THE R & M ENGINEERING JOURNAL

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# Reliability Review

Featured In This Issue...

## Sequential Testing Reliability Model

by

N.Schneidewind, Ph.D.

## Exposure Variables for Reliability Assessment: Exact C.I.

by Ph.D.s'

W.Harper, T. Eschenbach, and T. James

2008 February Volume 28, Number 1

# Reliability Review

## The R & M Engineering Journal




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***Submittal*****:** If more than one author, name each and designate correspondence author. Explicitly show addresses including Email for correspondence. We appreciate a hard copy of the manuscript. Send via postal mail to:

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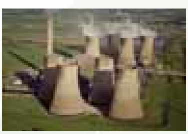
# The Review Presents

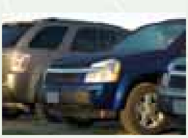
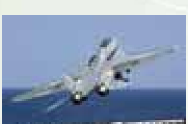
**Volume 28, Number One, March 2008**



**Titles of *Back To Basics* features are asterisked fore and aft**





# Managing Reliability During a Tight Economy

*Editorial by Harold W. Williams*

This spring we are observing a rapid downturn in the economy, initially apparent in the USA, but now spreading internationally. Very likely the impact during 2008 will affect most every industry and service. Credit tightening is already leading to workforce reductions not only in financial, housing and services sectors, but also many firms in broad market sectors are now anticipating decreases in market demand. A quick look at the manner in which such economic cycles have played out in the past should lead us to plan for a very austere approach in design and development during 2008.

When the economy is tight many customers apply more conservative analysis principles in their purchase decisions. This is a time to return to such basics as risk-based studies in product improvement decisions and life cycle cost analyses. Producers tend to offer more inclusive warranties to gain sales during such cycles. Return on investment analysis will influence decisions concerning process changes impacting capital improvements.

Management will encourage procurement of lower cost alternative parts and materials required for the production of mass market end item products. This deserves reliability and durability trade-offs analysis with careful evaluation of proposed substitutions prior to implementation of the "cost savings". Efficiencies are encouraged at all levels to achieve cost savings. Close attention to in-process yields will provide opportunities through analysis of failure causes and corrective actions to improve in-process reliability. The solutions may produce real savings.

The two feature articles in this issue are relevant to improvement of reliability risk assessment for hardware and software. The first offers a cost effective sequential testing method for software. The second calls attention to effective reliability risk assessment for noncomformance event variables.

# Chair Message

## Progress Report

***by Jim McLinn***

Reliability Division membership growth has continued at a slow and steady pace the past several years. The increase was 3.4% during the year just ended over the previous year. That places us in the middle of the growth curve among ASQ divisions and groups; and, RD is number one in member retention, retaining 75.3% of its members from year to year. Let me encourage you to find one person who needs the services that the division offers. Let them know what we provide. The following paragraph is a short list of the benefits of membership.

RD is a co-sponsor of the RAMS conference every January. This is the largest reliability conference in the world. We hold a division meeting at this conference every year. Great papers, a chance to discuss vital topics, and networking are all on the RAMS agenda. RD has an active discussion board on its website. A variety of questions are asked and answered in an open forum. If you have not looked at it, do so. Go to the RD home site and click discussion and see for yourself. You do need to be an RD member to get this service. Topics ranging from sample size, confidence limits, accelerated testing and establishing programs can be found.

There is some cooperative activity between the Reliability Division of ASQ and the Reliability Society of IEEE. Joint local meetings have been held in Denver, San Jose, Minneapolis and Boston during the past year. We are working on other cities as well for the future. This is one way to bring reliability topics close to the daily lives of the members. RD Publications staff is in the process of linking all of the past editions of *RR* within the new RD Forum Library. By year end it will be possible for RD members to access by topic articles from the early 1980s until the present time. This on-line benefit is exclusive to RD members. The topics offered cover the reliability B o K.. Many great articles readily accessed!

In May of each year the RD holds a second division meeting at the WCQI. Last year we had 3 speakers (in Orlando) and this year RD will sponsor one in Houston. and visit the RD Exhibit booth.

*(continued on page 22)*

# Sequential Testing Reliability Model

*by Norman Schneidewind, Ph.D.*

A risk-driven reliability model and testing process is developed that borrows concepts from classical sequential testing methodology applied to hardware. The model is adapted to software. Both consumer and producer risk are considered, reflecting the fact the consumer (e.g., customer) and producer (e.g., contractor) have different perspectives concerning what they consider to be tolerable risks of software failure. Similarly, there is also a differentiation based on what the consumer and producer consider to be acceptable reliability. Test rules are specified for determining at each decision point in testing whether the software and the model prediction accuracy are acceptable. In addition, the test rules serve as stopping criteria for testing. Both empirical and predicted quantities are assessed. Based on experience in using the model, lessons learned are provided with the objective of improving the model and process for future applications. This model and test scenario is applied to a real application involving the NASA Space Shuttle flight software. The model and test scenario may be tailored to commercial applications, as well.

**Model and Process Basics**

Software test scenarios involve the comparison of the software s actual outputs, resulting from test scenario execution, with its expected outputs, as documented by a specification [WHI00]. The model actual outputs are empirical values of risk and reliability and the expected outputs are represented by specified threshold values of risk and reliability.

In addition, risk and reliability predictions provide stopping rules for testing. The foundation for these concepts of software testing is based on classical methods addressed to hardware [LLO62], but with significant modifications to tailor the models to software testing and reliability. The classical methods of sequential testing, involving the concepts of consumer and producer risks [LLO62], are very useful for structuring a testing and reliability model. However, these concepts are lacking in the literature on software testing [HOR96]. Software testing emphasizes techniques such as statement coverage, decision coverage, branch coverage and data flow coverage [HOR96]. The classical methods are not entirely satisfactory for software because they are based on testing large quantities of homogeneous hardware items. This is not the case with software where, in many cases, one-of-a kind of software system is developed and tested. Thus, the classical methods require modification to be applicable to software.

Another important facet of the risk and reliability process is to evaluate not only the software but the model that predicts software risk and reliability, as well. If the model cannot predict accurately, the predictions cannot be used and we must try to validate another model.

The focus in the model is on consumer and producer risk in testing and models for quantifying the risk, with reasonable tradeoffs to balance competing consumer and producer objectives. This balance is important, because on the one hand, the consumer desires highly reliable software at a low cost. On the other hand, the producer desires to deliver software that meets “reasonable” reliability requirements and results in high profit. To make this tradeoff, a balance must be struck among risk, reliability, test time, acceptance and rejection criteria, and test sequence.

**Safety Critical Software Considerations**

Since the example application is about the Shuttle software, it is important to consider the risk and reliability requirement of this type of software. To assist in making informed acceptance decisions, software risk analysis and reliability prediction are integrated to provide a comprehensive approach to implementing test rules designed to reduce risk and increase reliability. This approach is applicable to all software, and. in particular, it is critical for certifying safety critical software because achieved improvements in the reliability of software, contribute to system safety [KEL97]. In addition, for this type of software, it is critical to have a feedback mechanism during testing to indicate when to continue to test and when to stop testing. Important feedback criteria are level of risk, reliability, and reliability growth. This approach was inspired by the feedback mechanism concept expressed in [CAN01] of using a test manager to monitor the difference between observed reliability and reliability predicted by a model. The difference is fed back into the test process to control the next step in testing. In my case, the differences between observed and required risk and reliability are used to control the test process.

**Other Reliability Testing Methods**

Reliability testing can be conducted at a macro or micro level. This model uses the former in which the concern is about the big picture of risk, failure occurrence, and reliability, and how to mitigate risk and increase reliability in sequential test scenarios. But in the micro view of testing, the focus is on methods that deal with the specifications, code, and data flow to produce effective fault removal in a cost-efficient manner. Specification-based testing produces test cases based on inputs, outputs, and program states. Code-based testing addresses computation results, predicate coverage, and control flow coverage. In data flow-based testing, test cases are produced to cover the execution space between where variables are declared and where they are used. Yet another method is mutation testing in which mutants of the original code are produced by introducing faults into program statements and observing the resulting execution behavior [JUR06].

Lyu provides a brief description of some of the important white box testing methods: White-box testing uses the structure of the software to measure the quality of testing. Other testing schemes include statement coverage, decision coverage, and data-flow coverage. Statement coverage testing constructs test cases such that each statement or a basic block of code, is executed at least once. Decision coverage constructs test cases such that each decision in the program is covered at least once. A decision is covered if, during some execution, it evaluates to true and in the same or another execution it evaluates to false. [LYU 98]

It appears that none of these methods is superior to the others in all cases and that their effectiveness and efficiency are application dependent. Selected tests at the micro level should be combined with a macro level approach, to provide a comprehensive attack on the software risk and reliability problem. My approach is to model testing at the micro level (i.e., white box testing) to provide failure count input to our macro level model (i.e., black box testing). The process does not have to stop there. You can use the two approaches synergistically by feeding black box testing risk and reliability predictions to white box testing so that the latter will have an assessment of likely operational risk and reliability. Then, the white box strategy would be adjusted to focus testing on the highest risk and lowest reliability software.

**Software and Model Performance**

In the analysis and evaluation of test results the engineer must be careful to distinguish between *software* performance and *model* performance. Therefore, before making predictions with the model, he or she must assess whether its prediction accuracy is unacceptable after two tests. If this is the case, try to validate another model. If the prediction acceptable, proceed with the risk and reliability tests.

With regard to model performance, I make the assumption that the model will perform in future operational time as it has during test time. Of course, this may not be the case, but is the best we can do until the future is reached when we can compare actual risk and reliability with the predicted quantities. You can continue this bootstrapping process to continually refine prediction accuracy as more failure data is collected. In addition, you can build confidence in the model by conducting multiple tests to train the model to improve its prediction accuracy.

**Test Rules**

One of the most difficult aspects of testing is to answer the question: "when to stop testing?" Myers suggests to stop testing when we have discovered and corrected a given number of faults [MYE79]. While this approach is certainly better than stopping when we run out of money and time, and it is *indirectly* related to reliability, I suggest criteria that are *directly* related to risk and reliability. With this approach, you can key the stopping rule to achieving acceptable levels of risk and reliability. This concept is embodied in the test rules .

Test rules should also include the criticality of the software being tested. This factor is mentioned in [MAT00], where the authors state: Many commercial products are not fully prepared for use in high assurance situations. In spite of the criticality of these applications, there currently exists a dearth of software assurance techniques to asses the robustness of both the application and the operating system under strenuous conditions. The testing practices that ordinary commercial products undergo are not thorough enough to guarantee reliability. High assurance applications require software components that can function correctly even when faced with improper usage or stressful environmental conditions.

My aim is to guarantee reliability by using a model and test schema that requires the software to pass several reliability (and risk) checks before it can be certified. "Improper usage" is reflected in the rate of failure incidence in the model and stressful environmental conditions is included by imposing the most stringent test conditions upon safety critical software.

**NASA Space Shuttle Application**

Now, I investigate the feasibility of applying the sequential reliability test concepts to the Shuttle flight software, using the Schneidewind Software Reliability Model (SSRM) [SCH97]. Any software reliability growth model (srgm) would suffice for this purpose.

An assumption of srgm s is that reliability will increase with time, as faults are removed as they are discovered. Thus, I use a sufficiently long test time to: 1) collect failure data in order to estimate the model parameters and 2) allow reliability growth to take place (e.g., reliability reaches an acceptable level). Once 1) and 2) have been accomplished, we can predict the reliability of the software for the specified mission duration tm.

The first step is to define model quantities:

**Definitions**

*Risk:* According to [NAS97], "risk is a function of: the possible frequency of occurrence of an undesired event, the potential severity of resulting consequences, and the uncertainties associated with the frequency and severity." I use this broad definition to encompass the specific model definition of risk as the *probability* (i.e., frequency of occurrence) of *failures* (i.e., undesired event), with *failure count* r (i.e., potential severity), and *variance of probability and failure count* (i.e., uncertainties) occurring on a software release.

*Safety critical:*___An application in which high risk and low reliability would jeopardize the safety of the crew and mission

*Actual (Empirical) Quantities:*

$\mu^*(t, r_c)$: actual consumer risk during test and operation

$\mu_p(t, r_p)$: actual producer risk during test and operation

$R_{ac}(t, r_c)$: actual consumer reliability computed over time t and failure count $r_c$

$R_{ap}(t, r_p)$: actual producer reliability computed over time t and failure count rp

$\rho_c$: actual consumer reliability growth

$\rho_p$: actual producer reliability growth

*Consumer Estimated or Predicted Quantities*

$P_c(t, r_c)$: probability of rc failures occurring at time t in consumer software

$\alpha(t, r_c)$: consumer risk: probability of consumer predicted failures: probability of accepting bad software at time t when rc failures have occurred

$a_c$: Consumer software failure rate at the beginning of interval sc [SCH97]

$s_c$: Consumer software starting interval for using observed failure data in parameter estimation [SCH97]

$b_c$: Consumer software negative of derivative of failure rate divided by failure rate (i.e., relative failure rate) [SCH97]

$\rho_{cp}$: Predicted consumer software reliability growth

$r_c(t)$: Number of consumer software failures whose faults have been removed in time interval t

$m_c(t)$: consumer software predicted mean number of failures predicted to occur in time interval t

$L_m$: maximum allowable consumer risk for all values of t

$R_c(t)$: consumer software predicted reliability at time t

$R_{cs}$: specified *minimum* consumer software reliability

$ER_c$: mean square error of the difference between actual and consumer predicted *risk*

SRc: squared error of the difference between actual and consumer predicted *risk*

$E_{rc}$: mean square error of the difference between actual and consumer predicted *reliability*

$S_{rc}$: squared error of the difference between actual and consumer predicted *reliability*

*Producer Estimated or Predicted Quantities*

$P_p$ (t, $r_p$): probability of $r_p$ failures occurring at time t in producer software

B(t, $r_p$): producer risk: probability of producer predicted failures: probability of accepting bad software at time t and $r_p$ failures

$a_p$: Producer failure rate at the beginning of interval $s_p$ [SCH97]

$s_p$: Producer starting interval for using observed failure data in parameter estimation [SCH97]

$b_p$: Producer negative of derivative of failure rate divided by failure rate (i.e., relative failure rate) [SCH97]
$\rho_{pp}$: Predicted producer software reliability growth
$r_p$ (t): Number of producer software failures whose faults have been removed in time interval t
$m_p$ (t): producer software predicted mean number of failures predicted to occur in time interval t

$R_p$ (t): producer software predicted reliability at time t

$R_{ps}$: specified *minimum* producer software reliability, where $R_{ps} \leq R_{cs}$ (i.e., in order to favor the consumer in mission and safety critical applications.

$E_{Rp}$: mean square error of the difference between actual and producer predicted *risk*

$S_{Rp}$: squared error of the difference between actual and producer predicted *risk*

Erp: mean square error of the difference between actual and producer predicted *reliability*

Srp: squared error of the difference between actual and producer predicted *reliability*

<u>Other Quantity</u>

$t_{cp}$: test time or operating time when Rc (t, $r_c$) = $R_p$ (t, $r_p$)

**Risk Analysis**

Next, I develop the consum-

*(continued on page 14)*

er and producer risk equations for the Shuttle. These equations are used in the test rules and scenario and in the risk plots. Because there are several streams of failure data available for a given software release (i.e., operational increment (OI)), I can use one failure stream for the consumer and another for the producer. The logic of this is that the producer would provide software with a certain reliability that the consumer would attempt to continue to increase by removing more faults. The next step is to formulate the probability of failure at time t in equations (1.1) and (1.2) for the consumer and producer, respectively, based on the Poisson distribution [SCH97]. These equations will be used in the formulation of consumer risk α and producer risk β.

$$P_c (t, r_c) = (m (t)^{r_c} e^{-m_c(t)}) / r_c! \qquad (1.1)$$

$$P_p (t, r_p) = (m (t)^{r_p} e^{-m_p(t)}) / r_p! \qquad (1.2)$$

In order to provide the *mean number of failures* component in equations (1.4) and (1.5), use equation (1.3) [SCH97]:

$$m (t) = \alpha/b \left(e^{-b(t-s)} - e^{-b(t-s+1)}\right) \qquad (1.3)$$

Furthermore, based on the definition of risk given previously, there are the following equivalences:

$$\text{Consumer risk} = \alpha(t, r_c) = P_c (r_c) * r_c = [(m_c (t)^r e^{-m_c(t)}) / r_c !] * r_c \qquad (1.4)$$

$$\text{Producer risk} = \beta(t, r_p) = P_p (r_p) * r_p = [(m_p (t)^r e^{-m_p(t)}) / r_p !] * r_p \qquad (1.5)$$

**Reliability Analysis**

In addition to risk, the second component of the model is reliability. Using a reliability growth model that has been used on the Shuttle, I develop the equations that are used in the test rules and scenario. The general form of consumer and producer reliability at time t is given by equation (1.6) [SCH97]:

$$R (t) = e^{-[a(e-b (t-s+1))]} \qquad (1.6)$$

It is of interest to know when consumer reliability has improved beyond that delivered by the producer. The reliability at time $t_{cp}$ when consumer reliability is equal to producer reliability can be found by equating $R_c (t) > R_p (t)$, using equation (1.6) and solving for $t = t_{cp}$. When $t > t_{cp}$, $R_c (t) > R_p (t)$, meaning at this test or operational time, consumer reliability exceeds producer reliability. The solution is found in equation (1.7):

$$t_{cp} = \left\{ \frac{[-\log(\alpha_p) / \log(\alpha_c) - b_c (1 - s_c) + b_p (1 - s_p)}{b_c - b_p} \right. \qquad (1.7)$$

The actual or empirical reliability is computed as follows for actual consumer reliability and actual producer reliability, in equations (1.8) and (1.9), respectively:

$$R_{ac}(t,r_c) = 1 - \left(\frac{r_c}{\sum_{t=1}^{N} r_c}\right) \qquad (1.8)$$

$R_{ap}$ (t, $r_p$) = $$1-\left(\frac{r_p}{\sum_{t=1}^{N} r_p}\right)$$

(1.9)

Reliability Growth

For safety critical systems like the Shuttle, it is important to demonstrate reliability growth, as contributing to the safety of the crew and mission. As pointed out by [MUS87], it may be necessary for an organization to demonstrate the reliability of its product "as delivered". For example, there could be a test where the consumer "buys off" the product from the producer. In this case, particularly for the case of safety critical software, the test model and schema must enforce a high standard of reliability (and risk) before the product is accepted.

Since the Shuttle uses a reliability growth model, test rules are conditioned to capture this important characteristic. To compute reliability growth quantitatively, Jeff Tian suggests that reliability growth can be measured by the purification level @. the ratio between the number of defects removed during testing over the total defects at the beginning of testing. He states that the purification level captures overall reliability growth and testing effectiveness [TIA95].

The objective of the model s use of purification level is to produce tests that have high testability (i.e., use tests that will cause failures to be detected and faults to be exposed and removed), as expressed in equations (1.10), ,(1.13).

The actual purification level for consumer and producer, using failures rather than defects, is computed in equations (1.10) and (1.11), respectively:

$\rho_c$ =

$$1-\left(\frac{r_c(t)}{\sum_{t=1}^{N} r_c(t)}\right)$$

(1.10)

$\rho_p$ =

$$1-\left(\frac{r_p(t)}{\sum_{t=1}^{N} r_p(t)}\right)$$

(1.11)

Since I want to assess the validity of my prediction system, I need to also predict the purification level [FEN97]. I do this to produce equations (1.12) and (1.13) for the consumer and producer, respectively.

$\rho_{cp}$ =

$$1-\left(\frac{m_c(t)}{\sum_{t=1}^{N} m_c(t)}\right)$$

\ * (1.12)

(continued on page 18)

$\rho_{pp} =$

$$1-\left(\frac{m_p(t)}{\sum_{t=1}^{N} m_p(t)}\right) \qquad (1.13)$$

With respect to actual risk, since it is based on empirical failure counts, use equations (1.14) and (1.15) for $P_{ac}(t, r_c)$ and Pap $(t, r_p)$, respectively.

$P_{ac}(t, r_c)$: actual consumer probability of $r_c$ failures in test time
t =

$$\frac{r_c(t)}{\sum_{t=1}^{N} r_c(t)} \qquad (1.14)$$

$P_{ap}(t, r_p)$: actual producer probability of $r_p$ failures in test time
t =

$$\frac{r_p(t)}{\sum_{t=1}^{N} r_p(t)} \qquad (1.15)$$

This leads to the equations for actual consumer risk and actual producer risk in equations (1.16) and (1.17), respectively.

$$\mu_c(t, r_c) = P_{ac}(t, r_c) * r_c \qquad (1.16)$$

$$\mu_p(t, r_p) = P_{ap}(t, r_p) * r_p \qquad (1.17)$$

**Test Rules**

Test rules are based on mandatory risk, reliability, risk prediction accuracy, reliability prediction accuracy, and reliability growth, and desirable reliability growth. While important, desirable reliability growth is not considered as important as the other criteria. This is a subjective judgment that the model user might want to change. In addition, as indicated Figure 1, Parts 1 and 2, the test scenario provides two complete tests for the software to be accepted or rejected.

Accept software if the following software rules evaluate to true . Accept model if the following model rules evaluate to true .

For all values of time t = tm (mission duration):

1) Risk

*Mandatory for Software*

Predicted and actual consumer and producer risks less than the limit:

a. $\alpha(t, r_c) < L_m$

b. $\beta(t, r_p) < L_m$ .

c. $\mu_c(t, r_c) < L_m$ , $\mu_p(t, r_p) < L_m$

*Mandatory for Prediction Model*

Consumer and producer risk prediction errors less than the limits:

(continued on page 21)

## Events Calendar

**Dates: Events**

**Mar.4-6 RIAC Training Programs**
**Reliability 101, Weibull Analysis, RCM, Probabilistic Risk Assessment**
Location: San Diego, CA
Contact: http://quanterion.com/RIAC/

**Mar. 17-19 Advance Systems Analysis**
Location: Tucson, AZ
Sponsor: ReliaSoft
Contact: www.ReliaSoft.org

**Mar. 18-20 RCM - 2008 Symposium**
Location: Las Vegas, NV
Sponsor: RCM org
Contact: customerservice @reliabilityweb.com

**Mar. 21 CRE Application**
May 4 Certification Exams
Location: WCQI, Houston, TX
Sponsor: ASQ-RD
Contact: www.asq.org/certification

**Apr. 10-11 FMEA Design/Analysis**
Location: Phoenix, AZ
Sponsor: ASQ Training
Contact: www.asq.org/courses/

**May 14-16 Reliability Growth Analysis**
Location: Tucson, AZ
Sponsor: ReliaSoft
Contact: www.ReliaSoft.org

**Jun.20-22 Intro to DFR**
Location: Tucson, AZ
Sponsor: ReliaSoft Corp.
Contact: www.ReliaSoft.org

**Jun.17-20 Applied Reliability Symposium**
Location: Reno, NV
Sponsor: ReliaSoft Corp.
Contact www.ReliaSoft.org

## News of the Division

**RD Council**

The council met on January 24, the day prior to the R & M Symposium in Las Vegas. Jim McLinn chaired the meeting. Key topics covered were: review of accomplishments pursuant to goals set in our Division Plan. Actions to promote and sustain membership participation in the RD on- line Discussion Board were formulated. Another project addressed is enlistment of Region Councilors in welcoming of new members to the RD.

**WCQI 2008**

Current status of the RD sessions planned for the 2008 WCQI in Houston and the RD exhibit were reviewed by RD Council. Plans were made to better inform members of the sessions prior to the WCQI.

**R & M Tech Briefs**

The fourth issue of *R&M Tech Briefs* is planned to be completed in February and posted to our web site. Announcements will be sent to members via e-mail. We invite comments and suggestions

RD Publications is pleased to announce that Fred Schenkelberg is joining the RD Pubs staff and preparing to soon assume responsibility for the *R & M Tech Briefs*. Our goal is production of a new issue every other month. This is dependent on RD members submital of draft brief articles (nominally 1 to 3 pages) describing and/or illustrating unique/ new approaches or methods addressing R & M problems.

**RD Forum Library**

Three RD members, Minxiao Jiang, Todd Heydt, and Ruth Wirawan, have volunteered to commence the task of linking articles from past issues of RR under a three word topic within the RD Forum Library web data base. The 27 topics cover the main topics of R & M body of knowledge. This resource is to afford members the ability to quickly retrieve *RR and Tech Brief* articles covering a B o K topic of interest.

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d. $[\mu_c(t, r_c) - \alpha(t,r_c)^2] < (ERc + 3\sigma)$

e. $[\mu_p(t, r_p) - \beta(t,r_p)^2] < (ERp + 3\sigma)$

2) Reliability

*Mandatory for Software Reliability Growth*

Predicted and actual consumer and producer reliabilities exceed the requirements:

a. $R_c(t) > R_{cs}$

b. $R_p(t) > R_{ps}$

c. $R_a(t) > R_{cs}$

d. $R_a(t) > R_{ps}$

*Mandatory for Prediction Model*

Consumer and producer reliability prediction errors less than the limits:

e. $[R_{ac}(t,r_c) - R_c(t,r_c)]^2 < (E_{rc} + 3\sigma)$

f. $[R_{ap}(t,r_p) - R_p(t,r_p)]^2 (< E_{rp} + 3\sigma)$

*Desirable for Software Reliability Growth*

Predicted consumer and producer reliability growths exceed the actual growths:

g. $\rho_{cp} > \rho_c$

h. $\rho_{pp} > \rho_p$

The Shuttle test rules, based on using risk, reliability, and reliability growth criteria, as well as application of this model will follow in the remainder of this article.

*The balance of this article will appear in the June issue of RR. Ed*

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# Exposure Variables for Reliability Assessment: Exact Poisson CI

by W.V.Harper, Ph.D., T. Eschenbach, Ph.D., and T.R. James

Often rates for reliability are given per unit of time, but this may not always be the best or only exposure variable. Are there other exposure variables that may add insight into the forces driving occurrences such as failure? This article briefly explores the issue as well as the exact confidence interval (CI) of such rates. Examples are provided for oil spill rates in the Gulf of Mexico, for quantification of stress corrosion cracking rates in pipelines, and for battery failure rates.

In Harper and Eschenbach (2007), exact CIs were developed for the ratio of two Poisson means (or rates). Our companion article on the Excel VBA function for computing the exact CI for a single Poisson rate will be found in the new issue of R & M Tech Briefs It includes how to trap a known error in the Excel inverse chi-square function, and substitute an accurate inverse chi-square approximation.

**Failure/Occurrence Rates and Exposure Variables**

Reliability (in terms of failure occurrence) rates are commonly given as the ratio of the number of incidents per time. These incidents may be failures or just counts of some item of interest. The occurrence rate relative to time is often an important one and is generally of interest. But time may mask the underlying cause. Consider tires, for example, where mileage may be a better predictor of failure than time and hence a better exposure variable. Even when time is important, the way in which time is recorded and used in the resulting rate may determine the validity of the estimated reliability. Elapsed calendar time (age) may be also be an applicable exposure variable for reliability of tires but distance in miles driven may be more relevant.

In some cases the age of a part or product clearly distinguishes it, as for example, in the battery failure rate summarized in Table 5. However, in the oil spill case described here, this is not possible because the infrastructure at risk is continually changing as pipelines and platforms are built, placed in service, idled, and retired. Wikipedia at http://en.wikipedia.org/wiki/Exposure_variable defines an exposure variable as follows:

The exposure variable, in reliability theory, is the discrete or continuous variable which differentiates distinct failure events. It is usually time, especially the time to failure of a device, or the time to death of a person. Time can be considered loosely as a hazard to which the device or person is exposed.

An exposure variable quantifies the amount of contact (or hazard) that the object of interest has faced. If there is a causal link between the failure event and an exposure variable, then as the accumulation of the exposure variable increases the likelihood of failure rises. This is often in terms of time. An example is car batteries that last around five years. Mileage is a better exposure variable than time for tires as it is a more closely correlated with tire wear; however, age (calendar time) is an important factor in tire deterioration .. Hence, time and another exposure variable taken together may prove to be an even better predictor of failure. For example operating time, temperature, and the number of pressure cycles for oil and gas pipelines impact their reliability. This leads to multivariate reliability which is an area that needs to be better understood and used where applicable. As another approach, this article describes exposure variables that measure the amount of infrastructure exposed per unit of time.

For the applications described in Tables 1 and 2 the amount of physical infrastructure at risk for failure is changing over time. Thus, time is an unreliable exposure variable, and variables linked to the volume of infrastructure are needed. Tables 1 and 2, respectively, provide examples of failure rates for oil spills and stress corrosion cracking. In a later section Tables 3 and 4 supplement these results with exact confidence intervals.

In Table 1, 36 pipeline oil spills exceeding 50 barrels occurred in the Gulf of Mexico from 1972 to 2005. For platform spills, there were 22 spills exceeding 50 barrels in the Gulf of Mexico from 1990 to 2005. Note the 1972 to 2005 time interval was sub-divided for platforms because the platform spill rate was nonstationary for the full time period. The spill rate was lower for the 1990

| Label | Exposure Variable | Sum Exposure Variable | # Spills | Rate |
|---|---|---|---|---|
| Pipeline Spills/ KMile-year, 1972-2005 | KMile-years | 161.796 | 36 | 0.223 |
| Platform Spills/ KPlatform-year, 1990-2005 only | KPlatform-years | 56.37 | 22 | 0.3903 |

**Table 1. Gulf of Mexico Oil Spill Rates for = 50 bbl Spills**

to 2005 years with a point estimate of 0.5041 for the ratio of its rate to the 1972 to 1989 period. Harper and Eschenbach (2007) further show the 95% CI for the ratio of the two Poisson rates was (0.3051, 0.8330). Since 1.0 is not in this interval the two rates are significantly different and hence the entire 1972 to 2005 time frame is non-stationary for platform spills.

KMile-years tracks the thousands of miles of undersea pipeline in use per unit of time. (Thus 1000 miles for a year or 4000 miles for three months would both have an exposure of 1.0 KMile-years.) However, there is a significant bookkeeping challenge in calculating the value of the exposure variable between events, when the data on the exposure variable is provided on an annual basis. For example, if the beginning of year value is 3578 platforms, and the end-of year value is 3530 platforms; what is the number of platform-years between May 3rd and July 8th? This challenge must be met for the crucial goodness of fit test for the inter-event exponential distribution.

The rates in Table 1 are the ratio of the oil spills divided by the exposure variable. For example the Pipeline Spills/KMile-year rate is 36/161.796 = 0.223. In a similar calculation the Platform Spills/platform year rate is 22/56.37 = 0.3903. The associated exact Poisson confidence intervals are found later in Table 3.

The second example in Table 2 involves stress corrosion cracking (SCC) which is a serious threat to oil and gas pipelines and may lead to sudden ruptures. This data is from an international pipeline company. Field measurements were made in the thousands of expensive excavations of buried pipe. The number of SCC colonies and the length of pipe dug were recorded along with numerous other variables. A colony is a set of interlinked stress cracks on the exterior surface of the pipeline that under certain conditions can quickly grow and lead to pipeline rupture.

For the data in Table 2 the coating condition of the pipe was evaluated prior to its removal, then the pipe was checked for SCC colonies. As can be seen there appears to be a strong relationship between the likelihood of SCC colonies and the pipe coating condition. Pipe coating condition can often be estimated from what are called direct assessment methods such as above ground pipe to soil potential measurements that do not entail the costly digging of the pipeline. Thus possible problem areas can be more cost effectively identified and more quickly addressed.

| Pipe Coating Condition | # SCC Colonies | Meters of Inspected Pipe | SCC rate/m |
|---|---|---|---|
| Excellent | 19 | 1756 | 0.0108 |
| Well | 181 | 1978 | 0.0915 |
| Fair | 1181 | 3915 | 0.3016 |
| Poor | 1078 | 1815 | 0.5939 |

**Table 2. Pipeline Stress Corrosion Cracking Rates for Different Pipeline Coating Conditions**

As much as possible, there should be a sound logic that links failure events to the exposure variable. This is important when the environment and infrastructure at risk are changing, as in the initial application of Tables 1 and 2. It is even more important when the event occurrence is being extrapolated to a different environment, such as spill rates from the Gulf of Mexico to the Arctic. The presence of this logic is reflected in a subtle, but important, change in language. The presence of a linking logic between exposure and occurrence probability allows the description of that exposure as a driving variable. In other words, the description is not of just a simple statistical correlation, rather a causal linkage is suggested. Relationships based on causality are considered more reliable than relationships based on correlation.

Eschenbach and Harper (2006) postulated that the current exposure variable of billions of barrels of oil (Bbbl) used by the Minerals Management Service, U.S. Department of the Interior, was not the only exposure variable of interest. We further suggested that it was not the best to translate Gulf of Mexico results to future Arctic off-shore pipeline and platform spills. Exposure variables examined included barrels of production, time (in years), Kmile-years of pipeline, and number of platform-years. In the Gulf of Mexico in 2005 there were about 3400 platforms and about 8500 miles of pipeline in active use in the areas regulated by the Minerals Management Service,U.S. Department of the Interior. The level, amount, and character of infrastructure development in the Arctic will differ since platforms are at different lengths from shore, platforms will serve larger areas due to improved drilling technology, and production rates per platform will be far higher. Exposure variables that can be adapted to very different conditions in the Arctic will be assessed by a variety of engineering and statistical measures.

Using exposure variables that can account for not only accurate assessments of known conditions in the Gulf of Mexico but also can be adjusted for new and varying conditions in the Arctic is preferable over other possible exposure variables that neglect such factors.

Relevant exposure variables should not be assumed as a given. Modeling of any type requires thought, patience, and a willingness to rock the corporate boat from time to time.

**Testing Goodness-of-Fit**

When counting any type of event, occurrence, or failure a Poisson distribution is often used. The Poisson distribution is a flexible discrete distribution that may adequately model the failure events; however, this must be tested. A chi-square goodness of fit test is frequently used on a discrete distribution like the Poisson. This requires binning or collecting the number of observations that fall into various cells. A more powerful approach to assess if the Poisson is adequate is to analyze the fit of the inter-event exposure variable to the continuous exponential distribution.

It is easier to assess if the continuous distribution adequately models the inter-event data. No lumping of data into bins or cells is required. This is a more powerful statistical test and one that removes any subjectivity over how to create the bin widths needed for the chi-square goodness of fit test (D'Agostina and Stephens, 1986; Huber and Glen, 2007; Stephens, 1974). Such tests are necessary for each exposure variable of interest. Examples of goodness of fit tests are found in Eschenbach and Harper (2006) and to a lesser extent in Harper and Eschenbach (2007).

Our personal experience has been that often the Poisson is found to be reasonable via a goodness of fit test (chi-square on the discrete Poisson or the Anderson-Darling or Kolomorgorov-Smirnoff tests on a continuous exponential). However there are instances where this is not the case. There seems to be a dearth of good discrete distributions when one compares the common discrete distributions to the plethora of continuous distributions. A more flexible option is a compound or mixed Poisson distribution (ch 5, Clark and Harper, 2000; or section 8.2.5, Johnson, Kemp, and Kotz, 2005). This can provide a longer tail than the standard Poisson to model rarer large values not uncommon in some disciplines such as with geologic data.

**Exact Poisson Confidence Intervals**

Once a Poisson distribution has been justified, one can begin to estimate the occurrence rate. The rate is the mean of the Poisson distribution which is the ratio of the number of occurrences over the summed exposure variable. Care must be given to determine if a time varying Poisson mean (also known as a non-stationary Poisson process or a non-homogeneous Poisson process) is needed. If the assumption of a stationary non-changing mean is not appropriate then intervals of quasi-stationarity might be found for which a given Poisson rate is reasonable. For the spill rate example of this article, the data on pipeline spills was stationary over the data set, while the platform spill data was partitioned into two intervals.

Building from Johnson, Kemp and Kotz (2005, pp. 176) and Buchan (2004) the formulas below explicitly address the incorporation of an exposure variable. The first formula represents an exact lower confidence bound for the mean Poisson rate while the second formula is the formulation for the upper confidence bound. Taken together these form the 100(1-)% confidence interval. Dividing equally into each tail results in a two-tailed exact confidence interval for the Poisson rate. These confidence intervals are based on the chi-square (@2) distribution.

$$l_L = \left( \frac{\frac{1}{2} c^{2}_{2x,\frac{a}{2}}}{\sum Exposure Variable} \right); \qquad l_U = \left( \frac{\frac{1}{2} c^{2}_{2(x+1),1-\frac{a}{2}}}{\sum Exposure Variable} \right)$$

Generally in statistics increasing the sample size decreases the width of confidence intervals. In these equations, the subscript x is the number of events (such as oil spills or failures), and is the basis for the number of degrees of freedom for the chi-square distribution. To check that this formula behaves as expected, assume that the number of occurrences and the amount of exposure are both doubled (which keeps the rate constant). Doubling the number of degrees of freedom more than doubles the lower @2 value. Since the exposure also doubled, the lower limit goes up and is closer to the estimated average. In like fashion doubling the number of degrees of freedom less than doubles the upper value, so the upper limit has decreased.

The chi-square value needed above is called the inverse chi-square. By this it is meant that the user will provide the appropriate confidence level desired (which in turns gives the value needed) and the number of incidents (x above). Then the inverse routine provides the corresponding value of the chi-square distribution.

**Excel VBA Solution Addressing Problems with Excel's Inverse Chi-Square Function**

The formula for the exact Poisson confidence interval has two major components. The first is the inverse chi-square distribution that is addressed in this article. The second is the sum of the relevant exposure variable (often total time on test) which can be more difficult in practice than one might initially anticipate, and potentially may present a challenge to be considered.

The Poisson confidence limits in the prior section would not be hard to implement in Excel if Excel's chi-square inverse routine was error free. For large degrees of freedom, Excel's inverse chi-square distribution (even in Excel 2007) aborts and sends an error message to the user. Iain Buchan (2004) offered a VBA solution but it required having a very specific U.K. statistical software package StatsDirect that could be linked to and called by VBA. In our approach which may be accessed on line in the current issue of *R & M Tech Briefs* no other statistical package is required.

The approximation used for the inverse chi-square is found in Johnson, Kotz, and Balakrishnan (1994). It is the Wilson-Hilferty (1931) approximation and follows:

$$F_{X_n^2}(x) = \Phi\left(\sqrt{\frac{9n}{2}}\left\langle\left(\frac{x}{n}\right)^{\frac{1}{3}} - 1 + \frac{2}{9n}\right\rangle\right)$$ where $\Phi(x)$ is the standard normal distribution.

$$X^2_{n,e} = n\left(\sqrt{\frac{2}{9n}}\,\Phi^{-1}(e) + 1 + \frac{2}{9n}\right)^3$$

where $\Phi^{-1}(e)$ is the lower $e$ percentage point of the standard normal distribution.

Thus $\Phi^{-1}(e)$ is the inverse of the standard normal distribution.

**Examples of Exact Poisson Rate Confidence Intervals**

This section supplements the earlier results for failure rates for different exposure variables by adding exact Poisson confidence intervals calculated with the Excel VBA routines. Table 3 shows the rates and intervals for oil spills, and Table 4 shows the rates and intervals for stress corrosion cracking. Table 5 shows confidence intervals for the hypothetical battery data given in Harper and Eschenbach (2007).

| Label | Exposure Variable | Sum Exposure Variable | # Spills | Rate | 95% CI |
|---|---|---|---|---|---|
| Pipeline Spills/ KMile-year | KMile-years | 161.796 | 36 | 0.223 | (0.156, 0.308) |
| Platform Spills/ platform-year | KPlatform-years | 56.37 | 22 | 0.3903 | (0.2446, 0.5909) |

**Table 3. Gulf of Mexico Oil Exact Poisson CI for = 50 bbl Spills**

| Pipe Coating Condition | # SCC Colonies | Meters of Inspected Pipe | SCC rate/m | 95% CI |
|---|---|---|---|---|
| Excellent | 19 | 1756.14 | 0.0108 | (0.0065, 0.0169) |
| Well | 181 | 1978.59 | 0.0915 | (0.0786, 0.1058) |
| Fair | 1181 | 3915.66 | 0.3016 | (0.2847, 0.3193) |
| Poor | 1078 | 1815.27 | 0.5939 | (0.5589, 0.6304) |

**Table 4. Stress Corrosion Cracking Exact Poisson CI for Different Coating Conditions**

| Battery Type | # Failures | Sum of Time, years | Failure Rate/year | 95% CI |
|---|---|---|---|---|
| A | 45 | 74.97 | 0.600 | (0.438, 0.803) |
| B | 50 | 151 | 0.331 | (0.246, 0.437) |

**Table 5. Battery Failure Rates for Two Battery Types**

**Conclusion**

Failure, event, or occurrence counts are important to product and system integrity. The development of rates and confidence intervals for appropriate exposure variables aids engineers and managers to predict reliability and protect our lives and the environment. Whenever possible, the quantification of uncertainty provided by sound CIs should be standard engineering practice.

**References**

The listing of references will appear with the authors' companion article on the Excel VBA function for computing the exact CI for a single Poisson rate in the February 2008 issue of "R & M Tech Briefs" It includes how to trap a known error in the Excel inverse chi-square function, and substitute an accurate inverse chi-square approximation.

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