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PROBABILITY OF FAILURE OF THE TRUDOCK CRANE SYSTEM AT THE WASTE ISOLATION PILOT PLANT (WIPP)

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New Mexico

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FOREWORD

The purpose of the New Mexico Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the Waste Isolation Pilot Plant (WIPP) Project to ensure the protection of the public health and safety and the environment. The WIPP Project, located in southeastern New Mexico, became operational in March 1999 for the disposal of transuranic (TRU) radioactive wastes generated by the national defense programs. The EEG was established in 1978 with funds provided by the U. S. Department of Energy (DOE) to the State of New Mexico. Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, Section 1433, assigned EEG to the New Mexico Institute of Mining and Technology and continued the original contract DE-AC04-79AL10752 through DOE contract DE-ACO4-89AL58309. The National Defense Authorization Act for Fiscal Year 1994, Public Law 103-160, and the National Defense Authorization Act for Fiscal Year 2000, Public Law 106-65, continued the authorization.

EEG performs independent technical analyses of the suitability of the proposed site; the design of the repository, its planned operation, and its long-term integrity; suitability and safety of the transportation systems; suitability of the Waste Acceptance Criteria and the compliance of the generator sites with them; and related subjects. These analyses include assessments of reports issued by the DOE and its contractors, other federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP. Another important function of EEG is the independent environmental monitoring of background radioactivity in air, water, and soil, both on-site and off-site.

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SUMMARY

This probabilistic analysis of WIPP TRUDOCK crane failure is based on two sources of failure data. The source for operator errors is the report by Swain and Guttman, NUREG/CR-1278-F, August 1983. The source for crane cable hook breaks was initially made by WIPP/WID-96-2196, Rev. 0 by using relatively old (1970s) U.S. Navy data (NUREG-0612). However, a helpful analysis by R.K. Deremer of PLG guided the authors to values that were more realistic and more conservative, with the recommendation that the crane cable/hook failure rate should be 2.5×10^{-6} per demand. This value was adopted and used.

Based on these choices a mean failure rate of 9.70×10^{-3} (1/yr) was calculated. However, a mean rate by itself does not reveal the level of confidence to be associated with this number. Guidance to making confidence calculations came from the report by Swain and Guttman, who stated that failure data could be described by lognormal distributions. This is in agreement with the widely used reports (by DOE and others) NPRD-95 and NPRD-91, on failure data.

The calculations of confidence levels showed that the mean failure rate of 9.70×10^{-3} (1/yr) corresponded to a percentile value of approximately 71; i.e. there is a 71% likelihood that the failure rate is less than 9.70×10^{-3} (1/yr). One also calculated that there is a 95% likelihood that the failure rate is less than 29.6×10^{-3} (1/yr). Or, as stated previously, there is a 71% likelihood that not more than one dropped load will occur in 103 years. Also, there is a 95% likelihood that not more than one dropped load will occur in approximately 34 years.

It is the responsibility of DOE to select the confidence level at which it desires to operate.

PROBABILITY OF FAILURE OF THE TRUDOCK CRANE SYSTEM AT THE WASTE ISOLATION PILOT PLANT (WIPP)

1. INTRODUCTION

In March 1999, the Department of Energy began emplacing transuranic waste into the Waste Isolation Pilot Plant (WIPP). The facility is located in southeast New Mexico in bedded salt at a depth of 650 meters. The repository is designed to contain 176,000 cubic meters (850,000 drum equivalents) of contact-handled transuranic (CH TRU) waste and 7,100 cubic meters (8,000 canisters) of remote handled transuranic (RH TRU) waste. The contact handled waste will be shipped from various defense generator and storage sites throughout the nation in an NRC certified container called a TRUPACT II or in a shorter version called a HALFPACK. In preparation for shipping, fourteen drums of waste, two standard waste boxes, or eight overpack drums are lowered into each TRUPACT-II. An inner lid and an outer lid secure the top of the shipping container.

Upon arrival at the WIPP, the drums or boxes need to be unloaded from the shipping container. This will be done in the Waste Handling Building where there are two TRUDOCK cranes. The two cranes are six-ton overhead bridge cranes, and are capable of operating alone or in parallel. To unload each shipping container, the outer lid needs to be lifted (3520 lbs.) and the inner lid needs to be lifted (895 lbs.). Each is set to the side. Figure 1 shows that two seven drum arrays can be lifted and handled as a single unit. The lift is over two meters and the payload can weigh as much as 7,265 lbs. Assuming at least three lifting operations for each TRUPACT there would be 182,000 lifting operations to unload 850,000 drum equivalents of CH TRU waste or about 5200 lifting operations per year (1500 crane transfers/year x 3 lifts/TRUPACT-II) for the 35 year operational life of the facility.

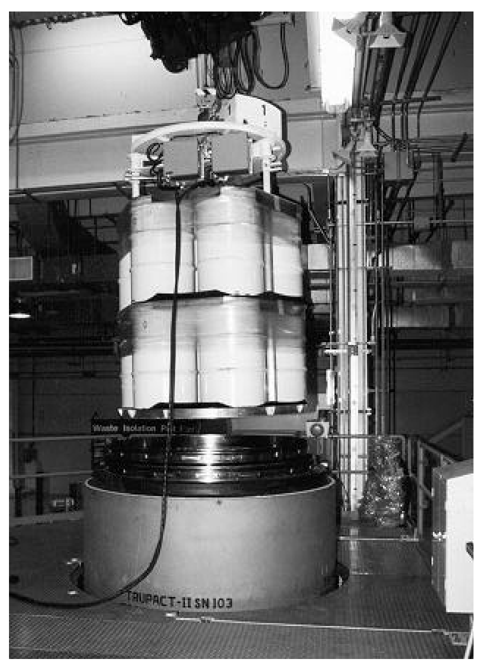

Figure 1. Lifting drums.

The DOE report, WIPP-WID-96-2196, Rev. 0, published in October 1996, studies and evaluates the possible frequency of failure of the TRUDOCK crane system, resulting in a dropped load and the loss of the drums' containment. The report turned to NUREG-0612 (July 1980) for failure data based on experience with U.S. Navy cranes in the 1970s.

However, the authors of WIPP-WID-96-2196, Rev. 0, 10/25/96, apparently had some concerns about using the data directly from NUREG-0612. The authors evidently turned for help to an independent source, Mr. R. Kenneth Deremer of PLG, an engineering consulting firm. Mr. Deremer's report is contained as Appendix A5 in WID-96-2196. According to Deremer's report, a preliminary version of the DOE report listed a failure "rate" of "<u>2.0E(-5) per demand</u> for crane cable/hook failures and cites NUREG-0612 as the basis for this value". Mr. Deremer is critical of that value, and then proceeded to his evaluation of a more realistic and more conservative value and he states that, "the crane cable/hook failure rate should be less than approximately <u>2.5E(-6) per demand</u>"; that is a reduction of almost a factor of 10. Mr. Deremer makes the point that the NUREG-0612 data were compiled in the 1970s; and he states that the operating environment at WIPP is much less demanding than those for Navy cranes. He also mentions the aggressive inspection and maintenance programs at WIPP, "to assure the continuing reliability of the cranes". He believes that the failure rates could even be lowered, but states that "it is difficult to quantify this additional improvement".

In his summary Mr. Deremer strongly restates his recommendation of a choice in the data base for the crane cable/hook contribution "of the order of 2.5E(-6) per demand". Mr. Deremer's recommendation was adopted by the authors of WIPP-WID-96-2196. In the key table of that report, on the Crane System Cutset Descriptions, page A2-5, the Event Probability for the Crane Cable/Hook Breaks is listed as 2.5E(-6).

Support for the critical view by Mr. Deremer of the operating experience of Navy cranes may be seen by noting the relative frequencies of equipment failures vs. operator failures reported in "Navy Crane Incidents" (reports obtained from the U.S. Navy), for the recent years 1996, 1997 and 1998 (Table 1). The number of incidents associated with operator failure is an astonishing 90 to 95%.

TABLE 1
Frequencies of Navy Crane Incidents

Year	1998	1997	1996
Total no. of incidents	196	167	154
No. due to equipment failure/percentage	11/5.6%	16/9.6%	7/4.6%
No. due to operator failure/percentage	185/94.4%	151/90.4%	147/95.4%

Another source of information of hoisting and rigging incidents comes from a recent report by the Office of Oversight, U.S. Department of Energy, Washington, DC, 20585. The report is "Independent Oversight Special Study of Hoisting and Rigging Incidents within the Department of Energy", October 1996. The report covers a 30 month interval, from October 1, 1993 to March 31, 1996. The report states that "Human error is the major cause of hoisting and rigging incidents" (page 8).

This is similar to the data in the "Navy Crane Incidents" reports, with major causes of incidents due to operator rather than equipment failures.

In sharp contrast, in WIPP-WID-96-2196, for WIPP crane system experience, the operators are not the major cause of incidents. As the report states, "Crane operators and load spotters are required to be trained in safe crane operation; therefore it is felt that the WIPP crane performance will exceed the data presented in NUREG-0612, and the estimated failure frequency is felt to be conservative."

2. CALCULATIONS

2.1 Operator Errors

Operator errors are described in the table on page A4-6, of WIPP-WID-96-2196, Rev. 0. For convenience this table is reproduced (as Table 2) in this report, with some additions.

TABLE 2

Symbol	HEP	Explanation of Error	Source of HEP	Page*
A_1	3.7×10^{-3}	Improperly mate a connector, including failure to test the locking feature for engagement	Table 20-12.* Item (13), mean value.	20-28
B_1	0.75	The operator repeating the action is modeled to have a high dependency for making the same error again. It is not complete dependence, because the operator moves to the second lifting leg and must physically push the locking balls to insert the pins.	Table 20-21.* Item (4)(a), high dependence for different pins. Two opportunities (the second and third pins) to repeat error is modeled as 0.5+(1-0.5)*0.5=0.75.	20-37
C_1	1.2×10^{-3}	Checker fails to verify the proper insertion of the connector pins, and that status affects safety when performing tasks.	Table 20-22.* Item (9), mean value.	20-38
D_1	0.15	Checker fails to verify the proper insertion of the connector pins at a later step, given the initial failure to recognize the error. Sufficient separation in time and additional cues to warrant moderate rather than total or high dependence.	Table 20-21.* Item (3)(a), moderate dependence for second check.	20-37
F_1	4.99×10^{-7}	Failure rate if first pin improperly connected.	Product of above HEPs.	
a_1	0.996	Given the first pin was properly connected.	$1\text{-}F_1$	
A_2	3.7×10^{-3}	Improperly mate a connector, including failure to test the locking feature for engagement.	Table 20-12.* Item (13), mean value.	20-28
B_2	0.5	The operator repeating the action is modeled to have a high dependency for making the same error again. It is not complete dependence, because the operator moves to the second lifting leg and must physically push the locking balls to insert pins.	Table 20-21.* Item (4)(a), high dependence for different pins. Only one opportunity for error (the third pin).	20-37
C_2	1.2×10^{-3}	Checker fails to verify the proper insertion of the connector pins, and that status affects safety when performing tasks.	Table 20-22.* Item (9), mean value.	20-38
D_2	0.15	Checker fails to verify the proper insertion of the connector pins at a later step, given the initial failure to recognize the error. Sufficient separation in time and additional cues to warrant moderate rather than total or high dependence.	Table 20-21.* Item (3)(a), moderate dependence for second check.	20-37
F_2	3.32×10^{-7}	Failure rate if first pin improperly connected.	Product of above HEPs.	
F_T	8.31×10^{-7}	Total failure rate due to human error.	$F_1 + F_2$	

* HEP stands for Human Error Probability.

* The source of the data is in a report by Swain and Guttman, "Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications", August 1983, NUREG/CR-1278-F.

2.2 Crane System Cutset Descriptions

The table in page A2-5 of the WIPP-WID-96-2196 report lists all the basic events that can contribute to crane failures, including crane cable hook breaks, disk brake actuator failures, crane motor failures, etc., in addition to the operator errors. The calculations of the "cutset probabilities" (chances of failing) are given in detail. Of the thirteen listed cutset probabilities, only the first four need to be considered, since the remaining nine are orders of magnitude smaller.

Table 3 is an abbreviation of the table in page A2-5, and it lists the four contributing components to the cutset probabilities. Note that the failure rate for a crane cable hook break is listed as 2.50 x 10^{-6} (1/demand), the value recommended by Mr. Deremer. The mean failure rate, per demand, due to operator error, is 8.31 x 10^{-7} (see in Table 3). As indicated in Table 3, the reduced sum of the probability of failure is 9.70 x 10^{-3} (1/yr), or approximately, one failure every 103 years.

TABLE 3
Cutset Probabilities

	Cutset Number	Ref.	Page	Failure Mode	Failure Rate mean, per demand	Number Crane Transfers/yr App. A_2, $A_{2\text{-}3}$	Event Prob. (cutset prob.)
Equipment Failure	1	Appendix A_5	3	Crane B cable hook breaks	2.50 x 10^{-6}	1.456 x 10^3	3.64 x 10^{-3}
	2	Appendix A_5	3	Crane A cable hook breaks	2.50 x 10^{-6}	1.456 x 10^3	3.64 x 10^{-3}
Operator Error	3	Table 2 (this report)		Improper connection due to Operator Error*	8.31 x 10^{-7}	1.456 x 10^3 (Crane B)	1.21 x 10^{-3}
	4	Table 2 (this report)		Improper connection due to Operator Error*	8.31 x 10^{-7}	(Crane A) 1.456 x 10^3	1.21 x 10^{-3}

$$P = \sum_{1}^{4} \text{E.P.} = \text{Reduced Sum of Probability of Failure} = 9.70 \times 10^{-3} \text{ (1/yr)}$$

or approximately one failure every 103 years.

*Note that the contribution of Operator Error is only about 25% of the total.

2.3 Use of Confidence Levels

The calculation in Table 3 of the probability of failure doesn't tell the whole story. One also wishes to know the confidence level that is associated with the failure rate of 9.70×10^{-3} (1/yr). It is helpful to follow the recommendations of the Nuclear Regulatory Commission to include mean estimates and to "take into account the potential uncertainties that exist so that an estimate can be made on the confidence level to be ascribed to the quantitative results." This quotation is taken from the Nuclear Regulatory Commission (NRC 1986). EEG makes the same recommendation, and a calculation of confidence levels is made in this report.

A suggestion of the distribution of HEPs (see Table 2) is made by Swain and Guttman (NUREG/CR-1278-F, page 7-1, page 2-18) to use lognormal distributions. Another helpful source on this matter are the reports NPRD-91 and the more recent NPRD-95, by Denson, Chandler, Crowell, Clark and Jaworski, 1994, "Nonelectronic Parts Reliability Data." Both reports NPRD-91 and NPRD-95 have been used as sources of failure data by DOE in their recent reports: WIPP/WID-96-2178, Rev. 0, July 1996 and WCAP-13800, February 1994 (Preliminary Draft Report).

Both NPRD-91 and NPRD-95 state that all listed failure rates "estimate" the expected failure rates, and that the "true" values lie in some confidence intervals about these estimates. The following statement is a quote from NPRD-91 (Denson et al. 1991), page 1-6:

> "To give NPRD-91 users a better understanding of the confidence they can place in the presented failure rates, an analysis was performed on the variation in observed failure rates. It was concluded that, for a given generic part type, the natural logarithm of the observed failure rate is normally distributed with a sigma (σ) = 1.5. This indicates that 68 percent of actual failure rates will be between 0.22 and 4.5 times the mean value. Similarly, 90% of actual failure rates will be between 0.08 and 11.9 times the presented value."

This is to state that if one wishes to include 90% of all the failure rates, one must include a range of values that somewhat exceeds two orders of magnitude $\left(\frac{11.9}{0.08} = 148 \right)$. Under these circumstances, representing the failure rate by a mean value alone disregards relevant information.

2.4 Lognormal Calculations

A general form for the lognormal distribution with the two parameters, μ, σ is given by (Aitchison and Brown, 1969):

$$d\Lambda(x) = \frac{1}{(x\sigma\sqrt{2\pi})} \exp\left\{-\frac{1}{(2\sigma^2)}(\log x - \mu)^2\right\} dx$$

where Λ is the cumulative distribution function (CDF).

The median of the distribution is given by:

$$x_{md} = e^{\mu} \tag{1}$$

The mean is given by: $x_{mn} = e^{\mu + \left(\frac{1}{2}\right)\sigma^2}$ (2)

According to the NPRDs (Denson et al., 1991, 1994) σ is taken as equal to 1.5.

from (2): $\mu = \ln\left[e^{-\left(\frac{1}{2}\right)\sigma^2} \bullet x_{mn}\right]$

since $\sigma = 1.5$; $e^{-\left(\frac{1}{2}\right)\sigma^2} = e^{-1.125} = 0.3247$

thus: $\mu = \ln\ [0.3247 \bullet x_{mn}]$ (3)

The values of (EP), the Cutset Event Probabilities, are listed in the right most column of Table 3. Let $x_{mn} = 10^3 \bullet$ (EP); the values of x_{mm} are listed in Table 4.

TABLE 4
Calculations of the Values of μ

Cutset Number	(From Table 3) $x_{mn} = 10^3 \bullet (EP) = e^{\mu + \frac{1}{2}\sigma^2}$	(From Equation 3) $e^{\mu} = (0.3247\ x_{mn})$	μ
1	3.64	1.1819	0.1671
2	3.64	1.1819	0.1671
3	1.21	0.3929	-0.9342
4	1.21	0.3929	-0.9342

Table 4 can be summarized as follows:

TABLE 5
Values of the Parameters μ, σ

P_i	μ_i	σ_i
1	0.1671	1.5
2	0.1671	1.5
3	-0.9342	1.5
4	-0.9342	1.5

The failure distribution, P, can be expressed as follows:

$$P = 10^{-3} \sum_{i=1}^{i=4} P_i \tag{4}$$

$$d\,P_i(x) = \frac{1}{\left(x\,\sigma_i\sqrt{2\pi}\right)} \exp\left[-\frac{1}{\left(2\sigma_i^2\right)}(\log x - \mu_i)^2\right] dx \tag{5}$$

The failure distribution, P, has been expressed as the sum of four lognormal random variables, P_i. The factor 10^{-3} is introduced to cancel the 10^{+3} used in the columns of Table 4. The methods used to compute the failure distribution functions are described in detail in the Appendix.

Table 6 lists the percentile values for the approximating probability distribution of the grand total of the four random variables.

TABLE 6
Percentiles and Probability Values of the Grand Total of the Four Random Variables

Percentile	Probability x 10^3 (1/yr)
0.5	0.65
1.	0.8
5.	1.4
10.	1.85
20.	2.8
50.	5.8
Mean = 71	9.70
80	12.8
90	20.
95	29.6
99	65.5
99.5	89.5

TABLE 7
Comparison of Means and Variance

True Mean	9.701
Approximating Mean	9.698
True Variance	249.83
Approximating Variance	246.51

For the grand total of the four random variables the approximating and true means and variance are listed in Table 7 without the factor (10^{-3}). The values of the approximations are close to the true values. This indicates that the approximations for the probability values listed in Table 6 have relatively small errors.

3. DISCUSSION

The data in Table 6 for the probability and the percentiles have been plotted on “probability-log” graph paper; see Figure 2. Some statements may be made, based on Figure 2 or Table 6.

(a) The mean failure rate is 9.70×10^{-3} (1/yr), and corresponds to a percentile value of approximately 71, i.e. there is a 71% likelihood that the failure rate is less than 9.70×10^{-3} (1/yr).

(b) At the 95 percentile, the probability is slightly less than 30×10^{-3} (1/yr) (actually 29.6 from Table 6); i.e. there is a 95% likelihood that the failure rate is less than 29.6×10^{-3} (1/yr).

(c) The above statements may be recast in another way:

There is a 71% likelihood that not more than one dropped load will occur in 103 years. Also, there is a 95% likelihood that not more than one dropped load will occur in approximately 34 years. One may calculate the corresponding time intervals for lower and higher levels of likelihood. Which level of likelihood does one select? That choice is the responsibility of DOE to make.

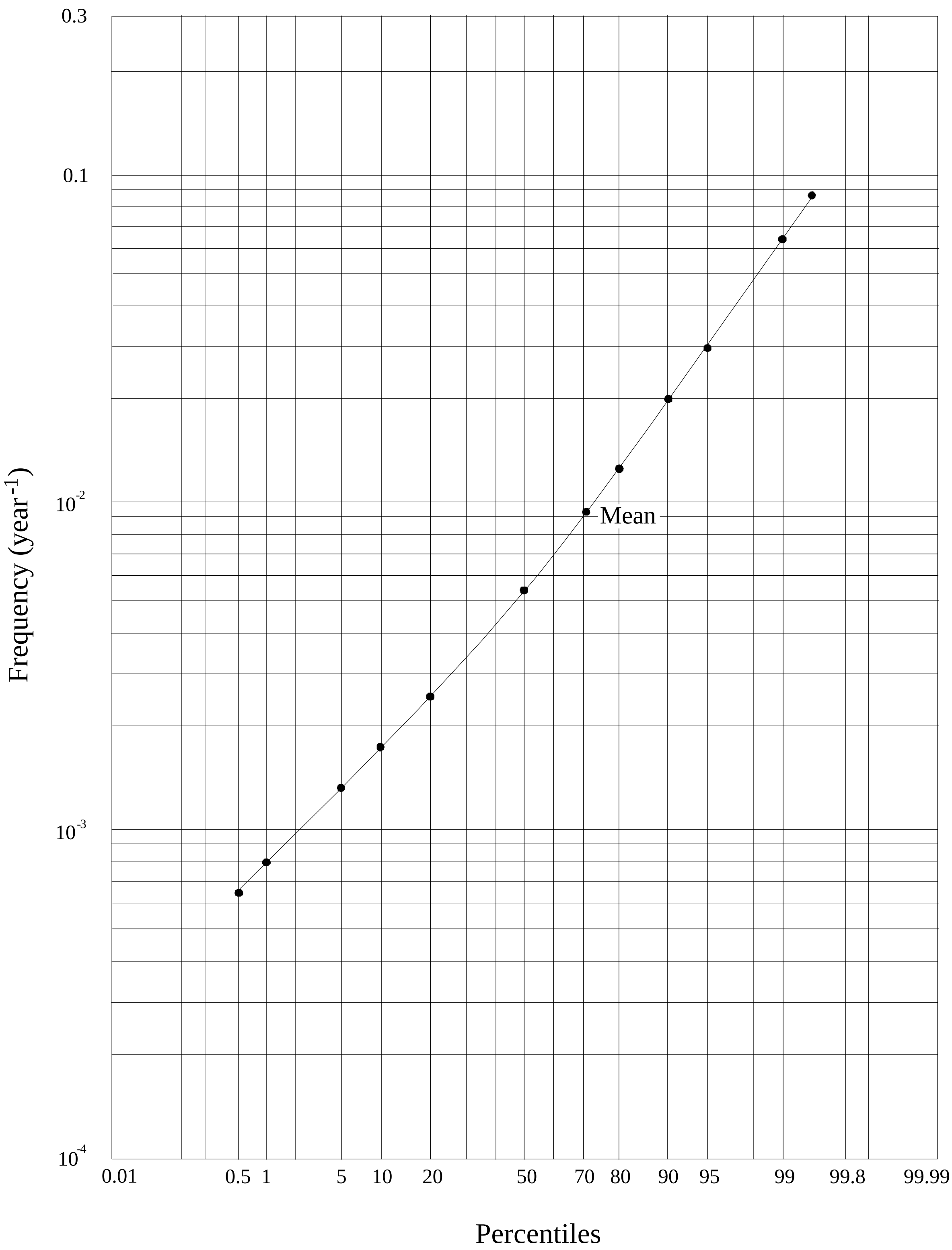

Figure 2. Cumulative distribution function for probability of failure of the TRUDOCK crane system

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LIST OF ACRONYMS

EEG	Environmental Evaluation Group
EP	Event Probabilities
NPRD	Nonelectronic Parts Reliability Data
NRC	Nuclear Regulatory Commission
DOE	United States Department of Energy
WID	Waste Isolation Division
WIPP	Waste Isolation Pilot Plant

APPENDIX

APPENDIX

This appendix describes how we numerically approximated the density of the random variable $x = \sum_{i=1}^{4} x_i$, where each x_i is distributed independently of x_j, $j \neq i$ and is log normal with parameters μ_i, σ_i. The distribution of a *sum* of two independent random variables is the convolution of the two distributions. But convolution in the time domain corresponds to multiplication in the frequency domain. This allows us to compute the distribution that we want by taking the Fourier transform of each density, multiplying them, and then inverse Fourier transforming.

Transform Methods

We want to compute the density function for a random variable that is the *sum* of two independently distributed random variables with known densities.[1] We use the following theorem:

Theorem: Let x be a continuously distributed random variable with density $f(x)$, and let y be a continuously distributed random variable with density $g(y)$. Let x and y be independently distributed. Then the random variable $z = x + y$ is distributed with density $h(z)$ given by the *convolution* of f and g, which is defined by

$$h(z) = \int f(u)g(z-u)du$$

A related theorem governs discrete approximations to continuously distributed random variables.

Theorem: Let x be a random variable that takes values on the set $X = [x_0, x_1, \ldots, x_{T-1}]$, with density $f_t = \text{Prob}[x = x_t]$. Let y be another random variable that takes values on the *same* set X,

[1]The mathematical theorems can be found in many books on operational mathematics. For example, see R.A. Gabel and R.A. Roberts, *Signals and Linear Systems*, Wiley, 1973.

with density g_t = Prob[$y = x_t$]. Let z be the random variable $z = x + y$, and let x and y be distributed independently. Then z has density h with

$$h_t = \sum_k f_k g_{t-k},$$

where h_t = Prob[$z = z_t$], and where z resides in the discrete set $Z = [2x_0, \ldots, 2x_{T-1}]$.

The next useful result is that the Fourier transform of a convolution is the *product* of the Fourier transforms of the two sequences being convoluted. The *Fourier transform* of a sequence $\{x_t\}_{t=0}^{t=T-1}$ is defined as the sequence of complex numbers $x(\omega_j)$ given by

(1) $$x(\omega_j) = \sum_{t=0}^{T-1} x_t e^{-i\omega_j t}$$

where $\omega_j = 2\pi j/T$ and $j = 0,1,\ldots,T-1$. The *inverse Fourier transform* is given by

(2) $$x_t = T^{-1}\sum_{j=0}^{T-1} x(\omega_j) e^{i\omega_j t}.$$

Equations (1) and (2) constitute the basic Fourier transform pair. Notice that the inverse Fourier transform of the Fourier transform is the original sequence.

The key theorem for us is:

Theorem: The Fourier transform of the convolution of two sequences $\{x_t\}$ and $\{y_t\}$ is the *product* of their Fourier transforms $x(\omega_j)\, y(\omega_j)$.

We apply this theorem as follows. For each of two continuous distributions, (f, g), the probability laws for (x, y), respectively, we put down a discrete 'grid' of points $X = [x_0, \ldots, x_{T-1}]$ on the real line, with the points spaced close enough together and over a sufficiently large set to approximate each continuous distribution well. Then we used (*f, g*) to generate approximating discrete probability distributions for (*x, y*). For computational consistency, we used the *same* grid for each random variable under study. We chose the grid carefully to make sure that each random variable as well as the relevant sums were well approximated by the procedure. For each approximating distribution $\hat{f}_t$ and $\hat{g}_t$, we computed the Fourier transform $f(\omega_j)$ and $g(\omega_j)$. Then we computed the Fourier transform of $\{\hat{h}_t\}$, the approximating distribution of the sum $x + y$, as

$$h(\omega_j) = f(\omega_j)\, g(\omega_j).$$

To compute the approximate density of $x + y$, $\hat{h}_t$, we then inverse Fourier transformed $h(\omega_j)$:

$$\hat{h}_t = T^{-1} \sum_{t=0}^{T-1} h(\omega_j)\, e^{i\omega_j t}.$$

Computational Details

We implemented these calculations using the *Fast Fourier Transform* (FFT) and the associated inverse transform, the IFFT. We used the computer language MATLAB on a Dell 450 MHz PC with 128 x 3 K of memory. This permitted us to put down very large and fine grids. We used one (inconsequential) approximation: each time a convolution is computed, the FFT in effect *truncates* the grid on which the relevant sum is distributed, and restricts it to the same domain on which the original two distributions are defined. In particular, the density of the sum is computed only on the *same* domain $X = [x_0, x_1, \ldots, x_{T-1}]$, rather than on the true domain $Z = [2x_0, \ldots, 2x_{T-1}]$. To control the error resulting from this approximation, we select the grid set X very carefully to make sure that it covers the region where the pertinent x, y, and sum $z = x + y$ have appreciable positive probability.

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