Predict Future Failures From Your Maintenance Records

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SUMMARY: Crow/AMSAA reliability growth plots use failure information from maintenance systems to provide a visual tool, with straight-line graphs, for predicting the next failure in systems where humans can influence the results. C/A plots work well with single failure or mixed failure modes. The simple log-log plots have easily calculated statistics to show if failures are increasing, decreasing, or exhibiting no-change in failure rates. The straight-line plots are helpful for forecasting future failures—the "fearless forecast" of future events catches the interest of people who can change the system to prevent the forecasted events. When implementing system improvements calculate and track the savings in failures between the old and new methods to convert maintenance situations into time and money for easy selection of alternatives.

Keywords: reliability growth plots, Crow/AMSAA plots, failure forecasts, mixed failure modes

1. WHAT ARE CROW/AMSAA RELIABILITY GROWTH PLOTS?

Cumulative failures plotted against cumulative time on log-log graphs form Crow/AMSAA reliability growth plots. The plots can handle data from single failure modes or multiple failure modes. Slope of the trend line is an important statistic telling if failures are increasing, decreasing, or the failure rate is unchanged. The method is simple and visual.

The challenge of every reliability engineer is to make reliability improvements to avoid failures. Improvements, with longer times between failures, will put a cusp on the trend lines. The cusp will demonstrate a real change has occurred by substantially stretching the time until the next failure. The longer intervals to the next failure will cause localized trend lines to appear with flatter slopes. When the former trend line is extrapolated to longer times, improvements must demonstrate measurable, vertical gaps, which measure the cumulative failures avoided by the improvements. Thus improvements are visual, and quantifiable — likewise deteriorating conditions produce steep slopes, and situations of no change are identifiable.

The view from your office may be spectacular, but can you see the future failures and make your information visual to the organization? You need a vision for forecasts of future expected failures along with their costs and alternatives for reducing the costs. The tools for gaining this vision are your maintenance failure data and Crow/AMSAA plots. The view for reliability growth plots comes from the simplicity of straight lines on log-log plots.

Today, log-log plots are emerging from unusual studies. The straight-line plots make explanations easy and understandable. Web crawler robot studies on the Internet find a "power law distribution" relating incoming links on web pages and outgoing links to web pages. Studies of computer networks spell out straight-line relationships on log-log plots. Science fails to see straight-line relationships on log-log plots because they have not looked for them (Barabási 2002). Barabási's unique exponents for his network equations have negative values, over a limited range of values, whereas reliability growth curves have positive exponents, again over a narrow range. The log-log plots describe natural laws at work.

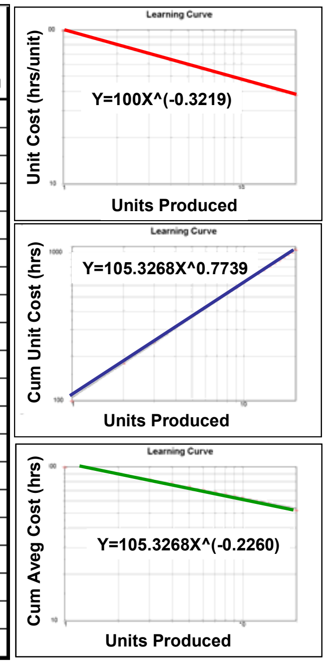
2. WHY DO CROW/AMSAA GROWTH PLOTS MAKE STRAIGHT LINES?

Why do Crow/AMSAA plots of cumulative failures versus cumulative time produce straight lines on log-log plots? The forerunner of the C/A concept has parallel roots in manufacturing with exhaustive demonstration as log-log phenomena. It is a natural occurrence of learning and improving. Consider the following parallel which began before Crow/AMSAA plots.

T. P. Wright (1936) pioneered an idea that improvements in man-hours to manufacture an airplane could be described mathematically--a very helpful concept for management production planning. Wright's findings showed that, as the quantity of airplanes produced in sequence, the direct labor input per airplane decreased in a mathematical pattern that forms a straight line when plotted on log-log paper. If the rate of improvement is 20% (the learning percentage is 80%) and thus when large processes and complicated operations production quantity is doubled, the time required for completing the effort is 20% less. Thus, a unit of production will decrease by a constant percentage each time the production quantity doubles. Figure 1 illustrates the concept. (Teplitz 1991)

Figure 1

Unit Number	Unit Cost (hrs/unit)	Cum Total Cost (hrs)	Cum Average Cost (hrs)
1	100.00	100.00	100.00
2	80.00	180.00	90.00
3	70.21	250.21	83.40
4	64.00	314.21	78.55
5	59.56	373.77	74.75
6	56.17	429.94	71.66
7	53.45	483.39	69.06
8	51.20	534.59	66.82
9	49.29	583.89	64.88
10	47.65	631.54	63.15
11	46.21	677.75	61.61
12	44.93	722.68	60.22
13	43.79	766.47	58.96
14	42.76	809.23	57.80
15	41.82	851.05	56.74
16	40.96	892.01	55.75
17	40.17	932.18	54.83
18	39.44	971.62	53.98
19	38.76	1010.37	53.18
20	38.12	1048.49	52.42



Wright's method in the 1940's was a helpful concept for the USA War Production Board in estimating the number of airplanes produced for a given complement of men and machines. After World War II, the US Government employed the Stanford Research Institute (SRI) to validate improvement curve concepts. SRI studied all USA airframe WWII production data to validate the concept and SRI developed a slightly different version than the simple case offered by Wright (DOD 2003) which also plotted on a log-log plot as a straight line. Today we know the log-log concept as learning curves when involved with production units and time/cost. Other names are cost improvement curves, or progress function, or Crawford curves (J. R. Crawford was on the SRI validation team—Crawford's model is considered less technical than Wright's model), or Boeing curves, or Northrop curves and so forth to represent the findings of each manufacturer of airframes. Each manufacturer developed a variation on T. P. Wright's simple equation.

The simple improvement curve was $Y = AX^B$. This curve will produce a straight line on log-log paper. Y is the unit cost (hours/unit or $'s/unit), X is the unit number, A is a theoretical cost of the first unit (hours or $'s) and B is a line slope constant that is related to the rate of improvement [B is literally equal to ln(learning percent)/ln(2) where the learning percent = 100-(rate of improvement)]. For example if the first unit took 100 hours to complete (A=110) and if we had an improvement rate of 20% the learning percentage would be 80%, so that B = ln(1.00-0.20)/ln(2) and B= -0.32193. Thus we would expect production of the 2nd item would require 80 hours and the 4th item produced would require 64 hours, and so forth, as the production quantity doubles we shave 20% from the production time. Some typical learning curve slopes are described at the NASA Cost Estimating Website (NASA 2003) and the learning % varies from a low of 96% for raw materials to a high of 75% for repetitive electrical operations with most values around 80-90%. The plots can have three different formats: 1) hours/unit or $/unit versus cumulative production, 2) cumulative (hours or $'s) versus cumulative production, or 3) cumulative average (hours or $'s) versus cumulative production.

General Electric Company made extensive use of learning curves in their manufacturing operations. A GE reliability engineer (James Duane) made log-log plots of cumulative MTBF versus cumulative time which gave a straight line for reliability issues (Duane 1964). Duane argued for the use of failure data on complex electromechanical systems. He recommended the Y-axis should be Y = (cumulative failures)/(cumulative time) = $KT^{-\alpha}$ where the value K is a constant which is dependent upon equipment complexity, design margins, and design objectives for reliability. Duane said the value for $\alpha \approx 0.5$ with the expectations that some designs would be better (meaning $\alpha > 0.5$) and some would be less (meaning $\alpha < 0.5$) and T is cumulative time. Duane drew his conclusions from studying 5 different data sets and found remarkable similarly in patterns for the curves (meaning the line slopes were about the same). Duane also rearranged his equations and showed cumulative failures $F = KT^{(1-\alpha)}$ so the formula allowed forecasting future failures based on past results. James Duane had a deterministic postulate for monitoring failures and failure rates of a complex system over time using a log-log plot with straight lines.

At the US Army Material Systems Analysis Activity (AMSAA) during the mid 1970's Larry Crow converted Duane's postulate into a mathematical and statistical proof via Weibull statistics. MIL-HDBK-189 (DOD 1981) describes the details. The military handbook addressed:

reliability growth-The positive improvement in a reliability parameter over a period of time due to changes in product design or the manufacturing process., and

reliability growth management-The systematic planning for reliability achievement as a function of time and other resources, and controlling the ongoing rate of achievement by reallocation of resources based on comparisons between planned and assessed reliability values.

The ultimate goal of the improvement program was to make reliability grow to meet the system reliability and performance requirements by managing the development program. The management effort required making reliability 1) visible, and 2) a manageable characteristic. Reliability growth programs required goals and forecast of progress. The failure data usually produced straight line segments on log-log plots with $N(t) = \lambda t^{\beta}$ where N is the expected number of failures, λ is the failure rate at time t = 1, t is cumulative time, and β is the line slope for cumulative failures versus cumulative time (and $\beta = 1 - \alpha$ from Duane's equation). Scientific principles determine that failure data fit $N(t) = \lambda t^{\beta}$ and thus failure data trends can produce a straight line on log-log paper.

Data from maintenance failure databases plotted on a log-log plot, will build a Crow/AMSAA relationship for finding the Y-axis intercept at t=1 to identify λ and the slope of the line will define β changes in the programs. Thus future failures can be forecasted and cusps on the data trends will tell if the system is improving (failures are coming more slowly, $\beta<1$), deteriorating (failures are coming more quickly, $\beta>1$), or if the system is without improvement/deterioration (failures rates are unchanged, $\beta\approx1$).

Recently AMSAA updated the information from the USA Military Handbook MIL-HDBK-189 and produced the AMSAA Reliability Growth Guide TR-652 (DOD 2000). TR-652 is available for download from http://www.barringer1.com/nov02prb.htm.

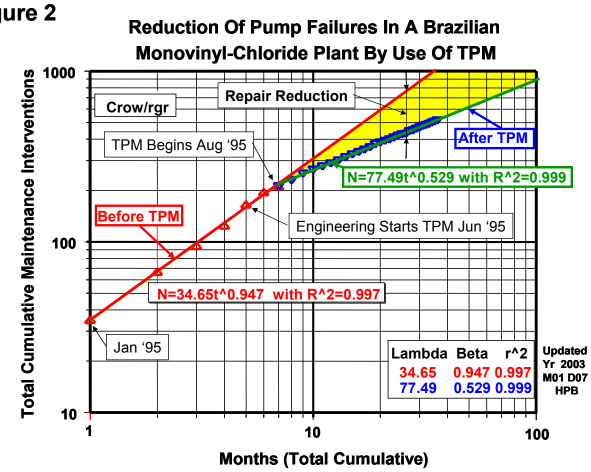
3. EXAMPLES

Example 1: Actual pump maintenance interventions are reported from a Brazilian chemical plant (Barringer 1997) based on data shown in Table 1. The Crow/AMSAA plot is shown in Figure 1 using reliability software (Fulton 2003) and Crow/AMSAA reliability technology (Abernethy 2002).

Table 1

Maintenance Interventions			
Month	1995	1996	1997
January	35	12	8
February	32	13	3
March	28	12	15
April	30	11	5
May	41	11	10
June	30	11	9
July	16	15	8
August	**18**	9	7
September	21	8	7
October	14	8	9
November	12	10	7
December	11	10	8
Total =	288	130	96
TPM Began August 1995			

Figure 2



The cumulative failures versus cumulative time produce two straight lines. The trend line before starting a TPM (Suzuki 1994) program shows slight improvement (β = 0.947). After introduction of a total productive maintenance program operators were taught a few fundamental things they could do to reduce failures. Notice how the failure trend line shows a distinct cusp in Figure 2. The improvement curve shows a slope $\beta = 0.529$ which is almost as predicted by Duane at $\alpha = 1 - \beta = 1 - 0.529 = 0.471$.

Using the data in Table 1 and Figure 2 the savings from the TPM program at time t=36 months (29 months into the TPM effort) have been N_{before} = 34.65(36)^0.947 = 1032 interventions, N_{after} = 77.49(36)^0.529 = 516 interventions which is an avoidance of 516 interventions in 29 months or ~18 interventions/month. Assume each intervention has an average cost of US$1000, the savings from the TPM program has been (516 interventions)*(1000$/intervention) =$516,000 over the last 29 months. The net savings for the TPM program will be amount saved less amount spent for introducing the TPM effort. In most cases, you can easily justify a TPM program based on this scorecard data. Every maintenance program requires factual justification of costs and benefits, and Crow/AMSAA plots organize the facts into straight lines.

Table 2 is a forecast of failures for the next 12 months using the trend line after implementation of the TPM program in Figure 2. This monthly forecast of failures will be for months 37 through 60 to cover a two-year forecast interval.

Table 2

Maintenance Interventions					
Month	1995	1996	1997	'98 Fcst	'99 Fcst
January	35	12	8	8	7
February	32	13	3	7	7
March	28	12	15	7	6
April	30	11	5	7	6
May	41	11	10	7	6
June	30	11	9	7	6
July	16	15	8	7	6
August	**18**	9	7	7	6
September	21	8	7	7	6
October	14	8	9	7	6
November	12	10	7	7	6
December	11	10	8	7	6
Total =	**288**	**130**	**96**	**85**	**74**
TPM Began August 1995					

Major improvements for Example 1 were achieved by putting pumps on the best efficiency point (BEP) and introducing a pump maintenance training program (Torres da Silva 1999). This required cooperative efforts between operations and maintenance. A Pareto distribution was established prior to the kick-off of the TPM program to identify bad actors (Bloch 1994) and build a Pareto priority list for action by the team—in most cases, the pumps required trimming of the impellers using the laws of affinity along with correction of net positive suction pressures. Pumps operate on their BEP by decisive action. Pumps operate off their BEP by benign neglect and errors. Insufficient net positive suction head and off-BEP causes vibration, cavitation, and other harmful actions which drive-up the need for maintenance interventions.

Example 2: Failures strongly influence most total maintenance department expenditures. The "failure data" is simply maintenance cost (as cost is a precursor for failures). A maintenance improvement program (TPM) was initiated in January 2002 (but not advertised), operator involvement began in February 2002, and hand held computers went active in July 2002 (advertised as commencing a new program). Maintenance costs are for a specific area of a petroleum refinery operation. The improvements involved use of mobile, hand-held data logging equipment to verify touching the equipment and proper equipment monitoring so operators take responsibility for <u>both</u> equipment and the process.

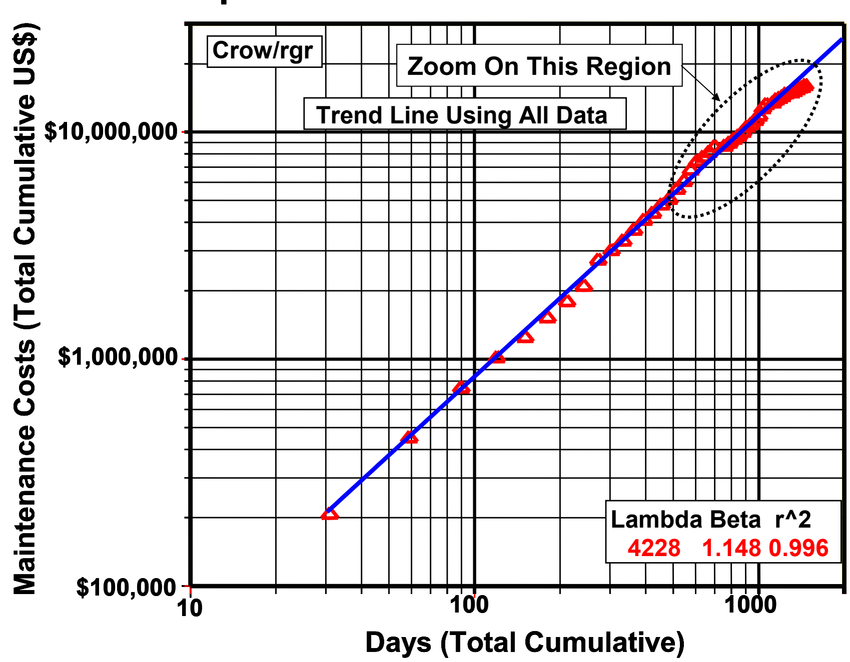
Table 3

Petroleum Refinery Department Maintenance Cost History For One Area

	1999		2000		2001		2002	
	Cum Days	Cum $'s	Cum Days	Cum $'s	Cum Days	Cum $'s	Cum Days	Cum $'s
Jan	31	$ 210,097	396	$ 4,146,017	762	$ 8,805,297	1127	$ 13,627,145
Feb	59	$ 456,441	425	$ 4,450,893	790	$ 9,077,531	1155	$ 14,076,446
Mar	90	$ 756,350	456	$ 4,846,968	821	$ 9,435,355	1186	$ 14,275,526
Apr	120	$ 1,028,044	486	$ 5,129,931	851	$ 9,746,244	1216	$ 14,537,284
May	151	$ 1,262,368	517	$ 5,673,580	882	$ 10,135,413	1247	$ 14,937,865
Jun	181	$ 1,540,101	547	$ 6,147,311	912	$ 10,674,844	1277	***$ 14,732,077***
Jul	212	$ 1,815,380	578	$ 6,896,160	943	$ 10,957,464	1308	$ 15,075,166
Aug	243	$ 2,121,788	609	$ 7,537,645	974	$ 11,420,963	1339	$ 15,310,813
Sep	273	$ 2,769,953	639	$ 7,856,635	1004	$ 11,932,656	1369	$ 15,589,596
Oct	304	$ 3,047,065	670	$ 8,254,432	1035	$ 12,857,704	1400	$ 15,826,120
Nov	334	$ 3,360,486	700	$ 8,716,149	1065	$ 13,402,128	1430	$ 15,944,082
Dec	365	$ 3,748,406	731	***$ 8,440,050***	1096	***$ 13,214,697***	1461	$ 16,275,941

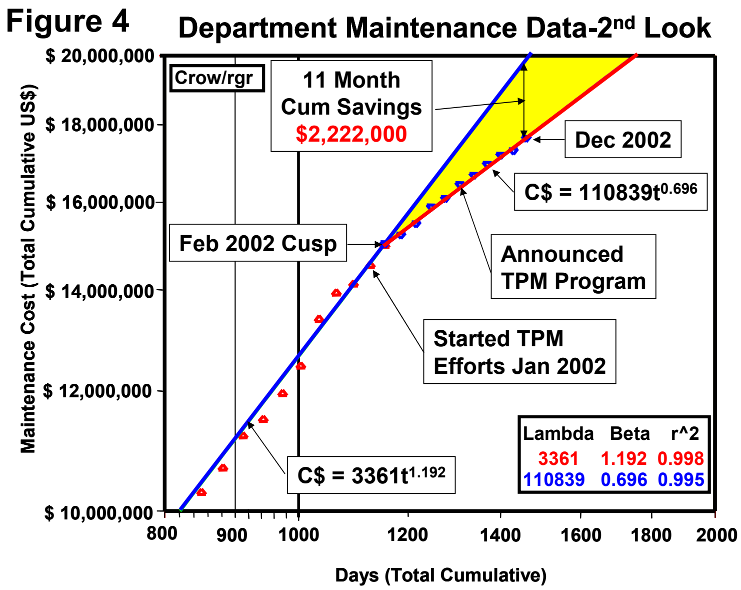
In January 2003, an assessment occurred to find the improvement savings. The data is not very clean as shown in Table 3. Note the data in Table 3 is not monotonically increasing in maintenance costs (i.e., a credit was received for maintenance costs over-charges representing two year end corrections and one mid year correction). Three italicized cost values show the specific data points not used in the calculation of trend lines (although the cumulative maintenance costs are included). Thus Table 3 represents dirty data with imperfections.

Figure 3 **Department Maintenance Data--1st Look**



The Y-axis of Figure 3 is US$ (not failures). Figure 2 shows savings began almost as soon as operators were involved in the improvement effort. Furthermore, Figure 2's trend line includes the data points to the left of the cusp. Notice the trendline slope, β>1, tells that maintenance costs (a precursor for failures) are accelerating with time.

Figure 4 zooms in on the plotted data points in the upper right hand corner, so that the cusp is clearer. The trendline for most of the data is based on years 1999 through 2001 plus one month of 2002. The trend line after the cusp is comprised of the last 11 data points in Table 3, and the cusp is literally computerd as 1151 days. The February 2002 was decided based on good engineering judment along with a few trial an error selections of the data points in each set. Figure 3 quantifies savings during the year 2002 from the improvement program.



In Figure 4 notice how much better behaved (lower variability) the data is on the plot following operator involvement in the maintenance programs. The trendline slope, β, after the cusp tells that costs are growing more slowly with time. Trend line savings at the end of year 2002 was $3361(1461)^{1.192} - 110839(1461)^{0.696} =$ US$2.222 million as the gap between the two trend lines at month 36 = 1461 days. Since the trendlines are diverging, the savings for 2003 will be larger than for 2002—does this remind you of the adage "the rich get richer and the poor get poorer"!

Now for the 2003 fearless forecast: the cumulative savings by the end of year 2003 (1461+365=1826 days) will be $3361(1826)^{1.192} - 110839(1826)^{0.696}$ = US$5.313 million. The savings for only the year 2003 will be (US$5.313-US$2.222) = US$3.091 million. No tree grows to reach the heavens, and no improvement program continues indefinately. It is reasonable to consider the line slope for the improvement curve will begin to swing towards a slope of β=1 in three to five years from the start of the program.

All TPM programs require selling (not telling) and persuading (not forcing) the workforce to "make a change to get a change" in performance. Most TPM programs require relinquishing control of maintenance decisions to the operators. All TPM programs require training of the operators in fundamental information about the equipment and how the process can effect the equipment all in the quest for reducing costs. Think of the capital expenditure and instruments required to achieve the information easily acquired by the operators with an assist from hand-held data logging equipment and the 5-senses of the operator on a mutual quest for making improvements. Supose you don't like the TPM concept, just find another smart way to make the improvements and then use your data to predict future failures—don't wait—time flies.

Example 3: A chemical plant, with a fairly stable level of employment, has recorded the following reportable safety incidences over a long time as shown in Table 4 for a 9 year time period. Each safety incidence represents a failure. The bold horizontal lines separate data by year. Is the plant safety program improving? How long until the next failure incident? Table 4 data produces the Crow/AMSAA plot in Figure 5.

Figure 5 shows a long term improvement in the safety records at this plant—incients are declining as reflected in the line slope with β<1. A forecast of when safety incidents (failures) can be expected are shown as an inset in Figure 5—next failure is expected in 49 days.

In Figure 5, notice the steep upward trends that highlight troublesome periods with a return to the trend line.

Safety failures (incidents) occur in an insidious manner. You need trend lines (preferable straight lines as sales tools) to show the team how safety programs are progressing.

The long term safety incident graph in Crow/AMSAA format shows two interesting line slopes. The "unlearning" trend lines display steeper slopes for degredation than the improvement trend line. Clearly safety improvements are a learning process and likewise deterioration in safety is an unlearning process where humans can impact the records.

Table 4

Safety Record--Major Chemical Plant Incidents

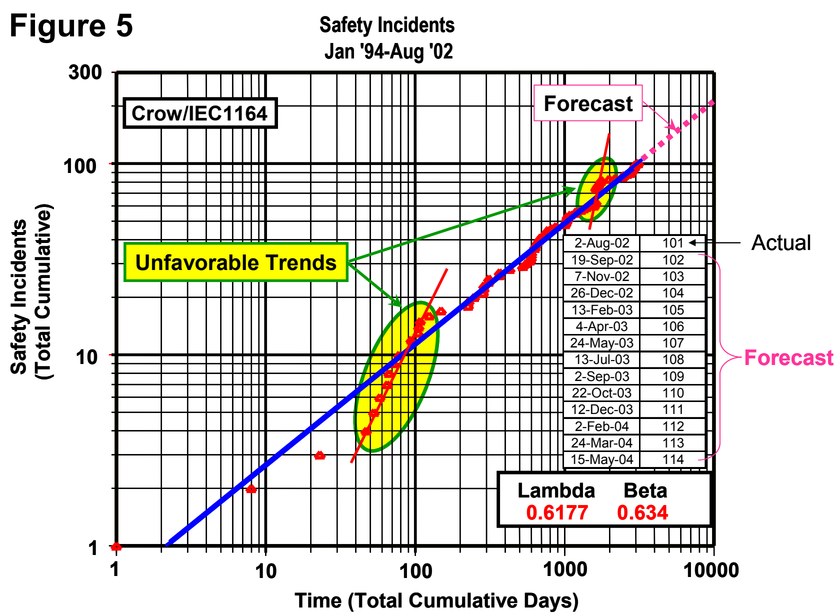
Cum Days	Cum Incidents	Cum Days	Cum Incidents	Cum Days	Cum Incidents	Cum Days	Cum Incidents
1	1	367	26	1046	53	2622	88
8	2	368	27	1096	54	2742	89
23	3	429	28	1184	55	2754	90
47	4	526	29	1195	56	2825	92
53	5	553	30	1291	57	2846	93
58	6	585	31	1345	58	2851	94
65	7	598	32	1397	59	2888	95
67	8	599	33	1565	60	2922	96
72	9	600	34	1591	61	2969	97
78	10	632	36	1598	62	2984	99
94	12	635	37	1624	63	3099	100
105	13	660	39	1626	74	3106	101
106	14	677	40	1634	75		
108	15	690	41	1655	76		
124	16	719	42	1670	77		
149	17	759	44	1692	78		
226	18	773	45	1711	79		
228	19	830	46	1753	81		
248	20	878	47	1759	82		
285	21	1009	48	1990	83		
288	22	1018	49	2186	84		
289	23	1031	50	2430	85		
310	24	1040	51	2472	86		
312	25	1044	52	2509	87		

The important task in safety programs is to put cusps on the data to make the trend line turn sideways toward more shallow slopes where incidents occur over increasing long time peridos. The goal is to have an safety incident free environment.

Safety failures are occuring over increasingly longer periods of time as shown in Figure 5 as inferred by β<1. This plant is operating with roughly ~50 days per incident. Is this good enough for a safety record?—Never!

Compared to other chemical plants, this facility has a good record. Yet, it can still be improved.

Figure 5



Example 4: Table 5 shows failure records for environmental spills. A double line separates the new improvement initiative from the old practice.

Spills are failures. Spills incurr clean-up expenses. Spills incurr governmental non-compliances. Clean-up for spills is hundreds of times the cost of lost fluids from the spills. Spill should never be taken lightly.

Figure 6 shows the Crow/AMSAA graph of the actual data along with a projection of failures reduced from the new initiative.

The gap between old practice and new practice is easily observed. Spill reduction is calculated from the simple equation $N(t)=\lambda t^\beta$ for the statistics defining the trendline of failures. The calculated failures saved from the improvement initiative is the delta between the improvement trend line and the old method trend line.

When processes are pushed for improvement, they often require continued nursing to maintain the improved conditions otherwise they have relapses. Unfortunately, for this case, the new track is only maintained for a short interval (3 failures in 899 days), then attention shifts to other issues and set backs occur. Many organizations accept deterioration without objection and resume the previous bad behavior unless they have clear signals for re-initiating improvements. This is illustrated in Table 6 and shown in Figure 7 where the relapse data shows 13 failures in 1283 days!

Table 5

Raw Data			Crow/AMSAA Data		Forecasts	
Spill Date	Days Between Spill	Spill Events	Cum. Days	Cum. Spills	Failures Predicted By Old Method	New Method Savings
11/18/1995	35	1	35	1		
1/31/1996	74	1	109	2		
5/8/1996	98	2	207	4		
5/22/1996	14	1	221	5		
7/29/1996	68	1	289	6		
8/23/1996	25	1	314	7		
8/25/1996	2	1	316	8		
6/20/1997	299	1	615	9	18	9
2/22/1998	247	1	862	10	27	17
2/10/1999	353	1	1215	11	41	30

Figure 6

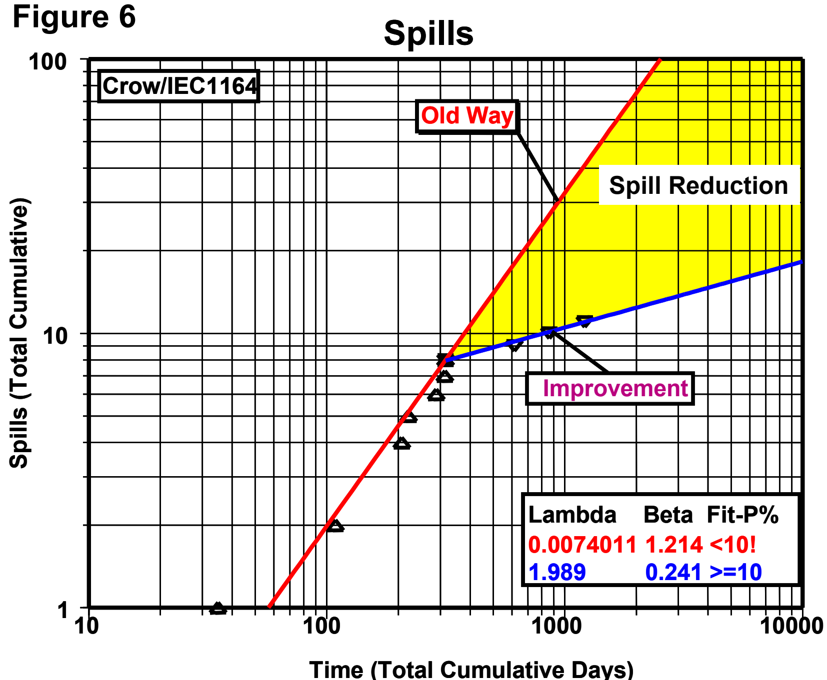
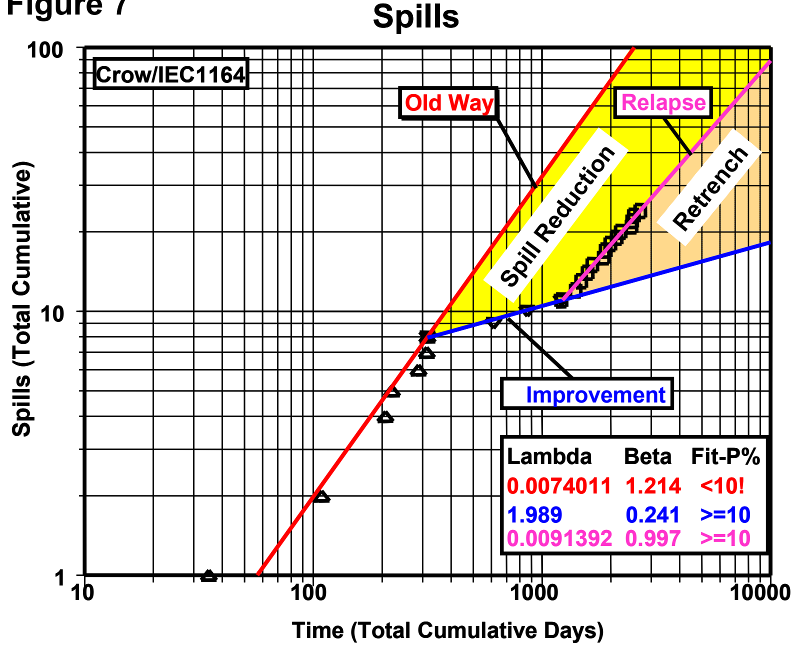


Figure 7



Without visual clues, too many organizations fail to correct the bad behavior resulting in significant retrenchment from good performance.

The missed opportunity column represents the delta between the improved trendline and the relapse line. You can argue that even with the relapse we have a savings and this is true. However, the relapse from better performance shows ever growing missed opportunities from not carefully tending to the farm.

The relapse line slope is β~1. The slope tells we are neither making improvements or suffering from deterioration.

Table 6

Raw Data			Crow/AMSAA Data		Forecasted Failures		
Spill Date	Days Between Spill	Spill Events	Cum. Days	Cum. Spills	Failures Predicted By Old Method	New Method Savings	Missed Opportunities From Relapse
11/18/1995	35	1	35	1			
1/31/1996	74	1	109	2			
5/8/1996	98	2	207	4			
5/22/1996	14	1	221	5			
7/29/1996	68	1	289	6			
8/23/1996	25	1	314	7			
8/25/1996	2	1	316	8			
6/20/1997	299	1	615	9	18	9	
2/22/1998	247	1	862	10	27	17	
2/10/1999	353	1	1215	11	41	30	
8/16/1999	187	1	1402	12			1
11/7/1999	83	1	1485	13			2
2/12/2000	97	1	1582	14			2
4/29/2000	77	1	1659	15			3
11/16/2000	201	1	1860	16			4
12/25/2000	39	1	1899	17			5
3/25/2001	90	1	1989	18			5
8/1/2001	129	1	2118	19			6
10/28/2001	88	1	2206	20			7
7/10/2002	255	1	2461	21			9
7/25/2002	15	1	2476	22			9
9/6/2002	43	1	2519	23			9
2/18/2003	165	1	2684	24			11

Generally speaking, processes either improve or deteriorate and the status quo rarely continues for very long. Experience says this process will deteriorate and failure will grow unless corrective action is applied to significantly reduce the number of spills. Unfortunately the action from many management groups is to declare the improvement changes are of no value and to trash the good work that achieved 2 spills in 18 months instead of correcting the problems associated with the relapse conditions. Here's where the Crow/AMSAA plots are of great use in providing the effective sales tools to show changes and sell the organization in getting back on track for the improvement curve.

Example 5: Chemical plants and refineries around the world are adding co-generation facilities expecting sale of their excess power into the national power grid to pay for the cost of the capital installation. The co-gen units generate electricity and produce steam for manufacturing processes and they function at high efficiency for the combined plants to get the biggest bang for capital expended.

The co-gen units have many different operating modes. Most co-gen plants supplement power supplied from the national grid (outages of the co-gen are not critical). A few other co-gen plants function as islands to carry the full demand load as any power outage has huge costs of unreliability for the manufacturing operations—but basic greed causes many companies to consider this for low cost power (island outages are extremely critical and highly reliable systems are required). Others function as islands of supply with backup power available from the national grid to provide uninterrupted electrical service--of course, this backup source has a fixed fee for the life-line to the grid (island outages are mitigated for a price paid by the life-line attachment to the national power grid).

Table 7 shows the failure record for a co-gen system. Data commences with the commission date and reflects 31 forced outages in 1432 days or ~46 days/forced outage. The typical thought process is "We're moving through the new problems and soon we'll be OK".

Figure 8 uses data from the two right hand columns in Table 7 for the Crow/AMSAA plot. The failure data makes a good straight line on the log-log paper with a β=0.996. The line slope infers a system functioning without improvement or deterioration.

Figure 8 tells we are **not** working our way through the problems (as if we were correcting infant mortality problems)! We are in a static condition of failures that respond as if the forced outages occur from chance events.

Use the λ and β statistics to predict 7 failures expected during 2003 for failures 32-38 where $t=(N/\lambda)^{(1/\beta)}$ where t is the cumulative future time and N is the cumulative future failures for the "fearless failure forecast" number/date:

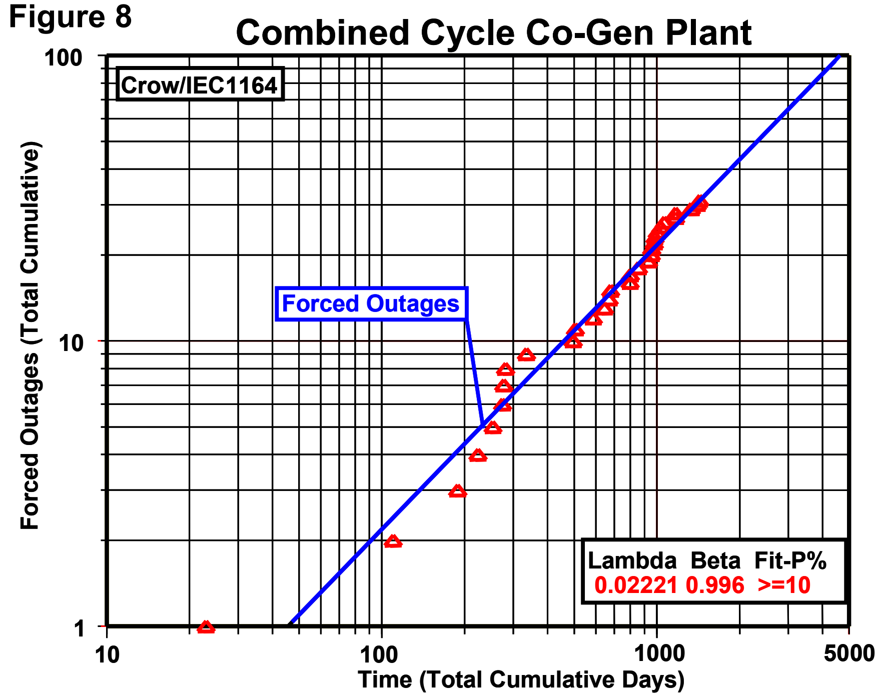
32) February 23, 2003
33) April 11, 2003
34) May 27, 2003
35) July 13, 2003
36) August 28, 2003
37) October 14, 2003, and
38) November 29, 2003.

Make fearless forecasts. Alert the organization to the high cost of expected failures. Take preventive action to avoid the future failures. Make this co-gen system more durable to avoid outages and prevent failures from occurring by funding the improvements from the pool of expected cost of unreliability. Do you suppose the design criteria for this system would have allowed "We expect this system will fail every 47 days"?—I'd make a substantial bet that the system was assumed to fail maybe once every 5 years so we have a huge reliability gap between expectations and reality!

Table 7

Date	Event Outage	Event Description	Days Between Event	All Outages Cum. Days	All Outages Cum Failures	Forced Outages Cum. Days	Forced Outages Cum Failures
2/1/1999	Planned	Tie In	0	0	0	0	0
2/20/1999	Planned	Tie In	19	19	1		
2/24/1999	Forced	Gas Line Outage	4	23	2	23	1
5/22/1999	Forced	Animal Contact	87	110	3	110	2
7/9/1999	Planned	Interconnect Energized	48	158	4		
8/9/1999	Forced	Switching Error	31	189	5	189	3
9/13/1999	Forced	Tie Wrap Failure	35	224	6	224	4
10/13/1999	Forced	Lightning Strike	30	254	7	254	5
11/3/1999	Forced	Static Wire Short	21	275	8	275	6
11/6/1999	Forced	Switch Failed	3	278	9	278	7
11/10/1999	Forced	Not Logged	4	282	10	282	8
1/3/2000	Forced	Cable Bond Fault	54	336	11	336	9
6/12/2000	Forced	Underground Cable Fault	161	497	12	497	10
6/21/2000	Forced	Bird Contact	9	506	13	506	11
9/11/2000	Forced	Lightning Strike	82	588	14	588	12
11/7/2000	Forced	Animal Contact	57	645	15	645	13
12/2/2000	Forced	Animal Contact	25	670	16	670	14
12/12/2000	Forced	High Winds	10	680	17	680	15
4/11/2001	Forced	Not Logged	120	800	18	800	16
4/12/2001	Forced	Not Logged	1	801	19	801	17
4/19/2001	Planned	Tie In	7	808	20		
6/7/2001	Forced	Not Logged	49	857	21	857	18
8/22/2001	Forced	Pole Damage	76	933	22	933	19
9/13/2001	Forced	Interconnect Opened	22	955	23	955	20
9/16/2001	Forced	Supplemental Power Out	3	958	24	958	21
10/6/2001	Forced	Power Dip	20	978	25	978	22
10/12/2001	Forced	Control Tripped	6	984	26	984	23
10/31/2001	Forced	Power Dip	19	1003	27	1003	24
12/1/2001	Forced	Power Dip	31	1034	28	1034	25
1/1/2002	Forced	Steam Outage	31	1065	29	1065	26
4/15/2002	Forced	Switching Error	104	1169	30	1169	27
4/18/2002	Forced	Load Shedding Error	3	1172	31	1172	28
9/27/2002	Forced	Water In Switch Gear	162	1334	32	1334	29
12/6/2002	Forced	Generator Air Intake Frozen	70	1404	33	1404	30
1/3/2003	Forced	UPS Failure	28	1432	34	1432	31

Figure 8



4. SUMMARY

Five actual examples of industrial failures show typical straight-line patterns of failures when plotting cumulative failures against cumulative time on log-log plots. The slope of the line (β) tells if failures are increasing, decreasing, or resulting in no changes in failure rates. Statistics for the straight-line (λ and β) plots of cumulative failures versus cumulative time allow forecast of future failures if the system proceeds on the same course since stable processes produce straight lines on log-log paper.

The purpose of "fearless future failure forecast" is to sound the alarm. Tell the organization about impending problems. Take corrective action for preventing future failures and thus avoid high cost of failures. Proactive involvement can prevent future failures. Passive involvement encourages failures.

Use failure data from your maintenance records to predict future failures. Set up a system to defeat the forecasted failures. Ignorance of future failures is not bliss and you cannot afford the failures!

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Reliability, engineering, and manufacturing consultant. Author of the basic reliability training course **Reliability Engineering Principles,** a practical financial evaluation course **Life Cycle Costs**, and **Process Reliability** which is a high level method of assessing and understanding process reliability. More than forty years of engineering and manufacturing experience in design, production, quality, maintenance, and reliability of technical products. He is a contributor to **The New Weibull Handbook**, a reliability engineering text published by Dr. Robert B. Abernethy. Barringer is named as inventor in six U.S.A. Patents and numerous foreign patents. Registered Professional Engineer in Texas. Education includes a MS and BS in Mechanical Engineering from North Carolina State University, and participated in Harvard University's three week Manufacturing Strategy conference. Other details and technical papers on a variety of reliability issues are available at **http://www.barringer1.com** for other background details or send e-mail to **hpaul@barringer1.com**.

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May 20, 2003—corrected early chronological dates in Tables 5 & 6.