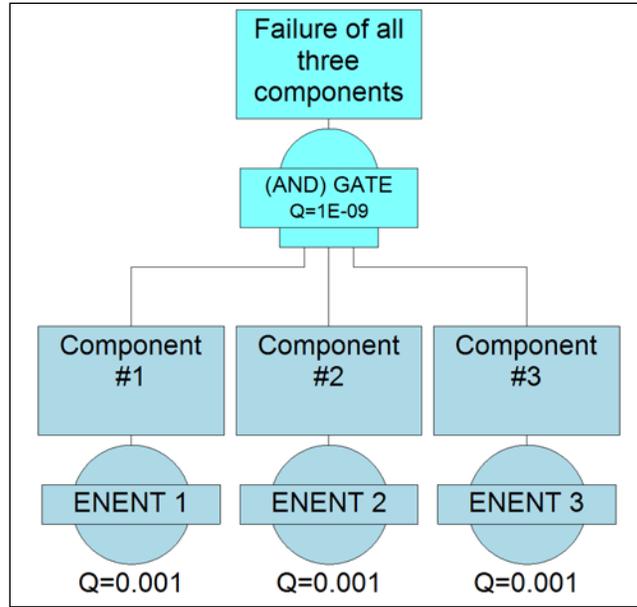Figure G-4-13.—Example of wire rope system fault tree.
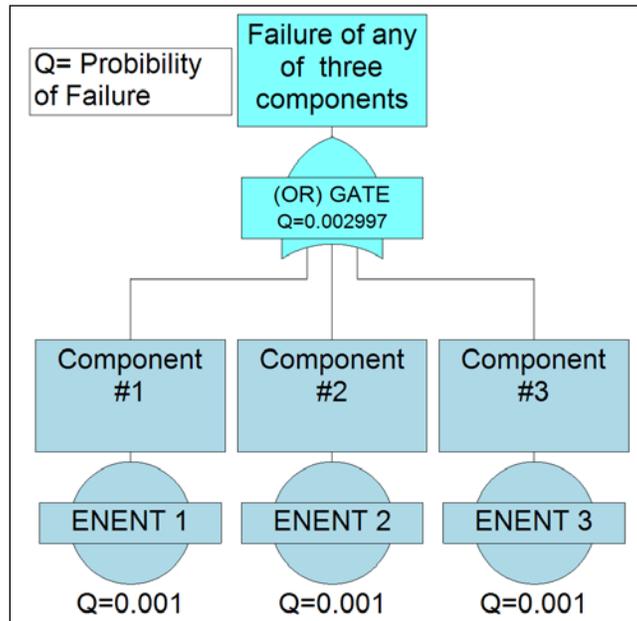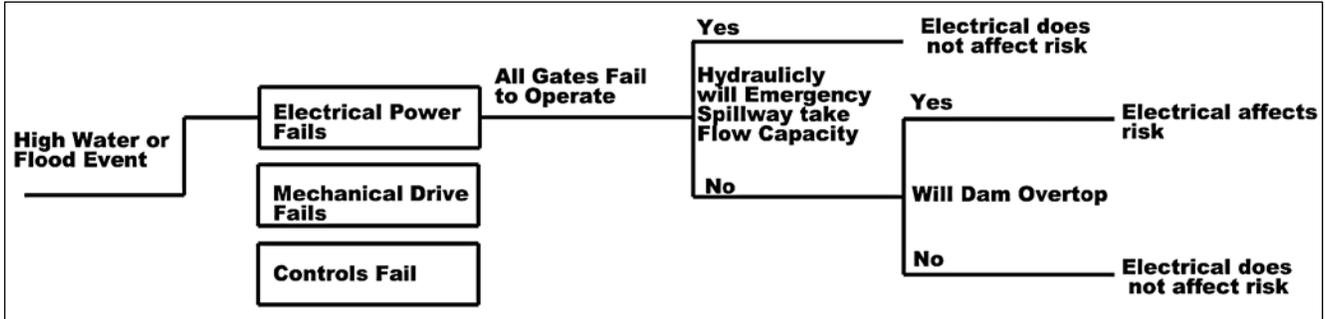
Figure G-4-14.—OR gates.

Figure G-4-15.—AND gates.

An example of a simple fault tree showing the probability of failure of a wire rope drive system based on a OR gate of four components is shown on figure G-4-16.

Figure G-4-16.—Electrical power failure affects risk.

There are many software developers which can perform FTA. Reliability Workbench is a FTA software tool developed by Isograph (2008) that is a typical software that is demonstrated in this chapter.

Event Trees for Mechanical and Electrical Equipment for Gates Now that we have calculated the probability of failure of the gates at a project we determine how it affects the overall project Risk Assessment Many scenarios can be developed for risk of failure of a dam and one of these is being the gates fail to open prevent passing of water through the dam thus possible overtopping of the dam. Event trees are developed to layout the events which could occur to cause a failure of the project. The probability of failure calculated earlier is used in the event trees.

Two simple event trees are shown below on figures G-4-17 and G-4-18 demonstrating the various ways electrical, mechanical, or controls failure could affect risk.
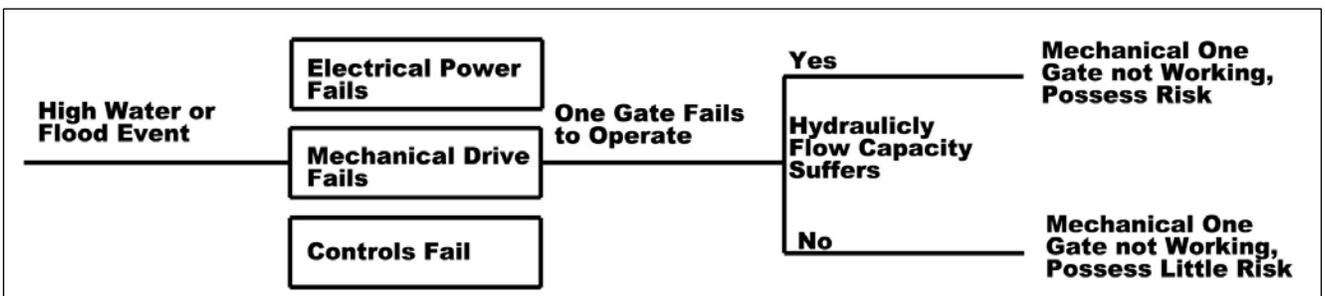
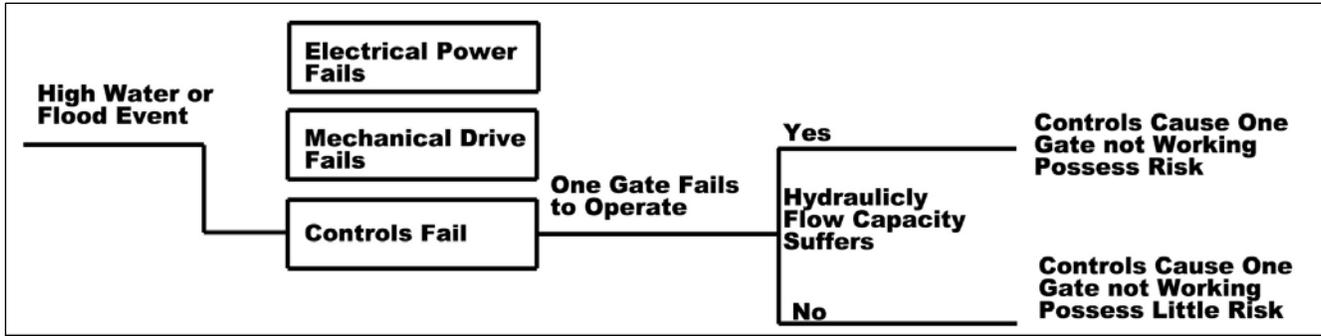**Figure G-4-17.—Mechanical drive fails to open gate.**

Figure G-4-18.—Controls fail to open gate.

G-4.6   References

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