Summary & Conclusions

For any company interested in predicting field reliability performance, finding a prediction technique that provides a high degree of fidelity to observed field data is essential. With the discontinuance of military handbook Mil-Hdbk-217, Reliability Prediction of Electronic Equipment, and the limited environmental applications of Telcordia SR-332, Reliability Prediction for Electronic Equipment, this paper evaluates the Reliability Analysis Center’s (RAC) PRISM® software tool as a potential improved methodology in predicting the field reliability of military systems. This evaluation compares the PRISM predicted failure rate to the actual observed field failure rate for three military electronics units. While initial results showed the predicted failure rate to be approximately one-half of the observed field failure rate, the ratio of predicted failure rate to observed field failure rate was consistent across three independent systems. Furthermore, the PRISM methodology has features such as process grade factors and field failure data incorporation through Bayesian analysis which show promise in allowing a more accurate field reliability prediction to be generated. As a point of comparison, the initial failure rate prediction by Raytheon is opposite to an earlier assessment performed by TRW Automotive where field data was not factored in through the use of PRISM’s Bayesian analysis option (Reference 1). TRW Automotive found a predicted failure rate that was twice the observed field failure rate.

This paper discusses Raytheon’s assessment of the PRISM software tool including the reason for choosing PRISM, application of the PRISM prediction methodology to three military electronic units, and analysis of the prediction results. This paper also discusses future plans for refinements in the use of PRISM’s features to produce a more accurate reliability prediction of field performance.

1. Introduction

While Mil-Hdbk-217 was never intended as a field reliability predictor, it remained a reliability prediction mainstay in the defense industry through the 1980’s until its discontinuance in 1995. With the increased use of commercial electronics in military applications and the lack of periodic update, Mil-Hdbk-217 has become notorious for generating overly pessimistic field reliability predictions. Over the past 10 years, the defense industry has faced a challenge in finding a field reliability prediction methodology that consistently provides a high degree of correlation with observed field data. Techniques such as physics-of-failure, while helpful in examining specific failure mechanisms, tend to be very cumbersome for complex systems, and Telcordia SR-332 has limitations given it was developed for commercial systems. In the past few years, defense contractors have tended to either extrapolate Telcordia environmental factors to address military environments or extrapolate Mil-Hdbk-217 part complexity and quality factors to address advances in device technology and increases in commercial electronics quality. Furthermore, these methodologies typically only address part operational failures while other system failure contributors such as inadequate design and manufacturing are not considered in the reliability prediction. While these practices have provided a stop-gap measure for producing field reliability predictions, a comprehensive reliability prediction tool to accurately predict field performance is desired.

Raytheon has conducted a recent assessment of the PRISM software tool to determine its ability to accurately predict field reliability. This assess-
ment consists of a comparison of the PRISM predicted failure rate to the actual observed field failure rate for three military electronics units used in an Air Force fighter aircraft, a Navy helicopter, and a Navy surveillance aircraft. The assessment includes understanding the details of the PRISM methodology, conducting a PRISM prediction of the electronics units, comparing the predicted failure rates with those observed in the field, analyzing how the various PRISM input parameters affect the predicted failure rates, and determining areas where further refinement could produce a higher fidelity field reliability prediction.

2. Background

2.1 PRISM Prediction Methodology Overview. The Reliability Analysis Center (RAC) has developed a methodology and associated engineering software tool, PRISM, to assess the reliability of electronic systems. This methodology includes component-level reliability prediction models as well as a process for assessing the reliability of systems due to non-component variables. The PRISM system reliability assessment program is comprised of component-level failure rate calculations taken from RACRates models, RAC data, or user-defined data and a system-level model that applies process grading factors.

2.2 PRISM Component Failure Rate Data. The building blocks of the PRISM prediction methodology are component-level failure rates. These failure rates are determined from RACRates models, RAC data, or user-defined data.

2.2.1 RACRates Models. RACRates are component reliability prediction models that use a combination of additive and multiplicative factors to generate a separate failure rate for each generic class of failure mechanisms for a component. Each of these failure rate terms is then accelerated by the appropriate stress. RACRates models have the following general form:

\[ \lambda_p = \lambda_o \pi_o + \lambda_e \pi_e + \lambda_i \pi_i + \lambda_{sj} \pi_{sj} \]  

(1)

where

- \( \lambda_p \) = predicted failure rate,
- \( \lambda_o \) = failure rate from operational stresses,
- \( \lambda_e \) = failure rate from environmental stresses,
- \( \lambda_i \) = failure rate from induced stresses including electrical overstress,
- \( \lambda_{sj} \) = failure rate from solder joints,
- \( \pi_o \) = product of failure rate multipliers for operational stresses,
- \( \pi_e \) = product of failure rate multipliers for environmental stresses,
- \( \pi_i \) = product of failure rate multipliers for environmental overstress,
- \( \pi_{sj} \) = product of failure rate multipliers for solder joint stresses.

By modeling the failure rate in this manner, factors that account for the application and component-specific variables that affect reliability ("\( \pi \)" factors) can be applied to the appropriate additive failure rate term. RACRates models are currently available only for capacitors, resistors, diodes, transistors, thyristors, integrated circuits, and software.

2.2.2 RAC Data. PRISM also contains data from the RAC Electronics Parts Reliability Data (EPRD) and Nonelectronic Parts Reliability Data (NPRD) publications. This data has been refined and scaled to fit into the calendar hour structure of PRISM. RAC data is available for a variety of components including transformers, inductors, switches, relays, and connectors. This data is helpful when a RACRates model or user-defined data does not exist for a particular component.

2.2.3 User-Defined Data. In the event that empirical data is available, the PRISM software tool allows for the input of user-defined failure rate data when RACRates model or RAC data does not exist.

2.2.4 PRISM System Failure Rate Model. The PRISM system failure rate model is defined as the sum of the component failure rates times a process grade factor. This system model is given by:

\[ \lambda_p = \lambda_{IA} (\sum I_i \Pi_i + \sum I_M \Pi_M + \Pi_E \Pi_G + \Pi_I + \Pi_N + \Pi_W) + \lambda_{SW} \]  

(2)

where the parameters are defined in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_p )</td>
<td>Predicted failure rate of the system</td>
<td></td>
</tr>
<tr>
<td>( \lambda_{IA} )</td>
<td>Initial assessment of the failure rate</td>
<td>Sum of component failure rates from RACRates models, RAC data, and user defined failure rates</td>
</tr>
<tr>
<td>( \Pi_i )</td>
<td>Parts process multiplier</td>
<td>Parts process grade</td>
</tr>
<tr>
<td>( \Pi_M )</td>
<td>Infant mortality multiplier</td>
<td>PRISM infant mortality model</td>
</tr>
<tr>
<td>( \Pi_E )</td>
<td>Environmental factor</td>
<td>PRISM environmental model</td>
</tr>
<tr>
<td>( \Pi_I )</td>
<td>Design process multiplier</td>
<td>Design process grade</td>
</tr>
<tr>
<td>( \Pi_G )</td>
<td>Reliability growth factor</td>
<td>PRISM reliability growth model</td>
</tr>
<tr>
<td>( \Pi_{SM} )</td>
<td>Manufacturing process multiplier</td>
<td>Manufacturing process grade</td>
</tr>
<tr>
<td>( \Pi_{SM} )</td>
<td>System management process multiplier</td>
<td>System management process grade</td>
</tr>
<tr>
<td>( \Pi_{IP} )</td>
<td>Induced process multiplier</td>
<td>Induced process grade</td>
</tr>
<tr>
<td>( \Pi_N )</td>
<td>No-defect process multiplier</td>
<td>No-defect process grade</td>
</tr>
<tr>
<td>( \Pi_W )</td>
<td>Wearout process multiplier</td>
<td>Wearout process grade</td>
</tr>
<tr>
<td>( \lambda_{SW} )</td>
<td>Software failure rate prediction</td>
<td>RACRates software model, RAC Data, or user-defined data</td>
</tr>
</tbody>
</table>
2.3 PRISM Process Grade Factors. Once a unit is designed, the failure rate value that is calculated by any model is an inherent or “seed” failure rate because it represents only the physical attributes of the components that comprise the unit, subject to the environmental conditions and operating profile characteristics associated with its application. The failure rate that the unit will actually experience in the field may be potentially better or worse than the inherent failure rate. The difference in the observed field failure rate and the inherent predicted failure rate depends on the design, requirement definition, and testing activities undertaken by the manufacturer to ensure that:

- Designs are reliable and robust
- Manufacturing practices do not degrade reliability performance
- Parts of acceptable quality are selected and controlled
- Management processes encourage good requirements definition and design practices
- The number of “cannot duplicate” (CND) incidents is minimized
- Maintenance activities do not induce failures
- Wearout and infant mortality issues are understood and addressed
- Reliability growth is emphasized throughout the design and development phases

The effect of process-related variability around the inherent (or seed) failure rate is accounted for within PRISM by applying process grade factors. By answering a series of questions within a specific process grade type, a scoring profile is generated and translated into a quantitative pi-factor multiplier. This score in a specific process grade type, a scoring profile is generated and translated into a quantitative pi-factor multiplier. This score combined into a module-level process grade set. For the “industrial average”, the process grade expression in the system-level process grade factors. By answering a series of questions within a specific process grade type, a scoring profile is generated and translated into a quantitative pi-factor multiplier. This score combined into a module-level process grade set. For the “industrial average”, the process grade expression in the system-level grade factor will increase if “less than average” processes are in place while the grade will decrease if “better than average” processes are in place.

2.4 PRISM Failure Rate Predictions. Most failure rate prediction methods allow only for an inherent reliability to be predicted, that is, the reliability of the components given correct manufacturing, requirement specifications, and handling. However, PRISM allows for two failure rate prediction types: inherent and logistics.

Inherent: The inherent failure rate calculation does not take into account induced failures or “cannot duplicate” (CND) issues. The induced process grade (\(\Pi I\)) and the no-defect process grade (\(\Pi N\)) are not included in the system-level failure rate calculation.

\[
\lambda_{P(\text{inherent})} = \lambda_{IA} (\Pi D \Pi IM \Pi E + \Pi D \Pi G + \Pi SM \Pi IM \Pi I \Pi G + \Pi I + \Pi N + \Pi W) + \lambda_{SW} \tag{3}
\]

Logistics: The logistics failure rate calculation takes into account induced failures and cannot duplicate (CND) issues. The induced process grade (\(\Pi I\)) and the no-defect process grade (\(\Pi N\)) are included in the system-level failure rate calculation.

\[
\lambda_{P(\text{logistics})} = \lambda_{IA} (\Pi D \Pi IM \Pi E + \Pi D \Pi G + \Pi SM \Pi IM \Pi I \Pi G + \Pi I + \Pi N + \Pi W) + \lambda_{SW} \tag{4}
\]

3. Evaluation Methodology

3.1 Field Data Assessment. For the purpose of the PRISM evaluation, three airborne electronic units were chosen that had well-documented field failure data and sufficient cumulative field-operating time. Their basic makeup involves multiple circuit card assemblies mounted in an enclosed chassis. All three units had at least 12 months of continuous field failure data that was detailed enough for categorizing by induced, could not duplicate (synonymous with no defect found), design, or part failure modes. This same field data was also used to baseline the observed performance of each electronics unit. For comparing the field and predicted data, the reliability metrics Mean Time Between Failures (MTBF) and Mean Time Between Unscheduled Removal (MTBUR) were used. The MTBF metric includes only inherent-type failures excluding cannot duplicate (CND) and induced fail returns. MTBUR includes both induced and CND returns along with inherent failures. These field MTBF and MTBUR values were directly compared with the PRISM inherent and logistics models, respectively. Using these relationships, common failure modes are kept consistent in both the field data and the methodology of PRISM, thus ensuring accurate correlation between the data.

The field data used in the PRISM evaluation is given in Table 2. The baseline used for comparison includes actual failure data taken over 12 months of continuous performance monitoring.

The observed MTBF and MTBUR calculations were normalized over the steady 12-month period. Field returns were analyzed, sorted, and combined so that the observed metric represents random equipment failures. Returns that were repetitive, systematically induced, or non-performance related were removed from the total failure count. The number of software-related failures was insignificant and therefore left out of the evaluation altogether. The PRISM methodology generates failure rate predictions in terms of failures
per million calendar hours, instead of the more common failure per million operating hours. Therefore, a translation from operating hours to calendar hours was accomplished by dividing the cumulative operating hours by the units’ respective duty cycle.

3.2 PRISM Evaluation Process. A four-step process was used to evaluate PRISM failure rate predictions against observed field data. The following four-step process was repeated for each of the three units:

1. Assessing known field data,
2. Inputting component/system data into the PRISM tool,
3. Calculating predicted failure rates using the inherent and logistics RAC models with both industry average and program-specific process grade factors, and
4. Comparing the PRISM prediction results with observed field failure rates.

Existing system models (also known as component tree structures) in Raytheon’s Advanced Specialty Engineering Networked Toolkit (ASENT) reliability analysis software tool were used from previous engineering efforts on each of the three units. All assembly models and component parameters such as part type, electrical stress, and temperature were exported from ASENT into PRISM. After importing parts data into PRISM, component parameters were checked to verify misplaced or corrupt data was not incurred during the data transport. Components that did not have RACRates models were assigned failure rates from the RAC data library or assigned a user-defined failure rate. Subassemblies and components having user-defined failure rates were converted from failures per million operating hours into failures per million calendar hours using the respective duty cycle of each unit.

PRISM’s default environment settings and operating profiles were not used in our evaluation. Instead, environment and profile information was obtained from actual field measurements and/or contract specifications for each program.

The composition component failure rate sources for each of the three units is shown in Figure 1. As can be seen, the failure rate sources varied greatly among the three units. Electronics Unit 1 had approximately an equal contribution of failure rates from RACRates models and RAC data. However, Electronics Unit 2 and Electronics Unit 3 had a predominant contribution from RAC data and user-defined data, respectively.

Because each of the three electronic units was designed, developed, and manufactured by different programs, each unit had its own process grade factor (PGF) set. PGF sets were created by surveying the program’s engineering personnel responsible for the respective process. Once attained, these factors were applied only to assemblies that were designed and manufactured by the respective Raytheon program. Parts and assemblies that were out-sourced to subcontractors were assigned PRISM’s default PGFs for this evaluation.

### Table 2. PRISM Evaluation Field Data

<table>
<thead>
<tr>
<th>Unit</th>
<th>Environment</th>
<th>Hours Determination (Hours)</th>
<th>Failure Count</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cumulative Operating</td>
<td>Duty Cycle</td>
</tr>
<tr>
<td>Electronics Unit 1</td>
<td>Rotary Wing Aircraft</td>
<td>81,300</td>
<td>3%</td>
</tr>
<tr>
<td>Electronics Unit 2</td>
<td>Fixed Wing Aircraft</td>
<td>23,222</td>
<td>4%</td>
</tr>
<tr>
<td>Electronics Unit 3</td>
<td>Fixed Wing Aircraft</td>
<td>48,234</td>
<td>10%</td>
</tr>
</tbody>
</table>

Figure 1. Comparison of Component Failure Rate Sources

### Figure 1. Comparison of Component Failure Rate Sources

4. Results

The ratios of the PRISM predicted failure rates to the observed field failure rates were compared for each unit and the relative differences evaluated. Percentage differences were also calculated so as to quantify the accuracy of the individual predictions as well as the evaluation average.

**Inherent Reliability Comparison.** First, the predicted and observed inherent failure rates of each unit were compared using both the PRISM default and program-specific process grade factor sets. Figure 2 illustrates the percent differences between the predicted inherent failure rates and the observed inherent field failure rates.

The primary observation is the accuracy of the predictions using the default PGFs compared to the program-specified PGFs. On the average, predictions made using the default PGFs were 57% closer to the observed values than ones made with the program-specific PGFs. The program-specific process grade factor sets have adjusted the overall failure rate to generate an optimistic
prediction. The standard deviations for both categories were approximately equal, which suggests relative agreement between the overall effect of each program-specific grade factor sets.

With the exception of Electronics Unit 3, the inherent default PGF reliability predictions for both Electronic Units 1 and 2 were very close to the observed failure rates exhibiting no more than a 3% deviation. Electronics Unit 3 showed an 18% difference between predicted and observed field failure rates. To understand the cause for the variance in prediction accuracies, the failure rate sources for each assembly of each unit were evaluated. Figure 1 illustrates the failure data percent makeup of each electronic unit. One distinct difference between Electronic Units 1 and 2 and Electronics Unit 3 is the percentage of user-defined values associated with the total predicted failure rate. The predicted failure rate of Electronics Unit 3 is 66% user-defined, whereas the user-defined contribution to Electronics Units 1 and 2 units is less than 20%. This large user-defined source in Electronics Unit 3 may contribute to the source of the prediction variance, and it will be assessed further in future PRISM evaluations.

4.2 Logistics Reliability Comparison. Next, the predicted and observed logistics failure rates of each unit were compared using both the PRISM default and program-specific process grade factor sets. For this comparison, CND and induced failure returns were incorporated into the field failure rate. Likewise, the PRISM model factored CND and induced process grade factors into the overall failure rate predictions. Figure 3 shows the percent differences between the predicted logistics failure rates and the observed logistics field failure rates.

To better understand this, the variations between the default and program-specific process grade factors were analyzed. Table 3 illustrates the percent differences between the RAC default and Raytheon-surveyed process grade factors. This table raises the possibility that the optimistic predicted failure rates may stem from the results of the program-specific PGF surveys. In six of the nine total process gradings, the three programs averaged at least a 35% lower value than the RAC default values. These differences signify lower process grade scores which, by the RAC model, lead to lower predicted failure rates.

Table 3. Comparison of Process Grade Factor Scores

<table>
<thead>
<tr>
<th>Process Grade Factor Type</th>
<th>Electr. Unit 1</th>
<th>Electr. Unit 2</th>
<th>Electr. Unit 3</th>
<th>Avg Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Quality</td>
<td>-32%</td>
<td>-47%</td>
<td>-28%</td>
<td>-36%</td>
</tr>
<tr>
<td>Infant Mortality</td>
<td>-48%</td>
<td>-42%</td>
<td>-55%</td>
<td>-48%</td>
</tr>
<tr>
<td>Design</td>
<td>-56%</td>
<td>-62%</td>
<td>-41%</td>
<td>-53%</td>
</tr>
<tr>
<td>Growth</td>
<td>+4%</td>
<td>-7%</td>
<td>-6%</td>
<td>-3%</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>-44%</td>
<td>-50%</td>
<td>-24%</td>
<td>-39%</td>
</tr>
<tr>
<td>System Mgmt.</td>
<td>-62%</td>
<td>-68%</td>
<td>-36%</td>
<td>-55%</td>
</tr>
<tr>
<td>Induced</td>
<td>-42%</td>
<td>-81%</td>
<td>-27%</td>
<td>-50%</td>
</tr>
<tr>
<td>No Defect</td>
<td>-9%</td>
<td>-22%</td>
<td>+4%</td>
<td>-9%</td>
</tr>
<tr>
<td>Wear Out</td>
<td>+4%</td>
<td>0%</td>
<td>-18%</td>
<td>-5%</td>
</tr>
</tbody>
</table>

4.3 Field Data Incorporation. Using the two prediction models already calculated, field data was incorporated into the PRISM software tool as “observed data” to evaluate the accuracy of the adjusted predictions. When applying the field data into PRISM, CND and induced field failures were removed from the PRISM model entry when adjusting the inherent model. Likewise, these failures were included when adjusting the logistics model predictions. The results of using PRISM’s Bayesian analysis is shown in Figures 4 and 5.

Reviewing the average percent differences of the default PGFs logistics model prediction, a similar difference was observed, both in value and error, to that of the inherent model prediction. It appears the effect of introducing CND and induced failures into the field data was consistent with the effect of the results of the same process grade factors. This correlation provides validity to the CND and induced process grade factors.

Again, the choice of PGFs greatly affects the overall accuracy of the predictions. In Figure 3, the average effective difference between using the default PGFs and program-specific PGFs is 54%. The outcome of a logistics model prediction using the program-specific PGFs is still optimistic.
After applying observed field data into PRISM, the failure rate predictions fell very close to observed field values. Using the observed field data, the predictions fell within 2% of the observed field failure rate values. This improvement in prediction accuracy is an example of how important historical field data can be for predicting the field reliability of a derivative electronics system.

5. Conclusions
This paper compares the predicted field reliability of electronics units using the PRISM methodology to the observed field failure rate. The initial results showed that:

- The PRISM inherent and logistics failure rate predictions both agreed well with observed field failure rates when using the PRISM default process grade factors.
- The PRISM failure rate predictions for both inherent and logistics reliability were optimistic by approximately 30-40% using program-specific process grade factors. It is interesting to note that the differences in the predicted values versus actual field values are opposite to those found in an earlier TRW Automotive PRISM evaluation (Reference 1). While TRW Automotive’s predicted failure rates were approximately twice the actual field values (where field data was not factored in through the use of PRISM’s Bayesian analysis option), Raytheon’s predicted failure rates were approximately one-half the actual field values.

The goal of this evaluation was to determine if PRISM would provide a methodology to accurately predict field failure rates. Based on these initial results, it can be concluded that PRISM does indeed have the potential to accurately predict field failure rates. It is encouraging that, given the variations in use environments, failure data, and failure rate sources (RACRates models, RAC data, and user-defined data), the predicted failure rates of the three electronics units track fairly well with each other for both the inherent and logistics reliability predictions.

6. Future Plans
Raytheon plans to continue its PRISM evaluation. While this initial evaluation was conducted independently with minimal consultation with the Reliability Analysis Center, future plans include working more closely with the RAC group to develop a more refined PRISM use methodology to increase the accuracy of the failure rate predictions. The ultimate goal is to develop a PRISM prediction process that accurately predicts field performance using program-specific process grade factors without the need for adding observed field data via PRISM’s Bayesian analysis methodology. The main areas of future emphasis will include:

- Focusing on the proper development and use of program-specific process grade factors.
- Evaluating the PRISM predicted failure modes/categories versus the observed field failure modes/categories.
- Evaluating the PRISM reliability assessment of more complex electrical and mechanical systems to determine if the observed data patterns remain consistent.
- Conducting independent field failure rate analyses and PRISM failure rate predictions for comparison (i.e., using two independent personnel to conduct the field failure rate analysis and the PRISM prediction to eliminate any bias that would tend to converge the two analyses).

References

Biographies
Christopher L. Smith is a Reliability Engineer with Raytheon Company’s Space and Airborne Systems Division located in McKinney, Texas. Chris earned a BS degree in Physics from Southwest Texas State University. He has worked with Raytheon Systems Specialty Engineering for 2 years.

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Petri Nets: An Alternative to Markov Chains

By: Captain Richard V. Melnyk, United States Army

Introduction

In the Third Quarter, 2003 issue of the RAC Journal, an article by Norm Fuqua discussed the application of Markov Chain analysis to reliability and maintainability analysis. In addition to Markov Chain analysis, other methods are available for stochastic modeling. This article provides one of these alternative methods for stochastic modeling known as Stochastic Petri Nets (SPNs). Petri Nets were presented in the 1960’s in a PhD thesis by Carl Petri in Germany (Reference 1). Designed to model dynamic systems, Petri Nets have been used for numerous applications to include software reliability, network reliability, and queuing theory.

The use of Petri Nets avoids two of the basic drawbacks of Markov Chain analysis. First, the model does not grow in size as the number of components in the model increase. Because Petri Nets model local states instead of global ones, they do not grow out of control as the model increases in complexity. This concept will be discussed later in more detail. Second, Markov Chain analysis is typically limited to modeling the probability of changes in the system with the exponential distribution (Reference 2). However, processes pertaining to reliability, availability, maintainability, and safety (RAMS) do not necessarily conform to an exponential distribution.

The author used a Petri Net to model and analyze the phase maintenance process for the U.S. Army’s AH-64 Apache helicopter. The phase inspection is a large inspection conducted every 250 flight hours. It is performed by phase teams made up of maintenance personnel from within the aviation unit, or by contractor phase teams. The purpose of the Petri Net analysis was to determine how reducing the duration of phase inspections or introducing Operational Readiness Floats (ORFs) to units would affect Operational Availability (Ao).

Elements of a Petri Net

Petri Nets consist of four basic elements: places, transitions, tokens, and arcs (Reference 3). Places represent a condition in the process. For example, in the phase inspection model, a place can represent the condition of availability or the condition associated with being in the process of a phase inspection. Transitions represent the stochastic, or time-based nature of changes in the model. Transitions can be immediate, deterministically time-delayed, or time-delayed based on a probability distribution defined by the user. A transition could represent the interval between phase inspections or the amount of time an aircraft spends in phase.

Tokens represent objects in the model. For instance, an aircraft or aircraft component could be modeled as a token. A token graphically appears as a small, solid circle. In basic applications the token is black but in more sophisticated tools, tokens can take on various colors to signify the various ‘ages’ of components.

Global vs. Local Models

As stated earlier, a Petri Net model employs local places, while a Markov Chain features global states. In a Markov Chain, the circles or states represent all the components in that model. On the other hand, in a Petri Net, each circle or place represents only a condition in that model. The difference is more easily illustrated with a basic example.

In this example, a system has three identical components. Each of these components is repairable and fails with the same probability. To build a Markov Chain, the analyst has to understand all the combinations possible for the system. Starting with operational components up, the user has to define all of the combinations of operational and failed components and label the combinations as states. Therefore, each state represents the entire system in a particular combination of conditions. Figure 2 depicts an example of a Markov Chain.

For the same application, the equivalent Petri Net is shown in Figure 3. For this application, the user only has to define the conditions the components can be found in; operational or failed. Then the user also assigns values to the failure and repair probabilities. However, the system can consist of 3 or 100 components; the construction of the model will not change.

Petri Net Application

To understand the simple way in which Petri Nets can be constructed, it is best to view an example. As stated earlier, the author used a basic SPN to model the phase maintenance...
Consider...

Your product is having major problems at a key customer site and your customer is losing faith.

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  - FRACAS
- MODELING TOOLS
  - RBD, Markov Simulation
  - Optimization
- RISK ASSESSMENT
  - Fault Tree
  - FMEA/FMECA
- R&M SUPPORT
  - Weibull
  - Maintainability
  - Life Cycle Cost

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- RELIABILITY CONSULTING
- TRAINING
- IMPLEMENTATION SERVICES
- TECHNICAL SUPPORT

Quality Assurance
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- TickIT 2000 STANDARD
- ASQ CERTIFIED RELIABILITY ENGINEERS ON STAFF
Petri Nets: An Alternative . . . (Continued from page 7)

The process begins in the upper left corner in the ‘Operate’ place. In this place, aircraft are considered to be out of phase maintenance. For this model, 19 aircraft are currently in this place. To the right of this place is a transition, referred to as Interval. This transition ‘fires’ approximately every 19 days to allow a token, or aircraft, to move from the Operate place to the next place, or ‘Prephase’. The 19-day metric is representative of how often an aircraft must enter phase maintenance, based on a typical attack battalion’s annual flying hour program. This value can easily be changed if a unit increases or decreases their operational tempo and can be approximated by a deterministic value, normal distribution, uniform distribution, etc.

In the ‘Prephase’ place, an aircraft is ready to enter phase. In this model, two immediate transitions allow movement from ‘Prephase’ to either of two phase teams labeled ‘Tm1’ and ‘Tm2’. Inhibitor arcs from the phase teams to the immediate transitions prevent the transitions from firing if a token is already present in the phase team. When the token reaches a phase team the ‘Duration’ transitions are enabled. In the current model, these transitions reflect the 26-day average phase inspection duration. However, these transitions can also be modeled with different values or distributions, depending on the application. Once the inspection is complete, the ‘Duration’ transition fires, allowing the aircraft to move to the ‘Spares’ place.

If a unit has an ORF aircraft available the model can start with a token or tokens in the ‘Spare’ place. Regardless, once a token moves to the ‘Spares’ place, the ‘Admin Delay’ transition is enabled. This transition simply delays the aircraft’s return to operation to account for paperwork, test flights, etc. An inhibitor arc from the ‘Operate’ to ‘Admin Delay’ also prevents more than 21 aircraft from entering the ‘Operate’ place, in this case. This arc is used in the event of ORF analysis to prevent more aircraft from entering the ‘Operate’ place than the unit technically has.

An analyst can use this model to study several issues related to Operational Availability. The user can add or subtract phase teams to study the effects. The duration of phase inspections can also be altered to reflect the effects of increasing the availability of maintainers on the phase team or spare parts. In addition, ORF aircraft can be added or subtracted to the model to determine the impact on overall availability.

Advantages and Disadvantages

The application of an SPN to the phase inspection process is only one example of how this form of stochastic modeling can be used in analyzing RAMS processes. However, the example clearly illustrates the advantages of Petri Nets.
First, the size of the model is easily manageable, regardless of the amount of tokens present. Once the model is constructed, the user can change the number of aircraft, without affecting the places and transitions. Conversely, a Markov Chain used to model a unit consisting of 21 aircraft would be larger than one for 18 aircraft. Both models would be extremely large.

Second, Petri Nets allow the analyst to model dynamic events using something other than the exponential distribution. This distribution, widely regarded as appropriate for electronic components, is usually inappropriate for mechanical components and real world processes. Petri Nets give the user more flexibility in creating a model.

Third, Petri Nets, used in a simulation, allow the user to actually observe the stochastic processes. The user can develop a model, and then observe the tokens as they move throughout the model in real or simulated time. This feature gives the user insight into the actual flow of the model and any potential conflicts.

Finally, Petri Nets are easy to modify. Since the model itself is very simple, it is easy to change the values of transitions or the number of tokens without having to change the entire model itself. This characteristic is useful when the user needs to analyze several different cases.

Currently, the major drawback of Petri Nets is the lack of readily available software packages. While Markov Chain analysis appears in most of the major reliability software tools such as those from Relex Software and Item Software, Petri Net software applications are obscure and difficult to integrate with existing software tools. However, the relative strengths of Petri Nets to model stochastic processes could be easily harnessed by software developers and incorporated into their reliability packages. This disadvantage will be discussed in greater detail in the next section.

Implementing an SPN

The underlying structure of all Petri Net software is a code-based architecture. Different programmers use different languages for each software package and the learning curve associated with each package can be steep.

Alternatively, more advanced software packages feature a graphical user interface (GUI) that allows a user to graphically build the Petri Net and implement it. The result would be similar to Figure 4. This approach is obviously easier for a new user to learn and implement.

The main purpose of building a Petri Net in either type of application is to perform a simulation with the model. All of the applications the author reviewed gave the user a way to simulate the dynamic nature of the model for a pre-determined amount of time with pre-set time intervals. With applications featuring a GUI, the user can actually observe the transitions activating and note the movement of tokens throughout the model.

One of the main obstacles to effectively implementing a Petri Net simulation and analysis, with some current applications, is the lack of tools for output analysis. Since the early uses of Petri Nets mainly involved software analysis, network analysis and queuing theory, simply watching the simulation take place was sufficient. The goal was to graphically determine if a token or tokens reached a certain place in the model.

However, for RAMS applications, typically it is important to track and measure a particular value. That value can include Operational Availability, MTTF, or MTTR of a component or system. Therefore, it is important to use an application that provides some way to measure indices within the model. Some applications provide an output window that graphically displays the number of tokens in a selected place over the duration of the simulation. Other more advanced applications include tools to measure specified metrics in the model. The relative strength of any software packages for RAMS usage depends on the ability to easily capture and display data from the simulation.

Summary

No matter the discipline, there is no perfect tool for every situation. RAMS analysis requires that various tools be used, sometimes in an integrated fashion, to accomplish the job. Petri Nets offer an analyst another powerful tool to simply, and effectively model stochastic processes. If the lack of software tools for implementing Petri Nets can be overcome, the advantages that Petri Nets present over Markov Chains could make them the tool of choice for dynamic models.

References


About the Author

Richard V. Melnyk holds an MS degree in Aerospace Engineering. His focus during his graduate study was on rotorcraft system design and reliability. He recently completed his thesis titled A Methodology for Analyzing Availability Improvements for Army Rotorcraft. Mr. Melnyk is a Captain in the United States Army and an AH-64A Apache helicopter pilot. He has experience in attack battalions at the platoon and company level and has held staff positions related to operations, personnel, and logistics. Captain Melnyk is slated to be an Instructor at the United States Military Academy, West Point in the Mechanical Engineering department. This article consists of personal research by the author and is in no way endorsed or funded by the Department of Defense.
Reliability Engineers: Why Certify?

“Information is not knowledge. Let’s not confuse the two.”
--- W. Edwards Deming

A Reliability Engineer’s success depends on the ability to use a wide variety of information to define, plan, organize, control, and complete a variety of complex, interdependent tasks using a finite set of data and resources. To enhance their value to employers, Reliability Engineers must develop the critical knowledge, interpersonal skills, technical tools, and management techniques needed in today’s evolving work environment.

The business case for ongoing training and certification is compelling. Indeed, the value of industry certification for Reliability Engineers has never been higher than it is today. Many senior executives realize that employee certification can improve their company’s bottom line and enhance business processes due to increased efficiency, less down time, and higher quality decisions. With the application of training from the American Society for Quality (ASQ) Certified Reliability Engineer (CRE) Body of Knowledge, the right things are done, and done right.

What’s Special About an ASQ Certified Reliability Engineer?

Certification as a reliability engineer is formal recognition by ASQ that an individual has demonstrated proficiency within and a comprehension of a body of knowledge in reliability at a point in time. It is peer recognition and not registration or licensure. Since 1968, when the first ASQ certification exam was given, more than 85,000 individuals have become certified through ASQ, including many of whom have attained more than one designation. Although ASQ membership is not a prerequisite for certification, most of the people who hold one of these designations do belong to the Society. Certification ranks as one of the top benefits of ASQ membership.

In today’s world, where quality competition is a fact of life and the need for a work force proficient in the principles and practices of quality control is a central concern of many companies, certification is a mark of excellence. It demonstrates that the certified individual has the knowledge to ensure the quality of products and services. Certification is an investment in your career and in the future of your employer.

How Do I Become Certified?

Candidates must meet three criteria to earn ASQ certification:

1. Have a specified level of education and/or experience
2. Provide proof of professionalism
3. Pass a standardized examination in the certification area.

(Exams are given in the English language only.)

Proof of Professionalism. Proof of professionalism may be demonstrated in one of the following three ways.

1. Membership in ASQ, an international affiliate society of ASQ, or another society that is a member of the American Association of Engineering Societies or the Accreditation Board for Engineering and Technology
2. Registration as a Professional Engineer
3. The signatures of two persons—ASQ members, members of an international affiliate society, or members of another recognized professional society—verifying that you are a qualified practitioner of the quality sciences

Standardized Examination. Each certification candidate is required to pass a written examination that consists of multiple-choice questions that measure comprehension of the Body of Knowledge (BOK). The Reliability Engineer examination is four hours in length and consists of 150 multiple-choice questions. The main areas of the BOK are:

1. Reliability Management
2. Probability and Statistics for Reliability
3. Reliability in Design and Development
4. Reliability Modeling and Predictions
5. Reliability Testing
6. Maintainability and Availability
7. Data Collection and Use

The exam is focused on management techniques as well as a broad range of technical tools. The interactions between the
Reliability Engineer’s role and the diverse functions within the company are emphasized. The Reliability Engineer is equipped to see the “Big Picture” for reliability within his company, thus enhancing his further career growth. In fact, ASQ’s December 2002 salary survey showed that Reliability Engineers with the certification earned an average of twelve percent more that those without the certification.

It is an unfortunate misconception that the CRE Exam is only for Reliability Engineers in traditional reliability roles. Engineers working in related areas such as Quality or Development can also benefit from learning and applying the areas of the BOK.

A broad range of reliability tools are covered by the exam, and the test questions focus on real-life process management, problem solving, and measurement techniques – fundamental areas for any good Reliability Engineer.

Indeed, as Deming said, information is not knowledge. As Reliability Engineers, we are bombarded with information, data, and opinions. The task of preparing for the CRE Exam can ensure that you have the skill to turn information into knowledge and make your organization successful.

That’s why this exam certifies Reliability knowledge for any type of organization. It’s all about the fundamental skills that drive performance excellence, whether your company is small or large, whether supplying products or services.

Maintaining Your Certification
To maintain your certification, you must recertify every three years. Recertification can be done in one of two ways.

1. **Recertification by Recertification Unit (RU) credits.**
   Recertification by credits is a simple process of obtaining a minimum of 18 RUs within the three-year certification period. The credits can be accumulated from professional activities that either increase your knowledge of the BOK or are job enhancing.

2. **Recertification by Examination.** Recertification by exam is required for those whose certification(s) have expired and are past the six month “grace period” (six months after your certification) expiration date of submitting their recertification journal application form and packet.

Recertification Pays
If you enjoy the prestige that comes from being the best in your field, then you’ll appreciate the professional advantages derived from becoming a Certified Reliability Engineer.

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- Increase your value to your organization.
- Affirm your commitment to excellence.
- Advance your career.

Get Certified
To learn more, go to <http://www.asq.org> and read about how to apply for certification and to prepare for the exam. A downloadable pdf of the CRE brochure is available at <http://www.asq.org/cert/pdf/cre_brochure.pdf>.

About the Author
Scott A. Laman is certified by the American Society for Quality (ASQ) as a Quality Engineer, Reliability Engineer, Quality Manager, and Six Sigma Black Belt. As a volunteer for ASQ, he is the Exam Chair for the Certified Reliability Engineer exam, and has responsibility for the CRE exam development program. He is a member of ASQ’s Certification Board and has also worked on the CQE and Six Sigma Black Belt exams.

Mr. Laman has eighteen years of experience in Research, Process and Product Development, and Quality. After obtaining his Master of Science degree in Chemical Engineering from Syracuse University, he joined the Central Research function of The Dow Chemical Company in Midland, Michigan. Eight years later, he moved to Reading, Pennsylvania to begin work with Quadrant Engineering Plastic Products (formerly DSM) as a Process Development Engineer. He moved into the Quality field after four years, and now as a Principal Quality Engineer has applied quality and statistical tools to complete many development, yield, and productivity improvement projects. He teaches quality-related topics such as SPC, statistical design and analysis, problem solving, continuous process improvement, and ISO.

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**Multivariable Testing™ (MVT™)**

By: Dr. Charles W. Holland, Kieron Dey, and David Cochran, QualPro

Typical objectives include reliability, quality, throughput, cycle time (e.g., time to market, install/repair times), and yield.

MVT™ works by surfacing and simultaneously testing a vast range of potential solutions known as “factors.” The output is a list of solutions that will help, actions that will hurt, and actions that will...
make no difference. Experience finds that only a quarter of the factors tested will help, about a quarter will hurt, the rest will make no difference. Of those that help, most (about 80%) will be simple, no-cost methods changes. The effect of each helpful solution is quantified and the total improvement calculated. In addition, combinations of factors which together work well (or poorly) are detected and quantified. About a third of the total improvement typically comes from these combinations, known technically as interactions. Finally, implementation of the helpful solutions is controlled and tracked to confirm the improvement, short and long term.

The tool was pioneered in the late 1960s by QualPro Inc. founder Charles W. Holland. The initial work was in nuclear materials and weapons research, design, development, manufacture, and field use. It has since been proven, by QualPro and its clients, through thousands of cases in virtually every type of application.

MVT™ has been applied on wide-ranging scales, as small as a welding process involving one person for two days, to as enormous as a complex electronic network spreading over multiple states involving thousands of people for two months. Time-to-market and cycle times are routinely addressed (Figure 1), involving both hardware and software. In one case, errors at software release were cut in half by testing in module design, coding, system, regression, and user acceptance testing.

![Figure 1. Late Circuit Installations](image)

QualPro evaluation of MVT™ cases over the past 20 years, using a rank correlation coefficient over hundreds of cases, shows little correlation between solutions that current knowledge indicates should work, and the empirical findings of MVT™ experimentation.

Therefore, MVT™ provides a standardized means to efficiently identify solutions that can be implemented to reliably achieve breakthrough performance improvements, while avoiding implementation of wasteful and counterproductive solutions that hurt results or make no difference. The following QualPro client examples illustrate the vast untapped potential in any process.

**Example 1**

A large electronic service organization was not meeting its customer commitments. In fact, the number of installations of high frequency circuits that were missing deadline commitments was 4.5 times the objective. This resulted in payroll of $5.6 million dollars in service guarantees per year, plus loss of revenue for the time missed. During a two-month period, an MVT™ experiment tested 37 improvement ideas in eight work areas of the installation process, ranging from Customer Service, to Design, to Installation Technician. The result was an 83% reduction in the number of circuit installations missing due dates, well ahead of the company’s objective (see Figure 1).

**Example 2**

A new turbine design was suffering more than 90% rework and 50% scrap due to high-speed balance problems with shaft and turbine wheel assemblies. These problems also significantly shortened the life of the system and resulted in high warranty costs and dissatisfied customers. MVT™ experiments on design, assembly, testing and measurement systems tested 26 factors and identified five critical actions that reduced rework to approximately one percent, and eliminated scrap completely. The solutions involved changing the application method of a special coating and improving the precision of assembly measurements. Manufacturing benefits were estimated to be approximately $1.2 million per year in materials and labor costs and $1.5 million in testing systems capital avoidance. The improved customer satisfaction and competitive position were valued at tens of millions of dollars. The entire project was completed in just over three months including the execution of four MVT™ experiments and implementation.

The same company used MVT™ experiments to increase system reliability dramatically from a Mean-Time-Before-Failure of 300 hours to greater than 20,000 hours. The MVT™ experiment identified several helpful factors involving the physical layout of components in the assembly. The solution could not possibly have been discovered without MVT™, since there were literally millions of possible layout combinations. Whereas the company’s engineering department estimated it would take 18 months to improve the reliability by redesigning the system, the operations department achieved the improvements in eight weeks, using MVT™ to optimize the existing system.

**Example 3**

A manufacturer of computer touch screens used in industrial and extreme environmental applications was frustrated with an engineering problem that resulted in a production yield of only 15%. The screens suffered from an intermittent contact failure that resisted repeated attempts to correct the problem. In less than one week, MVT™ experiments testing seven factors were executed on the production line. Two simple changes in the way the plastic screens were cleaned prior to assembly and the way oven curing was performed increased the production yield to over 97%. MVT™ findings eliminated this chronic problem, increasing production yields six-fold, and the result has been sustained for years.

**Management Process**

MVT™ project selection involves the appropriate levels of management to ensure that every initiative has the potential to provide a substantial return over a short time frame.
A standardized MVT™ management process is followed that involves a number of important elements:

- Research and analysis of historical data
- Involvement in the development and execution of the MVT™ experiments by numerous employees, from all levels of the organization
- Inclusion of 10 to 40 ideas that meet specific MVT™ criteria, as factors in experiments
- Execution of multiple MVT™ experiments, of varying types, to efficiently measure the impact of individual factors and explore interactions, or synergies, between combinations of factors
- Simple, clear communication of MVT™ findings to gain support of all employees for implementation

Rapid MVT™ speed is important to maximize Return-On-Investment (ROI) and to ensure that organizational inertia does not dilute benefits. Most MVT™ experiments are completed within one month, and they very rarely take more than a few months. The sheer quantity of test factors markedly accelerates everything from life testing, to inventory reduction, to new product/software design, to troubleshooting/problem solving. Complexity of the targeted process is typically not a constraint to project timelines. In fact, the roots of MVT™ are in weapons design and nuclear materials manufacturing - not inherently simple or quick processes.

Implementation of findings typically occurs in two steps. Partial implementation based on initial MVT™ findings is performed concurrent with follow-up MVT™ execution. Complete implementation, including execution of the best combination of solutions and verification of expected benefits, follows completion of follow-up MVT™ experimentation. The implementation process itself was researched by QualPro using a 2001 MVT™ and today is fully standardized.

One of the most important issues in managing successful MVT™ efforts is to test many factors as boldly as possible without damaging the process. The reason this is so important becomes clear by considering the sheer number of combinations of factors, as illustrated in Table 1.

<table>
<thead>
<tr>
<th>Ideas</th>
<th>Potential Test Combinations</th>
<th>Minimum MVT™ Test Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>1,028</td>
<td>8</td>
</tr>
<tr>
<td>20</td>
<td>1.06 million</td>
<td>24</td>
</tr>
<tr>
<td>30</td>
<td>1.09 billion</td>
<td>32</td>
</tr>
<tr>
<td>40</td>
<td>1.12 trillion</td>
<td>44</td>
</tr>
</tbody>
</table>

The efficiency of MVT™ experimentation is also illustrated, since only a small portion of the potential test combinations are required by the MVT™ approach. Notice that a typical MVT™ with about 30 factors will test approximately a billion ways to design or manage the product, system or process. The power of an MVT™ thus becomes overwhelming, compared to other problem solving approaches.

**Technical Process**

Traditionally, testing has involved “holding conditions constant” while varying one factor at a time, in an attempt to establish cause and effect. This mistakenly tries to standardize the real world for the test, rather than standardizing many factors for a truly real-world test. In an MVT™, if a factor helps, even though many other factors are also being varied, then it really does work in the real world. So, a practical advantage of MVT™ is a broader basis for inference—leading to robust solutions that truly work when implemented.

The nucleus of MVT™ is powerful statistical design. Statistical design stands apart from all other statistical methods by establishing cause and effect - every other technique establishes relationships, but not true cause and effect.

In 1969, QualPro founder, Holland [1] pioneered MVT™ and integrated customized statistical designs into a management procedure. The management process included people and organizational considerations, so that knowledge and ideas were harnessed and breakthrough improvement achieved. Early MVT™ successes were achieved in nuclear weapons/materials design/manufacture where this innovative technical approach pioneered the simultaneous testing of dozens of factors. Such large test designs yield starkly enhanced results compared to smaller tests. Smaller scale testing is much less effective due to statistical phenomena occurring with larger tests. The terms Multivariable Testing™ and MVT™ were popularized by Forbes [2] in 1996, in an extended article aimed at business executives. The Wall Street Journal [3], Industry Week [4], Business Week [5], CFO.com [6], and numerous other publications have subsequently documented MVT™ successes.

Each MVT™ involves multiple cycles of testing, as noted earlier. The initial cycle uses large MVT™ designs with many factors, while follow-up MVT™’s typically use smaller designs that focus on the helpful factors.

A standardized process of management work and statistical tasks precedes every MVT™ experiment. This process involves the selection of appropriate success measures, assurance of the validity of data gathering systems, and implementation of appropriate process controls.

**MVT™ vs. DOE**

The underlying mathematics of the MVT™ process employs orthogonal test designs allowing the effect of each factor, and important interactions, to be measured separately yet simultaneously. While advanced courses and texts in design of experiments (DOE) may discuss elements of MVT™ mathematics, DOE and MVT™ are as different as a hang glider and an F-14—both are aircraft, but their applications and capabilities hold few similarities. Table 2 summarizes some of the crucial differences between MVT™ and DOE.

(Continued on page 17)
If you are going to analyze Reliability Growth using Crow models, shouldn’t you be using Crow’s software?

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Multivariable Testing™ (MVT™) (Continued from page 15)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>MVT™</th>
<th>DOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Factors Tested</td>
<td>One to Four Dozen</td>
<td>Half dozen or less</td>
</tr>
<tr>
<td>Type of Factors Tested</td>
<td>Bold, Fast, Manageable</td>
<td>Not specified</td>
</tr>
<tr>
<td>Factor Selection</td>
<td>Objective process</td>
<td>Ranking and voting</td>
</tr>
<tr>
<td>Role of Industry Experts</td>
<td>Knowledgeable input</td>
<td>Edict by opinion</td>
</tr>
<tr>
<td>Capability of Statisticians</td>
<td>Insufficient</td>
<td>Sufficient</td>
</tr>
<tr>
<td>Linearity</td>
<td>Red Herring</td>
<td>Mandatory knowledge</td>
</tr>
<tr>
<td>Interactions</td>
<td>Clear strategy</td>
<td>Non-standard</td>
</tr>
<tr>
<td>Timing to Impact</td>
<td>1 to 3 months</td>
<td>Up to 18 months</td>
</tr>
<tr>
<td>Size of Impact</td>
<td>Breakthrough</td>
<td>Incremental</td>
</tr>
<tr>
<td>Pre-Experimentation Work</td>
<td>Structured</td>
<td>Ad hoc</td>
</tr>
<tr>
<td>Assurance of Data Integrity</td>
<td>Standardized</td>
<td>Improved</td>
</tr>
<tr>
<td>Process Control Strategy</td>
<td>Built-in</td>
<td>Standards not emphasized</td>
</tr>
<tr>
<td>Involvement of Workers</td>
<td>Extensive</td>
<td>Uncommon</td>
</tr>
<tr>
<td>Understanding of Testing Process and Analysis</td>
<td>Workers, Managers, Execs, Professional/Technical Staff</td>
<td>Statisticians</td>
</tr>
<tr>
<td>Statistical Confidence</td>
<td>Near certainty</td>
<td>95%</td>
</tr>
<tr>
<td>Documented Manufacturing, Service, and Sales Cases</td>
<td>13,000+</td>
<td>Fewer</td>
</tr>
</tbody>
</table>

Table 2. MVT™ vs. DOE

Table 3. Carbon-Foam Casting MVT™ Factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>–</th>
<th>+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Type</td>
<td>Single-unit</td>
<td>Double-unit</td>
</tr>
<tr>
<td>Mold Heating</td>
<td>Bottom</td>
<td>Bottom and sides</td>
</tr>
<tr>
<td>Mixing Blade</td>
<td>Turbine</td>
<td>Turbine and standard</td>
</tr>
<tr>
<td>Blade Diameter/Rotation Speed</td>
<td>6&quot; at 300 rpm</td>
<td>4&quot; at 800 rpm</td>
</tr>
<tr>
<td>Blade Position</td>
<td>0.5 inch</td>
<td>1.5 inches</td>
</tr>
<tr>
<td>Mixing Time</td>
<td>30 seconds</td>
<td>60 seconds</td>
</tr>
<tr>
<td>Turntable Speed</td>
<td>10 rpm</td>
<td>40 rpm</td>
</tr>
<tr>
<td>Can Position</td>
<td>On center</td>
<td>Off center</td>
</tr>
<tr>
<td>Pouring Speed</td>
<td>Slowly</td>
<td>Quickly</td>
</tr>
<tr>
<td>Pouring Method</td>
<td>Single spot</td>
<td>Circular</td>
</tr>
<tr>
<td>Hit Mold Against Floor?</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

These eleven factors were then tested using a large initial MVT™ experiment that involved the production of 16 castings in a single day. Five factors were found to have a significant impact on at least one of the defects. These five factors were then further investigated in three follow-up MVT™ experiments, each being of one- to two days in duration, and final conclusions were drawn.

Ultimately three factors were found to solve the yield problem. The helpful factors and their impact on each defect are shown in Table 4. Shortening the mixing time actually improved mixing effectiveness, which defied long held beliefs of the technical experts. An interaction, or synergy, was found to exist between blade position and turntable speed. While, individual testing indicated that a high blade position was superior, MVT™ tests revealed that, in combination with a slow turntable speed, the low blade position virtually eliminated black streaks, cracks, and fractures (Figure 2). This synergy, along with the helpful impact of a moderate blade speed, overcame the somewhat detrimental effect of a shortened mixing time on fractures, allowing mixing time to be used to eliminate voids.

Table 4. Carbon-Foam Casting MVT™ Findings

<table>
<thead>
<tr>
<th>Factor</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shortened Mixing Time</td>
<td>Decreased voids and increased fractures</td>
</tr>
<tr>
<td>Low Blade Position and Slow Turntable Speed</td>
<td>Decreased black streaks, cracks, and fractures</td>
</tr>
<tr>
<td>Moderate Blade Speed</td>
<td>Decreased voids</td>
</tr>
</tbody>
</table>

Case Study

The diversity of applications to date makes it difficult to adequately convey MVT™ in one case study. However, the following example is included for its strategic importance, problem complexity yet simplicity of MVT™ approach, speed, counter-intuitive results that had lain dormant for years, and strong return on investment.

Carbon-Foam Castings. In the midst of the cold war, with U.S. nuclear weapons production at its peak, a critical part became the constraint on manufacture of an important missile type. The part in question was a carbon-foam ring that held sub-assemblies in place within the missile housing. The part was produced via a casting process that involved mixing of ingredients, curing in an oven, and ultimately carving/machining the finished part.

Unfortunately, the production process was able to attain only a 15% yield (85% rejects). The contractor’s best technical experts studied the production procedures and concluded that this low yield was endemic to the process and could not be significantly improved. Therefore, when this part became the limiting factor to missile production, a new line was planned, at a $40+ million cost. As a last resort, executive management decided to apply the MVT™ process to the problem.

Working with production and supervision personnel, several dozen ideas to reduce one or more of the four types of defects (voids, black streaks, cracks, and fractures) were identified.

The many ideas were then narrowed to eleven test factors (Table 3) that could be easily tested and quickly implemented.

Figure 2. Interaction Between Blade Position and Turntable Speed

(Continued on page 19)
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- 299B Reliability Prediction
- RDF Reliability Prediction
- NSWC Mechanical Reliability Prediction
- Maintainability Analysis
- Failure Mode, Effects and Criticality Analysis
- Reliability Block Diagram
- Fault Tree Analysis
- Markov Analysis
- SpareCost Analysis

ITEM QA MODULES
- Design FMEA
- Process FMEA
- Control Plan
- Document Control and Audit (DCA)
- Calibration Analysis
- Concern and Corrective Action Management (CCAR)
- Statistical Process Control (SPC)

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Multivariable Testing™ (MVT™) (Continued from page 17)

The final impact of this MVT™ experimentation was the total elimination of defects from the Carbon-Foam Casting process. The $40+ million expense of a new manufacturing line was averted, and the final six years of production did not produce a single defective part.

Diversity of MVT™

MVT™ is universally applicable yet the MVT™ process is generic. Some examples of common application follow:

- New product design/introduction
- Manufacturing (batch, continuous and custom/short run processes; including nuclear, chemical, paper, non-wovens, textiles, electronics, ceramics, etc.)
- Complex system engineering and production
- Software design, engineering and test
- Turbines, generators, engines—design, test, production
- Measurement systems and sensors
- Testing, test efficiency and product efficacy
- Scientific research and problem solving
- Efficient testing of models vs. actual performance; scale-up problems
- Information systems and technology
- E-commerce/internet applications
- Finance and accounting (including receivables problems)
- Inventory, warehousing, distribution and freight (shipping, road, rail)
- Telecommunications
- Printing
- Call centers and technology
- Recovery and refining of petroleum and related products

References


6. Marie Leone, Need-to-Know Tech, The ten innovations that will have the biggest impact on business over the next five years. CFO.com, October 8, 2002.

About the Authors and QualPro

QualPro is a Process Improvement firm that focuses on helping clients use MVT™ to rapidly improve results. Since 1982, QualPro has helped 1,000+ clients execute more than 13,000 MVT™ experiments to improve manufacturing, service, and sales performance. QualPro teaches MVT™ seminars that have been attended by tens of thousands of technical, professional, and management personnel. On-site QualPro consulting support, using proprietary software to generate MVT™ designs and perform analysis, is frequently provided to clients to assure quick, reliable breakthroughs.

QualPro’s founder, Dr. Charles W. Holland pioneered MVT™ in the late 1960s with innovative designs in the nuclear weapons industry within DoD. For the next 35 years he researched and perfected application of MVT™ to virtually every type of problem, process and industry, always with breakthrough results. Dr. Holland holds an MS in Statistics from Florida State and a PhD in Management Science from University of Tennessee at Knoxville.

Kieron Dey joined QualPro in 1989 and is currently a Technical Director with broad responsibilities for process improvement/MVT™ in the field, also in-house customer seminars. Prior to joining QualPro Dey spent 15 years in reliability statistics and process improvement. He holds a BSc in mathematics/statistics from Reading University in England and an MBA from Rensselaer Polytechnic Institute.

David Cochran joined QualPro in 1994 and is now Operations Manager, with a continuing technical involvement in field applications of MVT™. Prior to joining QualPro, Mr. Cochran spent 15 years in research and operations management in chemical products/services moving to the position of Vice President of a nationwide business with full profit and loss responsibility. He holds BS and MS degrees from the University of Tennessee.
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From the Editor

An R&M Community of Practice

Since its inception in 1968, the RAC has worked to help foster and support the reliability and maintainability (R&M) community – those who work to develop and implement methods and tools for improving the R&M characteristics of systems. To that end, we have a web site that includes links to educational opportunities, related standards and software products, on-site tools for supporting R&M calculations, and an open forum for inquiries and discussion.

Now, under the leadership of Merrill Yee in the Enterprise Development Office of OUSD (AT&L)/SE, and with the support and guidance of the Defense Acquisition University (DAU) and others, the RAC is working to form a formal Community of Practice (CoP). Two well-recognized definitions of community of practice are:

Communities of practice are groups of people who share a concern, a set of problems, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis (Cultivating Communities of Practice: A Guide to Managing Knowledge; Etienne Wenger, William Snyder, Richard A. McDermott, HBS Press 2002).

Communities of practice are groups of people who come together to share and to learn from one another face-to-face and virtually. They are held together by a common interest in a body of knowledge and are driven by a desire and need to share problems, experiences, insights, templates, tools, and best practices (APQC’s Best-Practice Report, Successfully Implementing Knowledge Management, APQC, 2000).

As a major part of DoD’s AT&L Knowledge Sharing System <http://akss.dau.mil>, DAU has formalized a process for establishing different types of communities in DoD’s Acquisition Community Connection (ACC) system <http://acc.dau.mil>. DAU’s eLearning and Technologies Center (eLTC) is responsible for the management and operation of the CoP infrastructure. In addition to CoPs, DAU facilitates Special Interest Areas. A Special Interest Area (SIA) differs from a Community of Practice (CoP) in that the primary goal of SIAs is to distribute knowledge among the acquisition workforce, while CoPs also focus on cultivating interaction within the community.

Currently, DAU facilitates the six CoPs and ten Special Interest Areas shown in Table 1.

Table 1. Current CoPs and SIAs

<table>
<thead>
<tr>
<th>CoPs</th>
<th>SIAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contract Management</td>
<td>Earned Value Management</td>
</tr>
<tr>
<td>Facilities Engineering</td>
<td>Information Technology</td>
</tr>
<tr>
<td>Logistics Management</td>
<td>Performance-Based Service</td>
</tr>
<tr>
<td>Program Management</td>
<td>Acquisition Resources</td>
</tr>
<tr>
<td>Risk Management</td>
<td>Spectrum Compliance</td>
</tr>
<tr>
<td>Systems Engineering</td>
<td>Total Ownership Cost</td>
</tr>
</tbody>
</table>

The key players in an effective CoP are:

Community Sponsor(s). The Sponsor provides high-level sponsorship and support for the community at-large and acts as the champion for the community.

Community Leader(s). The Community Leader, an active member of the community, serves an integral role in the community’s success.

Subject Matter Experts. Subject Matter Experts are knowledgeable and experienced members of the community who use their knowledge of the discipline to judge what is important, groundbreaking, and useful, and to enrich information by summarizing, combining, contrasting, and integrating it into the existing knowledge base.

Content Editor. Content Editors are responsible for the content within their respective area(s). Qualifications for Content Editors should include familiarity with the structure, layout, and functionality of the content area being managed.

I invite our readers to visit the Acquisition Community Connection (ACC), where you can join current CoPs and acquire more information on CoPs, at the following web site: <http://acc.dau.mil>. In addition, if you are interested in learning more about and perhaps joining in our efforts to establish an R&M CoP, please contact me at <ncriscimagna@alionscience.com>.

From the Editor
Traditional failure prediction methodologies have indicated the failure rate of Plastic Encapsulated Microcircuits (PEMs) to be high compared to comparable hermetically packaged microcircuits. Recent data collected by RAC and others have identified that the quality of these non-hermetic devices has improved and their failure rates may be similar to their hermetic counterparts when properly selected and used.

In some cases, the failure rate of a non-hermetic device can be lower than that of a similar hermetic device. A potential reason for the better failure rate is the possibility that processes used in PEM manufacturing may be more robust than those for hermetic parts. This may be due, in part, to quantity of PEM vs. hermetic devices manufactured. There are caveats when selecting PEMs to assure reliability. The Original Equipment Manufacturer (OEM) using PEMs must have an effective parts control program, assure that components are used within specification and in an operating scenario. When using PRISM to calculate failure rates of any system, it is recommended that PRISM users define the processes that are being used in the design, development, manufacturing, and maintenance, etc. of their systems. These processes define what steps are (or are not) being taken to assure reliability in a design while some questions specifically address the use of PEMs. Additionally, the values for Junction to Case and Junction to Ambient thermal resistance used in a PRISM analysis should be modified to reflect the actual values for each PEM device analyzed.

The ideal scenario for PEMs is to operate at a 100% duty cycle. When a PEM is operating, moisture, which is an accelerant of corrosion mechanisms, has minimal opportunities to reach the die area of the PEM device since it is driven off by self-heating, which reduces contamination related effects for PEMs.

Our data, which was used to develop the PRISM microcircuit model, shows that PEMs can be as reliable or in some cases more reliable than their hermetic counterparts. Other studies confirm this finding. In a study by ELDEC Corporation/CALCE Electronic Packaging Research Center, University of Maryland, Condra, et al, performed a unique comparison of PEMs and hermetic microcircuits. Devices were manufactured using the same microcircuit die in both plastic encapsulated and hermetic packages. This was then evaluated under conditions of temperature cycling and temperature/humidity/bias (THB) [L. Condra, et al, “Comparison of Plastic and Hermetic Microcircuits Under Temperature Cycling and Temperature Humidity Bias”, IEEE Transactions on Components, Hybrids and Manufacturing Technology, Volume 15, Number 5, October 1992]. A semi-custom monolithic microcircuit, in an 18-lead Dual Inline Package (DIP), was used as the test vehicle. Two hundred non-hermetic and 200 hermetic devices were divided into groups and tested under conditions of temperature cycling (-55°C to + 85°C) and powered-on, powered-off THB (85°C, 85% relative humidity, 14-volt bias applied to the microcircuit, 30 minutes on, 30 minutes off). Variations included testing loose parts and testing parts that had been soldered to printed circuit boards. Throughout testing, only one valid failure was experienced. This failure occurred in a ceramic package. It was concluded that the overall performance of the PEMs was virtually identical to that of the ceramic devices with regard to temperature cycling and THB environments.

For more information on PRISM feel free to contact the PRISM team by phone (315-337-0900) or by E-mail <rac_software@alionscience.com>. To obtain additional information including a demonstration version of the software go to <http://rac.alionscience.com/prism>.

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