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INTRODUCTION

James Rodenkirch

With dramatic drops in funding resources across the U.S. Enterprise—from sea to shining sea, literally—the “topic of the day” is a new model of system concept and design. This emerging model and concept includes: the integration of the needs, resources and products/systems from contrasting stakeholders such as DoD, industry and state/local first responders.

An article by Sandra Erin in the November, 2012 issue of *National Defense, Defense Technology in Non-traditional Markets*, illustrates this new concept. Ms. Erwin makes the point that with funding for new systems, at the local and state levels, becoming a challenge, there are myriad public and private arenas where a synergistic approach to problem solving can work substantially better. She points to several examples that illustrate this integration of contrasting needs, products and resources: software, developed for the U.S. Army to create a battlefield network could be repurposed to protect the nation’s electrical grid and communication systems, similar to those used by our troops in war zones, are in high demand by law enforcement agencies. Integrating IED sensors into NASA’s interplanetary probes is still another application where a synergistic approach to problem solving is possible.

From an RMS perspective, this approach—a new and evolving landscape of “participation by a new mix of stakeholders,” e.g., users, developers, resource providers and, yes, private sector consulting providers from volunteer firms, all with varying societal, economic, cultural backgrounds with requisite differences coming together through a robust public (federal and state/local) and private partnership—needs to include one caveat: there will be new influencers on the resources and constraints of the existing model that will impact the way we practice RMS engineering.

Equally important is the fact that the new “non-traditional markets” model is an excellent illustration of a Complex System and some of a Complex System’s attributes must be recognized as potential *influencers* on our RMS efforts:

- Individual systems to be integrated have been acquired and managed across myriad Family of System(s) program management organizations where one finds *varying requirements* and *financial constraints* as well as *diverse societal and cultural backgrounds*.
- Many of the systems to be integrated were developed and *designed under myriad concept requirements*; thus, *compatibility at the external interface level isn’t assured and may be tricky to accommodate*.
- The overall System of System can occupy a large/wide geographic extent—meaning...*only information is exchanged, NOT mass or energy!* Thus, *management of it all will span*

equally wide geographic and the accompanying cultural and political extents.

I’ve opted to depict the current state via a basic IDEF0 model where entrance and exit criteria are depicted along with resource and constraint influencers—a state where the public or private sector, for the most part, work with other entities and organizations within each sector—as more *complementary* in nature and where synergy can be achieved more easily (see Figure 1). The stakeholders, for the most part, are recognizable. Consequently, entrance and exit criteria are similar or known and, with shared goals and vision, resources and constraints are more often consistent and stable. In short, the way it “is,” is easier to manage, participate in and facilitate the development and implementation of product(s) and the products are reliable, maintainable and supportable—the engineering vagaries, standards and approaches associated with RMS are understood.

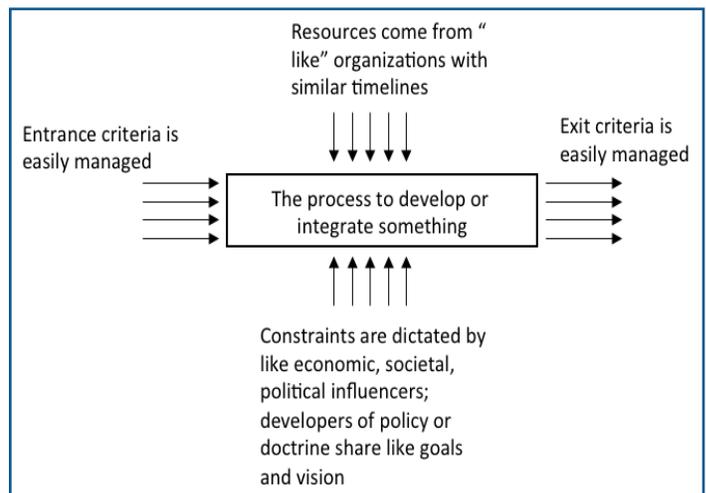


FIGURE 1 - COMPLEMENTARY INTERACTIONS

I view the new state of influencers—a public-private amalgam of potentially *contrasting* goals, vision, resources and resulting similar and dissimilar constraints—via a similar model but one where dissimilar influencers could impede the timely delivery of reliable and affordable products/systems, see Figure 2 below, and I have an example to share with you that illustrates, from an RMS perspective, some “areas of concern” or lessons learned if one is ever involved in such a project.

There was a project undertaken by DHS to install Wi-Fi broadband access on a thirty-mile corridor of the I-19 Interstate in Arizona during a two year period of time (2004-2006). That particular section of Interstate stretches from the Mexican border through Santa Cruz County into Pima County and, although sparsely populated, is the scene of intense Public Safety (Public

Safety) activity. Thus, there are numerous federal and state police agencies involved in policing this area and all of these government organizations required communication system(s) access for their offices and vehicles.

This project was intended to demonstrate the viability and effectiveness of wireless broadband for Public Safety, other agency, and commercial users in an area of strategic importance but sparse, unknown *demographics*; in short, the project design team knew little about the “make up” of the local population.

Here are the results of the systems use once it was up and running, albeit never completed, totally:

- Although installation and initiation of the system proved more difficult than anticipated, some of the total scope or goal(s) of the system was accomplished. The system delivered data transfer rates of 2-4 Mbps to mobile units throughout the corridor. However, at high vehicle speeds (75 MPH) and high data rates, the system was prone to drop the connection.
- Funding for the program terminated in 2006, *but it is continuing in operation as a commercial network for the local population.*
- Once installed, a number of applications emerged, and it is now being operated as an Internet Service Provider for the local communities. So, it “worked” or has value but not for its original funded purpose!

An “after it’s all over” review of the project found these “nuggets” of information—or *influencers*—regarding why it didn’t go “as planned”:

- *Political aspects* of the system became a major source of concern; e.g., some *local organizations* did not *demonstrate motivation* to support the system and *no mechanism was found to compel them.*
- Operational aspects of the project were disappointing. *It should have received more use than was actually experienced, but lack of enthusiasm of some area participants was noticeable.* Instances of “*not in my backyard*” (NIMBY) and “*that’s not the way we do it here*” attitude were common.
- *Local legacy systems weren’t compatible.* New systems chosen for integration into the legacy “network” exhibited *unacceptable performance variations due to extreme temperatures found in the Arizona desert.*
- There *was competition amongst the local, state and federal agencies for being “in control.”*
- Establishing vehicle connection(s) while moving was problematic, because of *conflicts between connection and handover and the potential for driver distraction.*

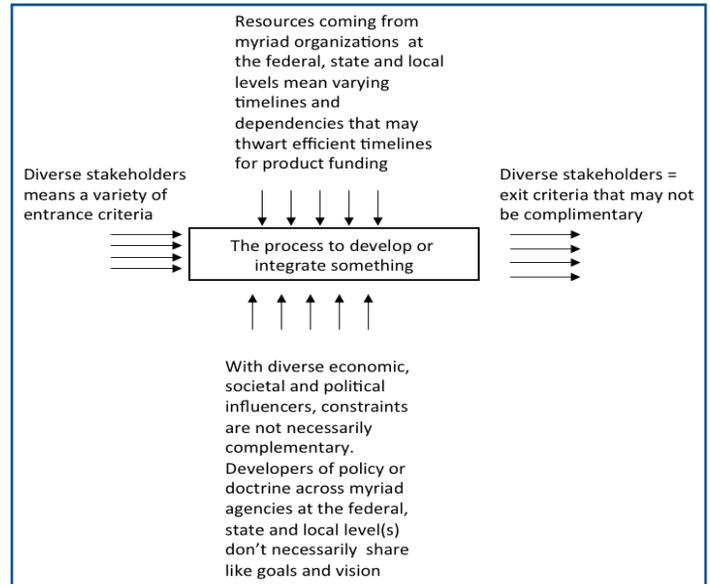


FIGURE 2 - CONTRASTING INTERACTIONS

All of those *influencers* were the direct result of contrasting interactions. Now, without knowing all of the circumstances surrounding the project’s makeup one can’t begin to say how he or she would have done things any different but that example certainly serves as an excellent ‘lessons learned,’ object lesson.

Given the dwindling dollars available for R&D and new system development these days, I believe this new “contrasting interactions” approach, with all of the potential “problems” that will need to be worked through, will be a viable approach to problem solving across contrasting stakeholder entities! Leveraging off other resources when one’s current resources are drying up is good but we need to be aware of the types of influencers that can impact the reliability, maintainability and supportability of the “new” types of integrated/designed systems we may be called on to support. The usual RMS engineering tools may not work as well as we’d like when we’re engaged in ensuring reliability of problem solutions when faced with societal, cultural and political pressures/manipulation(s). That means we will have to “consider” and engineer RMS from far more than just a Material solutions notion. Today, the buzzword is DOTMLPF: Doctrine, Organization, Training, Materiel, Leadership, Personnel and Facilities. That’s the new total solution set that “illities engineering” needs to embrace and I hope the example I used above, when coupled with the new systems design model I introduced that embraces partnerships across a new spectrum of stakeholders, helps to illustrate and provide context for it all.

Since I took on the role as Editor of the RMS Journal, I’ve attempted to focus reader attention, through some amount of adroit article selection, on the tenet(s) of engineering *across* the Enterprise. This new paradigm—providing technology and interacting with state, local and private organizations/entities is just one reason for continuing on with that focus. It’s the right thing to do but we need to insure we know what the new model looks like so we can contribute successfully from an RMS perspective.

The collection of articles for this Winter Journal continues to reflect a range of diversity in terms of viewing RMS issues and concerns from an “Enterprise perspective.” We’re leading off this Journal edition with an article, courtesy of VADM Walter (Wally) Massenburg, that focuses on how to reshape an existing organization, steeped in a stove pipe mentality and headed towards what can be characterized as a “burning platform,” in to an Enterprise. Admiral Massenburg took the correct approach to “righting the ship” by instilling an Enterprise thinking mentality and approach to it all; the result is the Warfighter being provided what he/she needs to be successful. We appreciate Admiral Massenburg taken the time to coordinate the approval needed to get this case study article republished in this Winter Journal.

The second article focuses on Reliability Centered Maintenance (RCM). The authors, Huairui “Harry” Guo, Athanasios Cerokostopoulos, Yuhai Liang, focus on the fact that equipment maintenance is at the heart of many company’s profitability—reliable equipment can mean huge savings in terms of future capital expenses and environment preservation concerns. They offer a new approach—RCM—to maintenance and operations specialists and we’re delighted they offered this article up to us for publishing. My interaction with the submission of this article was through Mr. Guo. Mr. Guo was easy to interact with and I hope he and his team will consider submitting future follow-on articles.

The third article, courtesy of Dr. Lloyd Muller, tackles the problems associated with heat generated in a reciprocating engine, how to reduce the generated heat which, in turn, allows for removing some of the more unreliable engine components. Dr. Lloyd H. Muller is a logistician with over 35 years of experience in all realms of the discipline. With his background in many forms of transportation—from operating school bus systems to developing and directing strategic sea and airlift requirements for military operations—as well as the management of petroleum, munitions, aviation supply and maintenance projects, we’re hoping to see contributions from him in future Journals.

Finally, our fourth “contributor,” Ms. Chris Peterson, approached me with a proposed article on an experiment that revolved around single and multiple vibration testing where the focus is on comparing the two methods in terms of time to failure. Chris’ writing style is easy to follow and, more importantly, her approach to it all—relying on a host of people across varied industries and organizations and more “Enterprise” in nature—resonated with me as I assembled the other articles and my thoughts on the new public-private model that I kick off my “intro section” with. We hope that Chris will consider submitting more articles for future Journals.

So, there you have it—more Enterprise thinking and approaches to problem solving that are directly related, or attributable, to sound RMS approaches. Good reading and best wishes for a safe and memorable Holiday Season!

Jim Rodenkirch, Editor

THE BIRTH OF AN ENTERPRISE: CULTURAL CHANGE IN NAVAL AVIATION

Vice Admiral Walter Massenburg, USN (Ret.)

This article is a case study with VADM Walter Massenburg, former Commander Naval Air Systems Command that details the development of the Naval Aviation Enterprise.

This article is adapted from Chapter 11, Leading at the Strategic Level, Dr. James Browning, Ft. McNair, Eisenhower School of National Security and Resources, 2012, pp. 399-437 – Ed.

Introduction

On September 10, 2001, Chief of Naval Operations Vern Clark was considering cutting the force. There were serious problems with Naval Aviation maintenance, supply, and logistics systems. Current readiness was at an all-time low, marked by parts shortages and aging aircraft. Though the Navy possessed a complement of eleven aircraft carriers, only four could be operated at any given time due to a lack of adequate aircraft, maintenance and deck support equipment, or precision ordnance. To make matters worse, Naval Aviation had a flying hour budget deficit of \$131 million and a low likelihood of that changing.

Fifteen months later, General Richard B. Myers, the Chairman of the Joint Chiefs of Staff, requested four aircraft carriers to support the March 2003 invasion of Iraq. CNO Clark proudly responded, "You bet! In fact, you can have eight!"¹ The transition that Naval Aviation (n.b., NAVAIR is the acronym for the Naval Air Systems Command and not all of Naval Aviation) underwent in this short period of time continued into 2007 under the guidance of a few key strategic leaders. Their combined effort to change the culture of Naval Aviation resulted in the creation of an empowered Naval Aviation Enterprise aligned to a single process owner (Commander, Naval Air Forces) and a single Fleet- (customer-) driven metric that benefited the Naval Aviation Fleet today, tomorrow, and into the future. This case study chronicles the methods and strategies used by the leaders of Naval Aviation to save the organization. The genesis of this change occurred in the providing arm of Naval Aviation—the Naval Air Systems Command (NAVAIR).

NAVAIR at a Glance

The following description of NAVAIR can be found on the organization's website:

Established in 1966 as the successor to the Navy's Bureau of Naval Weapons, the Naval Air Systems Command (NAVAIR) is headquartered in Patuxent River, Md., with military

and civilian personnel stationed at eight locations across the continental United States and one site overseas. NAVAIR's mission is to provide full life-cycle support of naval aviation aircraft, weapons and systems operated by Sailors and Marines. This support includes research, design, development, and systems engineering; acquisition; test and evaluation; training facilities and equipment; repair and modification; and in-service engineering and logistics support.²

The support or providing role of NAVAIR is one that is integral to national security of the United States. As a result, NAVAIR's emphasis and direction were constantly oriented towards warfighting and combat readiness. This served the organization well until it was confronted with a series of problems in the late 1990s. The organization, which consistently excelled at solving warfighting problems with ingenuity and skill, was nonetheless faltering from a business perspective.

The Burning Platform

In the summer of 2000, Naval Aviation's problems reached critical mass. While preparing to take over as CNO, Admiral Clark was informed that there would be a \$131 million flight budget deficit for the coming fiscal year. For an organization that already shortchanged funding for future readiness to boost current readiness, this budget shortfall would likely result in an even greater procurement deficit. These problems all came shortly after the Aviation Repair and Supply Readiness Study Group released a report enumerating 19 major problems with Naval Aviation.ⁱ At the same time, the Naval Inspector General released a report affirming the precarious position of Naval Aviation.ⁱⁱ Moreover, the reports mutually reinforced a single grim message: unless drastic changes to its structure and operations were made, Naval Aviation would no longer be capable of carrying out the naval air mission.

The Four-Carrier Navy

The readiness and retention problems identified by the studies and worsened by the budget shortfall were symptoms of more serious underlying conditions that afflicted Naval Aviation. A number of structural-operational barriers hindered efficiency and improvement of the organization. For one, there was an expansive lacuna between the amount of money spent by Naval Aviation and the amount of readiness produced. The operating budget was consistently exceeded, resulting in the sacrifice of future readiness to current readiness. Moreover, the metrics used to measure performance did not support current or future readiness.

1 Vern Clark, "Foreword" in Walter Massenburg and John Pierce, "Edge of the Envelope" Manuscript, unpublished.

2 <http://www.navair.navy.mil/index.cfm?fuseaction=home.display&key=9E99EE24-2F3D-4E23-A0C1-A54C18C3FFC8>

Naval Aviation also consistently failed to meet its retention goals in part due to poor job satisfaction. This compromised future readiness further by pushing would-be leaders from the organization, while increasing the cost of training new employees.

Furthermore, an historic division existed between Naval Air Forces, Pacific Fleet and Atlantic Naval Air Forces, Atlantic Fleet that led each to operate autonomously. This divide produced divergent behaviors, processes and tools across the groups. Information was disconnected; sub-groups and elite societies prevented cooperation toward a shared goal. To make matters worse, there were over twenty key stakeholder organizations in Naval Aviation with competing interests, different priorities, different measures of performance, and varying cultures.

Like other government organizations, Naval Aviation operated in a business paradigm that valued consumption of resources only tangentially connected to outcomes or success of ultimate customers. This culture justified wasteful behavior and stultified efforts to change. The *sine qua non* of Naval Aviation's culture of consumption was a "use it or lose it" mentality fueled by the rampant paranoia that future funding would be diminished if current funding was not consumed in its totality. Flying hours were entirely consumed; gasoline tanks topped-off just before the budget for the next fiscal year took effect.

This model of over-consumption was paired with a tribal competitiveness between subgroups of Naval Aviation that drove continued resource consumption. The competition divided Naval Aviation, justifying behavior that was harmful to the Fleet as a whole. Worst of all, because of their learned patterns of behavior, the leaders of Naval Aviation were not likely to change the organization for the better. All of their training had taught them to maximize readiness *at any cost*.

CNO Clark's Vision

CNO Clark resolved to bring a new approach to the Navy, and specifically to Naval Aviation. He was the first CNO (and the only one since) to hold an MBA. His education and background made him aware of the importance of bringing a fiscally responsible culture to the organization. His overall goal was simple: link readiness requirements to the money spent to achieve them by aligning the incentive and operational structures to one another.

Guiding Naval Aviation to change the culture would not be an easy task. What was needed, above all else, was a catalyst for change. Clark's first step was to craft a message. He conveyed the seriousness of the predicament that confronted the organization to its members, stating boldly that, if nothing changed, Naval Aviation would no longer be capable of defending the U.S. In short, the Four-Carrier Battle Group peacetime operating paradigm was not going to serve the country well in time of war—a very real pre-9/11 thought process.

It is significant to note that, despite its grim content, Clark's message was optimistic. He didn't blame people for following the organization's traditional habits of consumption, nor did he assume a fatalistic attitude about Naval Aviation's future. Instead, he made them aware of the severe consequences of maintaining those destructive habits while encouraging them to use their own capabilities to shape a more responsible culture. This message was one of empowerment—those within the organization were entrusted with the power and responsibility to save it.

Clark's Solutions

Clark's message alone would not be powerful enough to completely revamp Naval Aviation. Hence, he identified three solutions to dispel the major obstacles confronting the organization. *First*, Naval Aviation would need a single person to be responsible and accountable for alignment to a higher purpose. *Second*, the organizational stovepipes that inhibited collective goal accomplishment needed to be encouraged to operate cross-functionally and subordinate and reprioritize their activities in relation to the "Greater Good." *Finally*, the metrics used to gauge performance and readiness required revision to reflect a new goal—a Single Fleet Driven Metric—to drive the behaviors of the organization.

Clark enabled Naval Aviation's transformation by naming a single-process owner in Vice Admiral John Nathman. This provided the organization with a transparent, linear hierarchy that clarified communication, authority, and accountability. More importantly, this designation was the primary, necessary step in the alignment of Naval Aviation to a single metric and priorities to achieve success in pursuit of the metric. While there were subordinate metrics, they were only considered relevant if they moved the Single Fleet Driven Metric.

Clark's other two solutions were more difficult to achieve. Instilling subordination to a metric with a responsible and accountable process owner and revising supporting metrics necessitated involvement and a sustained effort from both internal and external stakeholders. Between 2000, when NAVAIR's problems became clear, and 2004, when the Naval Aviation Enterprise was formally named, there were three primary initiatives that combined to lend content to Clark's message: 1) the NAVRIIP Conference in Dallas; 2) Boots on the Ground; and 3) the Naval Aviation Readiness Integrated Improvement Program (NAVRIIP)—all of which will be discussed next. It is important to note that each of these initiatives operated on its own time horizon and influenced the emergence of the Naval Aviation Enterprise at different rates. Hence, the Boots on the Ground program lasted longer than the conference, began earlier, and delivered its major structural legacy *after* Naval Aviation's "main thing" was being honed.

Pause—take a moment to reflect on the following questions and capture your initial thinking and insights.

1. Have you been involved with an organization that was dealing with a burning platform? If so, how did the leaders deal with this issue?
2. We can see the difficulty that Clark faced when he attempted to change the culture of Naval Aviation. What potential roadblocks can you identify that would impede a transformational culture change in your organization?
3. Can you identify stovepipes within your own organization? If so, what types of issues do these stovepipes generate?

Metrics and Entitlements:

The NAVRIIP Conference in Dallas, July 2003

At an annual conference in the summer of 2003, NAVAIR began what would be a complete transformation of the way business was done. The conference in Dallas was a pivotal moment for Naval Aviation because it solidified the concept of entitlements and began an operating concept whereby those entitlements and an understanding of their relationships to cost were assigned to all of Naval Aviation Type/Model/Series aircraft.

Entitlements and Readiness

Prior to the Dallas conference, the definition of readiness within the Fleet varied considerably. Part of the goal of the conference was to begin to integrate these myriad definitions into a singular concept. At a basic level, these concepts shared a common trait that needed to be curbed—viz. a disregard for the amount of money spent to produce the desired amount of readiness. The model Naval Aviation was following, in Massenburg’s words, was chasing “readiness at all cost.”³ At the conference, the concept of entitlements provided the solution to the fiscally irresponsible behaviors of the organization by rationing the amount of readiness produced to coincide with the amount of readiness needed at a given time, bounded by cost and risk.

Alignment and Cross-Functional Leadership

Just as entitlements led to a rational system for revising readiness at predictable cost, the need to clarify and integrate readiness metrics created a demand for increased cross-functional work. Though the transformation effort could have been top-down, it was cooperative and involved empowered employees. This revised the metrics while also increasing buy-in for the altered measures.

As the organization underwent this process, it began to take on a structure that reinforced the importance of a single leader (a single “keeper of the metric”) entrusted to make holistic decisions. In integrating the manifold metrics used to define readiness,

³ Personal interviews with VADM Walter Massenburg.

there was an evident need to involve all of the major internal stakeholders in the redefinition of their metrics. Redefining the organization’s structure would come from observations of the air stations and ships, while revised readiness metrics provided the organization with a new, more focused mission.

Boots on the Ground

In the beginning of 2001, the leadership of NAVAIR began to tour the air stations under their auspices. These visits were part of an initiative known as “Boots on the Ground,” which was designed to connect the providing Admirals to the Fleet customer so that they could be exposed to the result of the shortcomings and better understand how the organization could improve to compensate for their lack of funding.

Several of these visits framed unique realizations for Naval Aviation’s leadership. The first visit, to the Naval Air Station at Whidbey Island, Washington, revealed the importance of focusing on broad process improvements as integral to improving readiness and reducing costs, as opposed to superficial single-point solutions. Perhaps the most important visit was the third, which occurred at Mayport, Florida. There, Naval Aviation leadership put into practice a triangular working model—the Type/Model/Series team—that focused leadership and accountability in a cross-functional, rational manner.

The Type/Model/Series Teams

During their third official Boots on the Ground visit in the spring of 2002, the Admirals validated the design of the Type/Model/Series structure for managing the affairs of each aircraft community and authorized implementation of the new way of doing business. An aircraft community is created around the type of aircraft flown and maintained at a given facility. Figure 1 depicts the relationship in a single community between the commodore (a Navy Captain), the resource managers, the requirements officer, and the squadron for a given type, model, and series of aircraft.

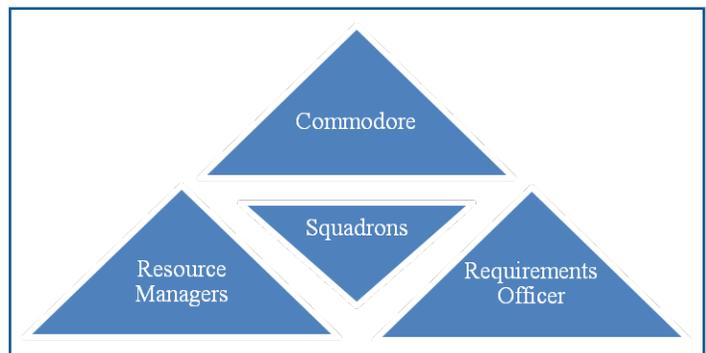


FIGURE 1 - TYPE/MODEL/SERIES STRUCTURE FOR A COMMUNITY

The significance of the Type/Model/Series structure is diverse. It creates a clear organizational structure with a single-process

owner close to the aircraft communities, while nonetheless encouraging cross-functional communication and subordination toward the attainment of collective goals. These teams also brought together the internal stakeholders from each of the three major parts of the organization—warfighting requirements, providers, and resources. Most importantly, the teams served as the blueprint for organizational efficiency and cooperation that would inform the structure of the Naval Aviation Enterprise.

Pause—take a minute and reflect on the following questions. Note your initial thoughts and insights.

1. Do you think that a change in metrics could lead to an overall improvement of your organization's efficiency? If so, what new metrics would you recommend?
2. Do you believe that the “boots on the ground” approach in Naval Aviation was the best way to examine the new metrics? How do you think this approach would work in your organization?

Naval Aviation's “Main Thing”: The Fleet-Driven Metric

At the same time as the Boots on the Ground initiative was underway, the disparate metrics used to measure readiness were finalized under the Naval Aviation Readiness Integrated Improvement Program (NAVRIIP). In addition to focusing on the metrics themselves, a new philosophy governed the numbers that were agreed upon: How much readiness was enough?

At the beginning of this study, it was noted that CNO Clark told General Meyers that he could give Meyers more carriers than Meyers had asked for. In part, this demonstrated to Meyers that Naval Aviation had moved away from its serious readiness crisis and was back in the business of defending the nation. Clark was confident that a greater amount of readiness could be produced in time for Operation Iraqi Freedom. This was not to say that there was an excess of readiness already present, but instead that Naval Aviation's new purpose, culture, and sense of urgency could bring about this elevated level of readiness in a shorter time frame than would have been expected prior to change. It also allowed for focused continuous process improvement to get to the readiness required “AND NO MORE.”

Nonetheless, this revealed that Naval Aviation still needed to revise its metrics so that readiness was being produced only to the extent that it was required. With its newfound efficiency, Naval Aviation had transitioned from a problem of under-production to the problem of over-production.

While Naval Aviation had eight carriers ready in 2003 (seven subsequently deployed in support of Operation Iraqi Freedom), it had done so at tremendous cost in money and resources. The consequence of this approach was that *future* readiness was being compromised, even though the organization had made considerable progress since the 1990s. The problem was one of *overproduction* or “unconstrained output,” as demonstrated by a

surplus of 237 pilots at the cost of \$60 million. Aligning resources and requirements would entail not only creating entitlements that *allow* resource allocations and expenditures, but also *preventing* resources from being allotted where they were not necessary. The metrics failed to reward the desired behavior and therefore needed to change, and the program became one that would get to the readiness required “AND NO MORE”—but now with the added pressure of reducing the cost so that the future could be realized.

The combined reform of the organization led to a Fleet-centered readiness metric that became the organization's “main thing.” The “main thing,” a concept borrowed from *The Power of Alignment*, is “the single most powerful expression of what [an organization] hopes to accomplish, its instrument for producing growth and profits [in this case, savings or surplus].”ⁱⁱⁱ The authors identify three key points about any organization's “main thing:”

- The main thing as a whole must be a common and unifying concept to which everyone can contribute.
- Each department and team must be able to see a direct relationship between what it does and this overarching goal.
- The main thing must be clear, easy to understand, consistent with the strategy of the organization, and actionable by every group and individual.^{iv}

Naval Aviation's “main thing” evolved from *Aircraft Ready for Training* (2001) through several iterations to become *Aviation Units Ready for Tasking at Reduced Cost* (2006). This emphasis focused on realigning readiness requirements based upon the system of entitlements tailoring resources to those requirements. Also, the new Fleet-driven metric curbs overproduction and emphasizes continuous process improvements while still preventing *underproduction* of readiness. With the creation of a novel organizational structure in the Type/Model/Series teams and a recalibrated Fleet-driven metric, the stage was set for Naval Aviation to become an Enterprise. In July 2005, the NAE was officially named.

A New Structure and Culture: The Naval Aviation Enterprise

The Naval Aviation Enterprise was a fundamental reinvention of the Naval Aviation warfighting business model. Yet, even before this structure was formally created, the groundwork already existed for a new culture. The progressive realization of the importance of cross-functional and distributed leadership, alignment, and the need for revised metrics and entitlements all began to pull the culture of Naval Aviation toward an Enterprise approach long before the structure became a reality to the Admirals who created it.

The Enterprise Structure

Notice that the structure of the NAE is remarkably similar to that of the Type/Model/Series teams. (See Figure 2 below.) While the T/M/S teams each have an aviation community as their domain, the NAE addresses the concerns of the Fleet as a

whole: a Fleet-centered model. In the Enterprise triad, the top—warfighting requirements and risks—consists of commanders who remain accountable for resourcing manning, training, and equipping the Force to fight. These commanders work cross-functionally with the key leaders of the other corners of the Enterprise triangle: bringing requirers, providers and resourcers together to generate the required readiness. The group of providers includes a number of organizations, each of which plays an integral support role for Naval Aviation, such as handling its procurement, maintenance and supply duties. Those in charge of resources deal with procurement, discretionary funding, and future spending to ensure that the organization remains funded and capable of defending the nation with the technology in a balanced way to ensure Warfighting capability and availability—today, tomorrow, and in the future—with respect for the value of a dollar.

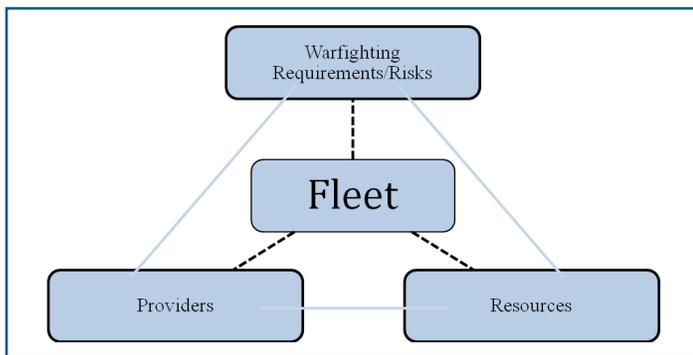


FIGURE 2 – STRUCTURE OF THE NAVAL AVIATION ENTERPRISE

To borrow a phrase from VADM Massenburg, the Enterprise triad created alignment and balance between Naval Aviation’s “people, dollars, and stuff.”⁴ These groups, which only occasionally talked to one another in the past, now obligated themselves to meet on a regular basis (drumbeat) with all other stakeholders to work toward the advancement of the collective goal—i.e., The Single Fleet Driven Metric.

Pause—take a moment to reflect on the following questions and capture your initial thinking and insights.

1. What lessons can you extrapolate from Naval Aviation’s successful transition to an Enterprise?
2. Are there any aspects of the change that seem especially relevant to your own area of expertise?
3. Are there any changes that are potentially destructive?

Analysis: Leading Change in NAVAIR

Having presented a detailed portrait of the transformation of Naval Aviation from an inertia laden, stove piped structure into a fully integrated Enterprise, it will now prove worthwhile to elucidate the stages that went into this change and making it last. The stages introduced above⁵ will serve as the guideline for assessing this effort

⁴ Personal interviews with VADM Walter Massenburg.

⁵ See pages 57-65.

and therefore provide the organization for the following section. The reader will benefit most from this section by comparing his or her change model to the ten-step approach discussed below.

Step 1: Assessing the Need for Transformational Change

The first stage of transformational change is asking the question of whether or not such a large-scale alteration is necessary. Ideally, this should be the outgrowth of a detailed analysis of organizational strengths and weaknesses, in which the potential benefits should outweigh the risks. For Naval Aviation, the Aviation Maintenance and Supply Readiness (AMSR) Study Group’s report functioned as the internal scanning component of the change process. It not only turned a critical eye to the organization’s structure and purpose, but also provided a detailed list of discrete and actionable problems that compromised effectiveness and efficiency. In some sense, the report dispelled the idea that transformational change was *not* necessary. The leadership of the organization came to believe that failure to transform was not a viable option.

Step 2: Strong Strategic Leadership

The second stage asks leaders to become fully aware of their personal strengths and weaknesses. In the context of Naval Aviation, the foremost leader and enabler of the change effort was CNO Clark. Because he came into his position expecting and demanding change, Clark was uniquely qualified to bring a new attitude to the organization that would allow the change. Furthermore, he had considerable business acumen that gave him the skill set and confidence needed to lead and inspire others.

Step 3: Creating a Sense of Urgency

The third stage involves creating a sense of urgency throughout the organization that keeps employees motivated and focused on the change mission. This stage was not only followed but also embraced by the CNO Clark and the Admirals in charge of leading Naval Aviation. Clark’s first public action addressing the Fleet was one that put the organization in perspective with a single message: if things didn’t change, Naval Aviation would fail and compromise our Navy’s ability to wage war.

Step 4: Building a Strong and Committed Executive Team

The fourth stage demands the creation of a capable and invested executive team. In some sense, part of the problem that afflicted Naval Aviation was a team divided between East and West coasts, Active and Reserves, and providing commands and operating commands. Specifically, with regard to the East Coast/West Coast division Admiral Clark did not hesitate to name a single-process owner for the organization in VADM Nathman, the newly assigned Commander of Naval Aviation on the West Coast. This brought the organization into alignment under his direction, thereby creating the vehicle for a single message for the changed vision to take hold.

Step 5: Get the Vision Right

The fifth stage of leading transformational change concerns the content of the change-vision. “Getting the vision right” is generally challenging because success depends upon how well the vision is understood by individuals throughout the organization. A strategic change vision must incorporate a solution to the organization’s existential problems.

In the case of Naval Aviation, the vision steadily progressed over time from CNO Clark’s general vision to improve the organization by inculcating a financial conscience in its members and aligning resources and requirements. This broad vision narrowed and hardened into a number of structural reforms involving single-process ownership and cross-functional elements, etc., and operating changes involving metric recalibration. The current vision for Naval Aviation, as presented in the Enterprise structure, is to produce the right amount of combat readiness at reduced cost—now and in the future.

Step 6: Communicate for Buy-In

The sixth step requires that the strategic leader(s) communicate their vision to obtain buy-in from internal stakeholders. This process can often be complex because of the unique behaviors of individuals and sub-groups within large organizations. Nonetheless, the communication efforts responsible for transforming Naval Aviation were relatively straightforward. Memos and executive briefs delineated the vision and purpose of the organization, constantly reinforcing and honing the message to strengthen buy-in. Conventions, lectures, and other large gatherings all reiterated the same messages, albeit using different words or concepts. Visibility of senior leadership (Boots on the Ground/Boots on the Deck) in the customer community for which they were responsible was a key tenet of change. Repetition of the constant theme from all stakeholders, vertically and horizontally, affects successful alignment.

Step 7: Empower Action, Enhance Collaboration and Learning, and Recognize the Influence of the Organization’s Culture

The seventh step involves empowerment, collaboration, and culture. Each portion of this step was adhered to in the Naval Aviation transformation process. First, servicemen and women were empowered to make decisions within their own realm, especially those in charge of sub-groups within the Type/Model/Series teams. Also, a system of entitlements was generated in order to give individuals the visibility to be able to detect change. Tools were provided—AIRSpeed (Lean Six Sigma, Theories of Constraints, and other process improvement tool sets)—and became the enablers to success, but were not used as an end to themselves. An environment of continued process improvement always in relation to the “Main Thing” developed. Second, Naval Aviation’s transformation expanded the collaboration and

learning of those within the organization immensely. Stovepipes were deconstructed and cross-functional cooperation became an indispensable part of decision-making. Clear connections were developed between the vision guiding Naval Aviation’s change effort and the outcome-culture it created.

Step 8: Create Short-Term Wins

The eighth step entails the creation of benchmark victories that demonstrate the value of the changes made. These wins are significant because they validate the direction of the change being implemented. For Naval Aviation, these wins were pronounced. At some point, though, these victories served more to affirm the importance of specific programs rather than a monolithic strategic vision. One example of such a victory was the Flying Hour Program, which saved millions of dollars by aligning flight schedules and sorties to entitlements. Other cases involving process improvements also trumpeted the importance of taking initiative toward more financially-aware attitudes.

The vision that motivated Clark and others (of bringing a business-like mentality to Naval Aviation) was consistently being emphasized by the successes of these programs. Subordination, collective acceptance of the concept of “Greater Good,” and continued process improvements gave further credence through these short-term wins.

Step 9: Don’t Let Up

The ninth step presents the challenge of sustaining momentum despite lethargic progress. Once the Enterprise was formally created in 2005, the problems it faced were no longer as difficult to address as before that construct was adopted. With the creation of cross-functional teams, more reasonable and sustainable readiness metrics, single-process owners at various levels, and continued process improvement initiatives, the NAE was capable of preventing future problems from occurring and taking a more proactive approach to foreseeable difficulties.

Step 10: Make Change Stick

The tenth and final stage of successful transformational change requires the strategic leader(s) to make change stick. The main obstacle when leading change is the constant allure of reversion to old habits and behaviors. For a number of reasons, the change to the Enterprise system wasn’t going to revert to its former pre-change culture. This is because, under the incremental reforms leading to the NAE, power had already been distributed to those at the lower ranks of the organization. Once that power was ceded to them, the Admirals would have a hard time wrenching control back to the “way it used to be.” The NAE empowered employees and gave them the tools they needed to succeed by helping themselves and the organization. Their success in this mission transformed their own 12-hour days into 8-hour days, leaving them generally more satisfied. As a result, anyone threatening to

remove the Enterprise was also threatening to strip servicemen and women of their newfound satisfaction and purpose. If nothing else, the success of the NAE system illustrates that empowering employees will help change stick.

Pause—take a moment to reflect on the following questions and capture your initial thinking and insights.

1. In your view, did the presence of four-star, top-down direction and the intrinsic value of fixing a critical national security shortfall make this an easier task than would be the case in the civilian sector?
2. Does the above analysis seem accurate? What lessons can be learned about concepts like empowerment and alignment from the above account?
3. Does any single concept seem more important than any other or are all concepts of equal value when leading change?

Final Notes on NAVAIR's Transition to Enterprise

In the introduction of their book, *The Heart of Change*, John Kotter and Dan Cohen note, "People change their behavior less because they are given *analysis* that shifts their *thinking* than because they are *shown* a truth that influences their *feelings*." [italics in the original] This affective approach to change guides all of Kotter's eight steps of transformational change. According to this model, people must see and *feel* the need to change as well as the power and charisma of leadership instead of merely being told about it. This was the character of the transformation within Naval Aviation.

Maintaining motivation throughout the change process was integral to success, and the key mechanism behind this sustainment was the forward-looking attitude displayed by Naval Aviation's leadership and mirrored by those at all ranks. The problems that confronted Naval Aviation were a product of its own shortsightedness, but CNO Admiral Clark and others understood that the culture, not the people, were directly responsible for this bad behavior. Rather than chastising servicemen and women for their wasteful actions, Clark encouraged them to look onward and upward to change their behavior for the better. If only one lesson is learned from this case study, it should be that purpose, charisma, and optimism of this nature could lead to remarkable success in any organization.

About the Author

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Abstract

Equipment maintenance is now at the heart of many companies' activities due to its vital role in the areas of safety, liability, productivity, quality, system reliability, regulatory compliance, profitability and environment preservation. With this new paradigm, new awareness, realities, challenges and opportunities are being presented to maintenance and operations specialists in various industries. In the center-stage spotlight of maintenance, there is a strategy called Reliability Centered Maintenance, or RCM [1-3]. In this paper, we will first review the general process in RCM and then we will discuss how to apply quantitative reliability analysis tools such as Weibull analysis, reliability block diagram modeling and simulation to help achieve an efficient and cost-effective RCM process.

1) Introduction

RCM analysis provides a structured framework for analyzing the functions and potential failures of a physical asset (such as an airplane, a manufacturing/production line, an oil refinery, a nuclear power facility, etc.) in order to develop a scheduled maintenance plan that will provide an acceptable level of operability, with an acceptable level of risk, in an efficient and cost-effective manner. A successful RCM should be based on solid reliability analysis results, and achieves the following tangible and actionable outputs: a) effective maintenance schedules (which could include on-condition tasks, scheduled restoration tasks, scheduled discard tasks or failure-finding tasks), b) improved operating procedures for the operators of the asset, and c) a list of recommended changes to the design of the asset that would be needed if a desired performance is to be achieved. To get these benefits from RCM, system operation data such as equipment failure time, failure repair duration, and other downing event information must be correctly collected and analyzed. The analysis results then are used in designing maintenance strategies in RCM. However, many of the RCM standards in published resources are too general and only focus on the management part in RCM. In order to find optimum maintenance policies that are suitable for your system, quantitative reliability analysis of your system data is needed.

2) Why perform RCM?

Companies across industries nowadays are facing a never-ending pressure to reduce operating costs and become more efficient. System downtime can be a significant source of capital spending in industries such as oil and gas, manufacturing, telecommunications, IT infrastructures etc. Typical costs

associated with downtime are loss of revenue, lost inventory, labor costs, loss of business opportunities, loss of customer goodwill and brand damage. Given the fact that hourly downtime can result in hundreds of thousands or millions of dollars losses, there is a clear need for a maintenance system that will assure high system availability. On the other hand, given the need for a cost effective operation, companies cannot afford to overspend on maintenance. As a result, a balance needs to be found between the need to minimize downtime and minimize maintenance costs.

Traditional thinking holds that the goal of maintenance is to preserve equipment. On the surface, this mindset might sound reasonable, but in fact it has been proven to be flawed at its core. The blind quest to preserve equipment has produced many problems, such as being overly conservative in maintenance actions (which could cause damage due to intrusive actions and increase the chances of human error), thinking that all failures (or parts) are equal or performing maintenance activities simply because there is an opportunity to do so.

Recent decades have brought in many initiatives and management strategies aimed at reducing cost, optimizing the use of resources and becoming sensible about the effect on the bottom line of any action we take. The "preserve equipment" mentality consumed resources quickly, put maintenance plans behind schedule and overwhelmed even the most experienced maintenance personnel. What is worse, it sometimes caused maintenance actions to become totally reactive. Budget cuts made the scene even uglier and many people simply lost control of their maintenance management.

The development of the Reliability Centered Maintenance approach has provided a fresh perspective in which the purpose of maintenance is not to preserve equipment for the sake of the equipment but rather to preserve system function. Therefore, in order to develop an effective maintenance strategy, one needs to know what the expected output is and the functions that the equipment supports. The primary focus of RCM is to achieve a high level of understanding of the failure modes/causes of equipment, the likelihood of occurrence and the related effects; then to define a maintenance plan that prevents or proactively addresses the potential causes of failure in such a way that the overall cost of doing business is reduced. The general process of conducting effective RCM is given next.

3) RCM Process Overview

Although there is a great deal of variation in the application of RCM, most procedures include some or all of the seven steps shown below [1-3]:

1. Prepare for the analysis
2. Select the equipment to be analyzed
3. Identify functions
4. Identify functional failures
5. Identify and evaluate (categorize) the effects of failure
6. Identify the causes of failure
7. Select maintenance tasks

If we were to group the seven steps into three major blocks, these blocks would be:

- Project definition stage (steps 1, 2 and 3)
- Failure analysis stage (steps 4, 5 and 6)
- Maintenance action stage (step 7)

3.1) Project Definition Stage

In the project definition stage, the RCM analysis team should be assembled. The team has to reach a decision about the level of the asset at which the analysis should be conducted (e.g., part, component, subsystem, system or plant). Once the level of analysis has been established, the next step is to select the equipment for the RCM project. The candidate systems that would benefit the most from a new maintenance program should be identified and prioritized. Various criteria, such as safety, legal, and economic considerations, can be used in determining the benefit obtained from maintenance. After the system is selected, we need to identify the important functions of this system. The function definition should be as quantitative as possible. For example, a function should not be defined as “to produce as many units as possible,” but rather “to produce a target of 25 units with a minimum of 22 units in an eight-hour shift.”

3.2) Failure Analysis Stage

In the failure analysis stage for the selected equipment, the first step is to identify functional failures. A functional failure is defined as the inability of an asset to fulfill one or more intended function(s) to a standard of performance that is acceptable to the user of the asset. Once the functional failures are identified, the next step is to evaluate (categorize) the effects of failures. Many RCM references contain logic diagrams that can be used to evaluate and categorize the effects of failure. After the effects of a failure are identified, the next step is to identify the causes of failure (failure modes). The day-to-day issues of maintenance are mostly managed at the failure mode level. Extensive discussions about failure mode identification in this step of the RCM process will have a great beneficial impact on the success of the RCM project. It is what could make the difference between a reactive and a proactive maintenance management plan.

3.3 Maintenance Action Stage

In the maintenance action stage, a failure management strategy should be defined for each failure mode. There are several different strategies. They are discussed briefly in the following sections.

a. Scheduled Inspections

The purpose of an inspection is to discover a failure that has already happened but has not yet surfaced or to detect a failure that is about to happen.

b. Scheduled Preventive Maintenance

This maintenance type is scheduled in advance to occur at a “hard time” regardless of the apparent condition of the equipment. It aims at restoring the initial capability of the equipment. Preventive maintenance can include service, repair or replacement of a component or a device.

c. Run-to-Failure

A deliberate decision is made to run the equipment to failure and fix it when it fails, but not to perform scheduled maintenance actions.

3.4) Choosing the Right Maintenance Strategy

Among all the above maintenance actions, which one is the best for a specific piece of equipment? Choosing the appropriate maintenance strategy for each potential failure relies on a combination of factors such as technical feasibility, judgment/experience and whether the task is worth performing. Making a good choice starts with a good understanding of the behavior of the failure mode we are trying to address. This means we need to know the distribution model (probability density function, or *pdf*) that governs the failure mode. So we need to determine how much we really know about the failure behavior over time. This is the “R” in RCM, which is often overlooked in an RCM process.

In the absence of at least a reasonable reliability estimate, implementing a task could lead to unproductive or counterproductive results. The failure distribution and reliability model of a system can help us define an optimum maintenance policy, such as finding the optimal interval for preventive maintenance, determining the necessary number of spare parts for crucial devices and allocating the right number of maintenance crews. Without knowing the reliability nature of a system, it is hard to make the right decisions for maintenance tasks. In the following section, we will explain how to conduct quantitative reliability analysis for a system.

4) Quantitative Reliability Analysis in RCM

There are three steps in quantitative reliability analysis for a system. First, we need to collect failure or degradation data for each subsystem or component, and then build a distribution for the collected data. The second step is to use all the subsystem/component failure distributions to model the system reliability.

Once the system reliability model is ready, simulation can be used to study different maintenance strategies and to choose the best strategy for implementation.

4.1) Component Reliability Modeling

If there is no existing reliability model for a component, usually two ways are employed to get it: using failure time data or degradation data. If the failure times of a component can be obtained directly, they should be used to get the failure time distribution. Alternatively, if a component is very reliable and it is not practical to get enough failures through life testing, information about how a critical performance characteristic degrades over time (e.g., tread wear, crack propagation, etc.) can be used for reliability modeling. For more detail on failure and degradation data analysis, please refer to [4].

The following example illustrates how an analyst can obtain a failure distribution by analyzing observed failure times. Assume the following failure times are collected from a life test for a florescent light. Twenty devices were tested for 1,000 hours. Six of them did not fail by the end of the test.

Number in State	State F or S	State End Time (Hr)
1	F	150
1	F	323
1	F	381
1	F	423
1	F	435
1	F	541
1	F	602
1	F	619
1	F	697
1	F	738
1	F	773
1	F	851
1	F	886
1	F	996
6	S	1000

TABLE 1 - FAILURE DATA FOR A FLORESCENT LIGHT

If we fit the data using a Weibull distribution, the estimated parameters are beta = 2.176 and eta = 913.375 hours. The distribution is given by:

$$R(t) = \exp\left(-\left(\frac{t}{\eta}\right)^\beta\right)$$

For a Weibull distribution, if beta is greater than 1, it means this component's failure rate increases with time. For components or systems with an increasing failure rate, preventive maintenance can be used to reduce the total cost due to failures. The question is: how often should a preventive maintenance (PM) be conducted (e.g., every 200 hours, or every 400 hours)? If the PM is conducted too often, it will increase the PM cost. If the interval is too long, failures may occur and will increase the corrective maintenance (CM) cost. A cost-based method can be used to find the optimum interval for preventive maintenance. The following equation is solved for the time, t , that results in the least possible cost per unit of time (CPUT).

$$CPUT(t) = \frac{C_p \cdot R(t) + C_f \cdot [1 - R(t)]}{\int_0^t R(s)ds}$$

Where $R(t)$ = reliability at time t , C_p = cost per incident for preventive maintenance and C_f = cost per incident for corrective maintenance due to a system failure. For the above example, if we assume $C_p = \$100$ and $C_f = \$800$, the solved optimal PM is about 350 hours and the minimal CPUT is 0.5394, as given in the following screenshot from the calculation performed automatically with ReliaSoft Corporation's system analysis software tool, BlockSim 8.

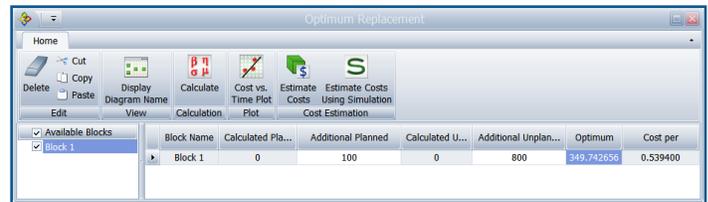


FIGURE 1 - OPTIMAL PREVENTIVE MAINTENANCE INTERVAL CALCULATED IN BLOCKSIM

Once the reliability models for all components in a system have been obtained, we can use them to model the system reliability. For each component in a system, the above analysis shows that we can find its optimal PM interval. When there are many components in a system, simulation can be used to find the best PM strategy that is optimal for the entire system instead of for an individual component.

4.2) System Reliability Modeling

There are two common methods for system reliability modeling, fault tree (FT) and reliability block diagram (RBD). A fault tree can be easily converted to an equivalent RBD, and vice versa. For example, assume a lighting system has three identical light bulbs whose failure data and reliability model are as given in Section 3.1. As long as there is one working light bulb, the system is working. This is a 1-out-of-3 parallel system. Its RBD and FT are given below.

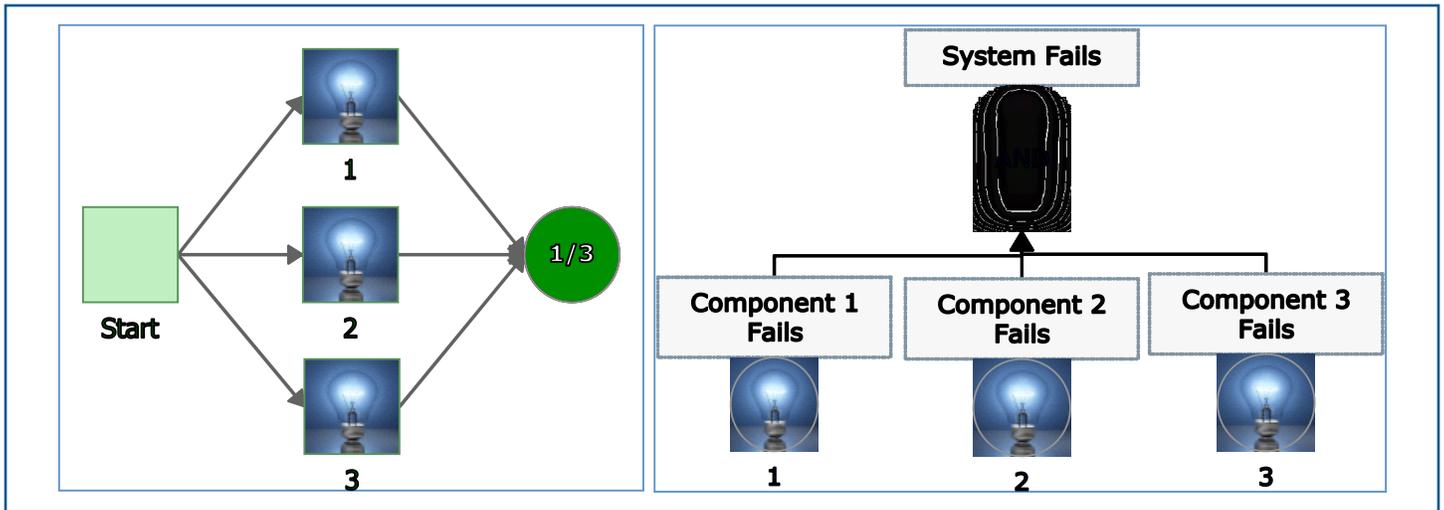


FIGURE 2 - SYSTEM RBD AND FT FOR A 1-OUT-OF-3 PARALLEL SYSTEM

Once the system RBD or the FT is available, we can study the system reliability. For this simple example, the system reliability is given by:

$$R_s(t) = 1 - \prod_{i=1}^3 F_i(t)$$

Using an RBD or FT, we also can study the reliability importance of each component in a system. The weakest link in the system will be identified and resources can be allocated to it in order to improve system reliability. For more discussion on reliability importance studies, please refer to [5].

For a repairable system, we often want to know its availability during a given time period. Clearly, system availability is affected by both system reliability and maintainability. Due to the complexity, it is impossible to analytically study the availability of a complex system. Therefore, Monte Carlo simulation is often used.

4.3) Simulation for Selecting the Right Maintenance Strategy

For the 1-out-of-3 lighting systems given in Figure 2, there are several possible options for the maintenance strategy. They are:

1. Whenever a light fails; replace it immediately. The cost for replacing one light bulb is \$50.
2. When there is only one failed light, do not replace it. Conduct replacements only when there are two failed lights. The cost for replacing two light bulbs together is \$60.
3. Conduct replacements only when all three lights have failed (i.e., when there is a system failure). The cost for replacing three light bulbs at the same time is \$66.

3. Conduct replacements only when all three lights have failed (i.e., when there is a system failure). The cost for replacing three light bulbs at the same time is \$66.

The time-to-failure distribution for each light bulb was obtained in Section 3.1. We assume the duration for replacing one light bulb follows an exponential distribution with a mean time to repair of 50 hours. Obviously, Maintenance Strategy 1 will result in the smallest number of system failures. But it requires more PM actions than the other two. Maintenance Strategy 3 is the opposite. It will result in the largest number of system failures, but requires fewer PM actions. Depending on the cost of each PM and the cost of each system failure, either strategy 1, 2, or 3 can be the best option.

Assume that when a system failure occurs, in addition to the replacement cost, it also creates a system downing cost of \$600 per failure. Given the above information, which maintenance strategy should be used in order to reduce the total cost over an operating period of 5 years (43,800 hours)? Without doing simulation, there is no way we can answer this question. The following table shows the simulation results from BlockSim. It shows that strategy 2 is the most cost-effective maintenance option because it results in the lowest total cost.

The example used in the above analysis probably is the simplest case in RCM. In reality, a system can be very complicated and constraints such as the number of spare parts and the number of maintenance crews also need to be considered. BlockSim is a powerful tool that can help us select the most effective and efficient maintenance strategies. Many useful reliability, availability and maintainability (RAM) results can be quickly obtained and viewed. Figure 3 shows some of the results for strategy 3.

Maintenance Strategy	Expected Number of System Failures	Total PM Cost	Total System Failure Cost	Total Cost	System Mean Availability
1	0.5153	7597.18	309.20	7906.38	0.99981
2	2.6210	3729.66	1572.60	5302.26	0.99849
3	36.0330	2376.29	21619.80	23996.09	0.98629

TABLE 2 - COMPARISON OF DIFFERENT MAINTENANCE STRATEGIES

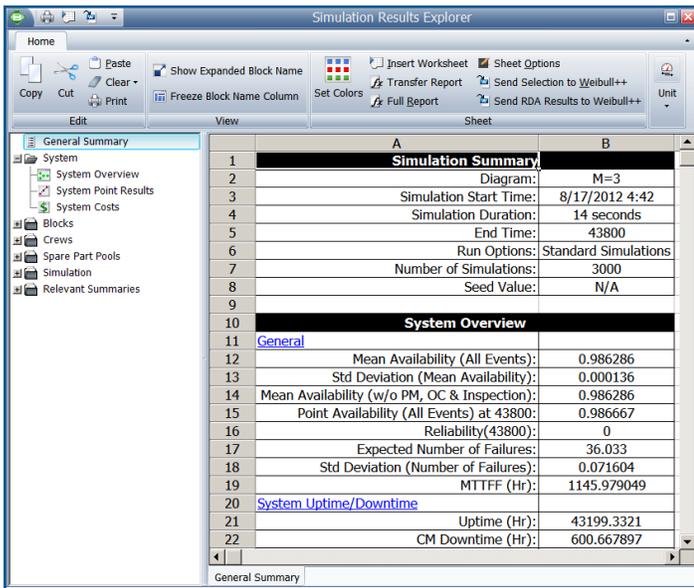


FIGURE 3 - SIMULATION RESULTS IN BLOCKSIM

5) Integrate Reliability Analysis into the RCM Management Process

From the above discussion, we can see that an RCM project has two parts: management process and quantitative analysis. Traditional RCM methodologies somehow did not pay enough attention to the “R” part in RCM although the management part was well defined. To have an effective RCM, one needs to integrate these two parts together. Many organizations have their own in-house RCM tools, either a simple spreadsheet or an advanced maintenance management software tool. There are many commercial RCM software packages on the market. However, RCM++ from ReliaSoft is the only one that seamlessly integrates the RCM management process and quantitative reliability analysis together. As part of the newly released Synthesis Platform, which provides integration for reliability, availability maintainability and other reliability analyses, RCM++ can communicate with Weibull++, BlockSim and other quantitative reliability analysis tools. RCM++ includes many widely used methodologies from industry standards, such as the criteria for selecting the equipment to be analyzed, the process of conducting the functional failure analysis and the process of defining maintenance tasks.

Following the RCM process that was outlined earlier, after the initial preparation, we need to select the equipment to be analyzed. One of the quality characteristics of a successful RCM is that the team focuses on high-risk equipment first. This enables the team to place the highest priority on issues that are really important to address, and leave lower-risk equipment for later, or even ignore equipment that the team does not think are worth putting any further effort into investigating. This can be achieved using the risk discovery tool in RCM++. By assigning a rating to a number of different factors, the team can quickly prioritize equipment and assure that time is well spent on critical items. The following figure shows an example list of factors and assigned ratings.

Category	Factor	Rating	Comments	Category Rating
Safety	Potential for Personal Injury	4 - High		17
	Severity of Personal Injury	4 - High		
	Health Hazards	3 - Moderate		
Maintenance	Fire / Explosion Event Possible	6 - Unlikely		9
	Downtime Impact	4 - Significant		
	Repair Costs	4 - Significant		
	Spare Parts Availability	1 - In-Line spare		
Operations	Affected Downtime Area			12
	Capacity Reduction Impact	3 - Moderate		
	Regulatory Requirements	1 - No		
	Impact on Energy Consumption	1 - No		
	Impact on Scrap	5 - Yes		
Environmental	Failure Frequency Potential	2 - > Semi-Annually		12
	Spill/Release Haz. Material	10 - Yes		
	Pollution Control Device			
	Env. Impact Potential	2 - Minimal		
Quality Control	Radiation Detection			4
	Quality Impact Potential	1 - None		
	Quality Severity	1 - None		
	Missed Delivery	1 - No < 2 day delay		
	Customer Claim Possible?	1 - No		

Overall Rating: 54

FIGURE 4 - EQUIPMENT SELECTION THROUGH RISK DISCOVERY

Once critical equipment have been identified, the next step is to conduct functional failure analysis, identify critical failure modes and define maintenance tasks. The next figure shows an example of a system hierarchy and a functional failure analysis in RCM++. A system tree clearly shows the functions and functional failures, as well as the effect for each failure mode.

RCM++ allows engineers to define maintenance tasks either based on the equipment manufacturer’s recommendation, or based on your own quantitative analysis results for each failure mode. As we discussed in previous sections, the best maintenance tasks can be selected using Monte Carlo simulation based on component and system reliability models. For a maintenance task, an engineer can define the labor cost, part cost, downtime duration, effect of the maintenance, and other parameters. The following figure shows a typical definition of a maintenance task in RCM++.

In addition to forecasting failures and taking preemptive repair actions outside of regular production hours, a good practice would be to assemble maintenance packages in order to reduce the cost of maintenance actions. Maintenance packaging allows the RCM team to not only forecast when and what maintenance actions need to be done, but also provides the opportunity to group activities so that multiple maintenance activities can occur together. Maintenance crews can provide maintenance services based on timing developed from life data and maintenance crew schedules, and therefore machine downtime schedules can be optimized. This can significantly reduce the cost of keeping the equipment running when needed. The following figure shows an example of maintenance packages in RCM++.

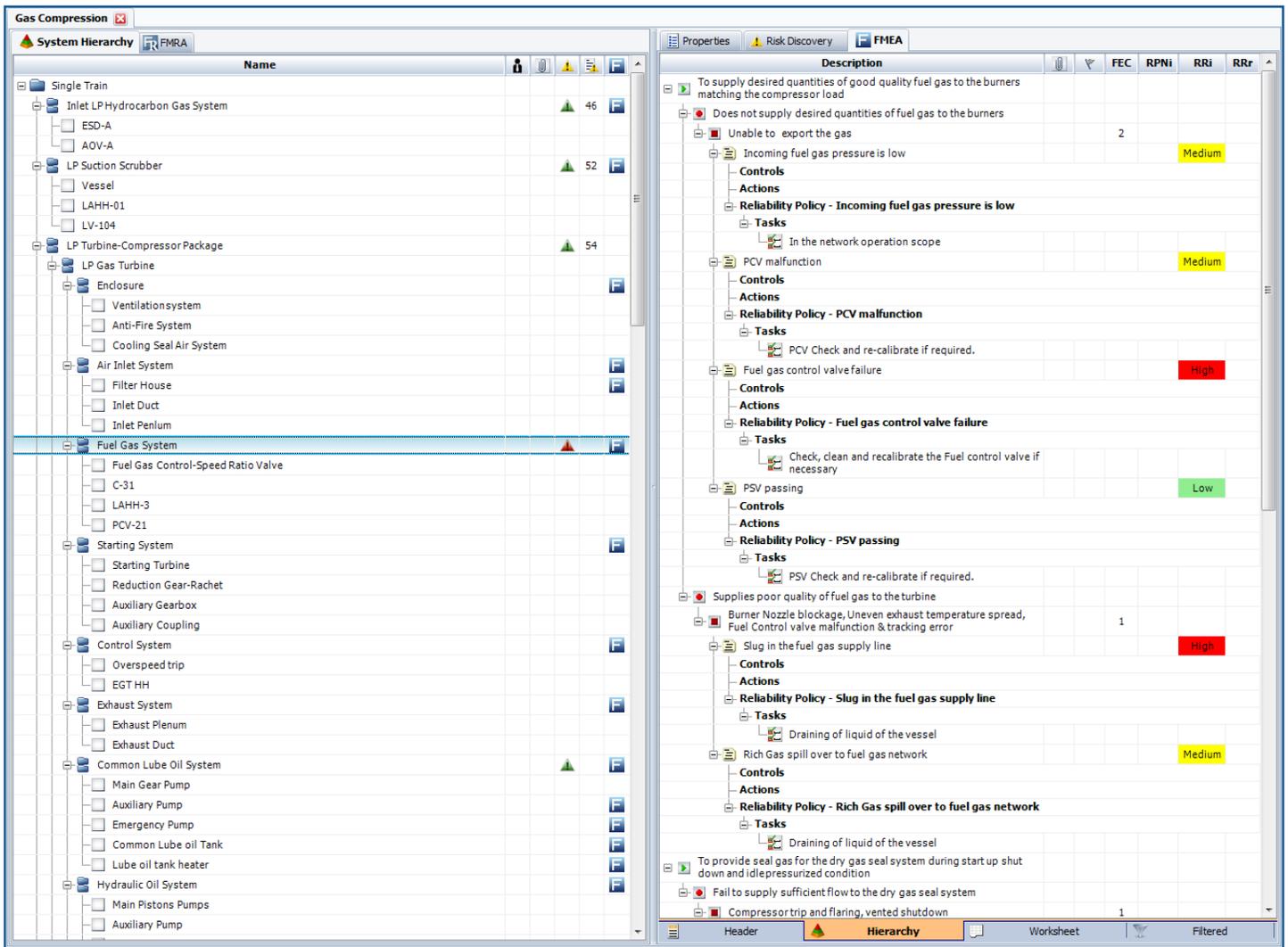


FIGURE 5 - FUNCTIONAL FAILURE ANALYSIS STRUCTURE IN RCM++

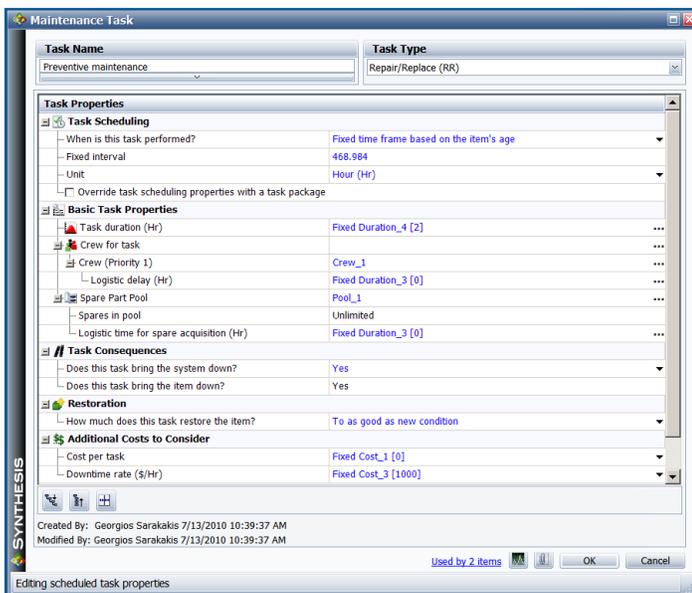


FIGURE 6 - MAINTENANCE TASK DEFINITION IN RCM++

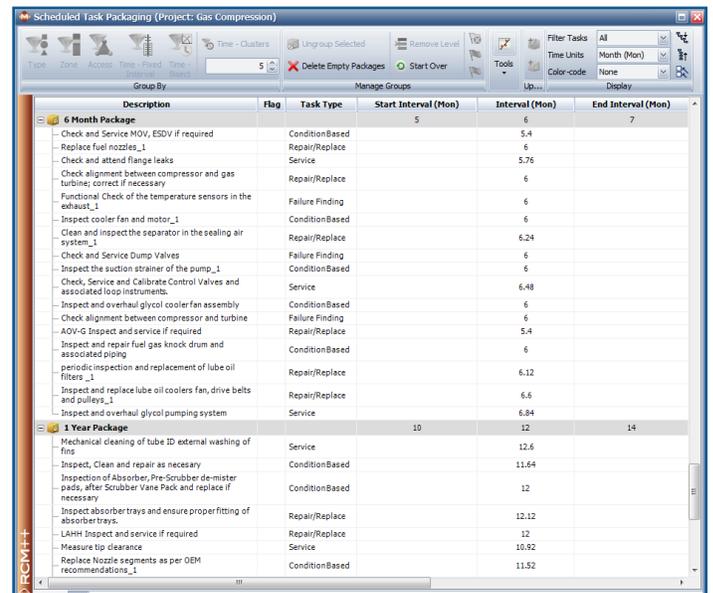


FIGURE 7 - TASK PACKAGING

It is clear that RCM++ will help organizations manage RCM projects more efficiently. It will guide you to roll out a project following RCM procedures either from published standards, or defined by your organization. It also has many built-in security features and project management utilities. For example, if a task assigned to a team member is due soon, it can automatically send a reminder e-mail to that person. More examples on using RCM++ can be found at [6].

6) Conclusion

In this paper, the general procedure of conducting RCM and the role of quantitative reliability analysis in RCM are discussed. Methods such as life data analysis, system reliability modeling using RBD and FT, and maintenance strategy selection using simulation were explained briefly. In summary, to have a successful RCM, we must integrate process management and quantitative reliability analysis together. Software tools developed in-house or purchased from other companies can help us manage an RCM project efficiently and conduct reliability analysis accurately as long as they can address both the process management and quantitative reliability analysis aspects of RCM.

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6. <http://www.weibull.com/basics/rcm.htm>

CERAMICS: A PATH TO IMPROVED RAM

Dr. Lloyd H. Muller, CPL

Abstract

This article proposes that a significant reduction in reliability, availability and maintenance (RAM) problems associated with reciprocating engines can be achieved through the use of heat resistant ceramics as an alternative to steel, a material that needs elaborate cooling systems to be functional. Because ceramics can withstand the heat associated with such engines, sub-systems such as fans, radiators, belts, pulleys, oil pumps, etc. could be eliminated, thus avoiding associated reliability and maintenance issues. However, because of ceramic's inherent brittleness, the violent shaking associated with a reciprocating engine must also be eliminated through a redesign. The author proposes that the Wankel engine meets that criterion.

Introduction

Manufactured products have come a long way from the wry Ford acronym of "Fix or Repair Daily." For marketing reasons, cars, motors, appliances of all sorts are now more reliable than ever before. For example, Kia Motors offers a 10 year, 100,000 mile power train warranty with other variations available to its customers.¹ The early 3,000 mile/6 month warranties the author remembers are simply a thing of the past because customers now want more.

This change in policy means that manufacturers are accepting many more of the maintenance responsibilities that owners used to handle. Consequently, to reduce the costs associated with this acceptance, manufacturers are making the reliability of their products as high as possible. After all, as shown by Figure 1 below, sixty per cent of a product's life cycle costs are tied up in operations and maintenance. So, it makes sense to reduce this maintenance cost as much as possible.

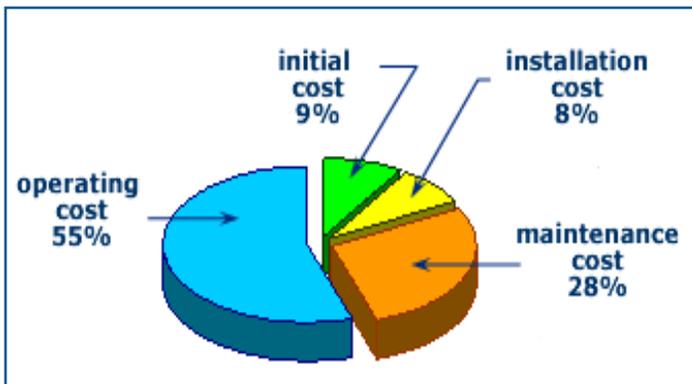


FIGURE 1²

1 Kia Motors America. <http://www.kia.com/#/warranty>. 19 October 2012.

2 www.corrosionfluid.com/life_cycle_management.aspx. 22 October 2012.

To achieve these cost reductions, the results of quality control processes, e.g., TQM, Six Sigma and Lean, world manufacturers are producing decidedly more reliable products. Computerized monitoring technologies and other fundamental design improvements are now able to monitor components on a constant basis and warn users of impending problems before disaster strikes; other advances in reliability are well known and need not be repeated here—the point is well made.

However, here is a question that might well be answered by future technologies in ceramics: what would the effect on reliability be if "stressed" components simply were designed out of the products? That is, if something doesn't exist, then it can't break. If it doesn't exist, it doesn't need repairs. Such is the proposition of using ceramics in place of steel in engines. Let's take a look to see what this proposal means.

Ceramics as an Alternative

Engines generate a lot of heat and need many cooling elements. Typically, combustion temperatures are about 3,600 degrees Fahrenheit (°F) in their cylinder centers.³ Since, typical steels will melt around 1425-1500 °F, a protective cooling system is mandatory.⁴ This system involves radiators, water pumps, oil pans and pumps, and piston rings. These are shown in figures 2 and 3 below.

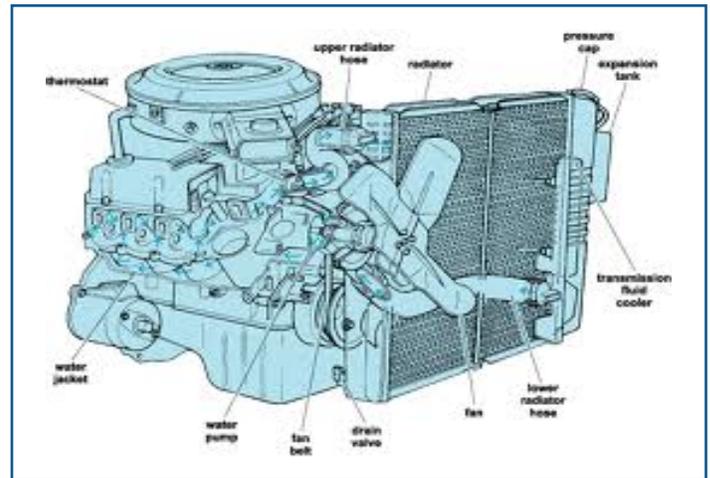


FIGURE 2⁵

3 Answers. http://wiki.answers.com/Q/What_is_the_average_temperature_inside_the_combustion_chamber_of_an_internal_combustion_gasoline_engine. 22 October 2012.

4 Metals Melting Temperatures. http://www.engineeringtoolbox.com/melting-temperature-metals-d_860.html. 22 October 2012.

5 http://search.aol.com/aol/image?s_it=topsearchbox.imageDetails&v_t=keyword_roll_over&imgsz=&imgtype=&imgc=&q=automotive+engines+cooling+systems+and+illustrations. 19 October 2012.



FIGURE 3⁶

Now, this cooling process has a cost - cooling the engine diverts heat expansion energy from torque output. Thus, the cooling process itself represents a loss of energy and operating the cooling accessories themselves require energy to operate which could otherwise be directed again to torque output. All this equals productive heat waste.⁷ Finally, and the point of this article, these accessories require maintenance that must be reduced through reliability improvements.

Now, imagine if all these accessories were eliminated. If gone, then, they wouldn't need maintenance. Their reliability design issues would simply disappear. Rings that provide combustion seals would no longer be needed along with a film of ever-present oil to reduce friction. Instead, ceramic pistons would simply fit snugly up against their cylinder walls to ensure combusting gases are not escaping but rather turning the crankshaft. Instead of cooling the rings and cylinder walls with heavy water and oil circulating throughout the engine, it would simply not be needed. Rather, the engine's heat would increase expansion and improve torque delivery. All this, of course, obviates the need for such things as radiators, fans, pulleys and belts, which further improves the engine's efficiency and eliminates maintenance requirements.

What could create this reliability improvement? Ceramics is offered as a plausible replacement to steel. It has heat resistance properties up to 5,500 °F which is well in excess of the 3,600 °F temperatures generated by engines.⁸ By manufacturing all of the propulsion components from ceramics, heat waste through the need for cooling would be largely eliminated. Reliability problems would become a non-issue as well as their attendant maintenance problems.

⁶ <http://www.automotive-illustrations.com/engines.html>. 19 October 2012.

⁷ Wikipedia. Internal Combustion Engine Cooling. http://en.wikipedia.org/wiki/Internal_combustion_engine_cooling. 22 October 2012.

⁸ Kopeliavich, Dmitry, Dr. Thermal Properties of Ceramics. http://www.substech.com/dokuwiki/doku.php?id=thermal_properties_of_ceramics&DokuWiki=e0a3d8e3a0e063c2d40d0f366893545c#maximum_service_temperature. 22 October 2012.

Wankel Engine Design

However, obtaining these advantages also creates problems. Specifically, as can be imagined in Figure 2, reciprocating engines have a pretty violent interior. Crankshafts, in particular, must be able to withstand the tremendous thrusts imposed by the plunging pistons. Resiliency that steel provides cannot be matched by ceramics; it is simply too brittle. What to do?

The answer to this conundrum may lie in the use of Wankel engines. Developed by a German engineer, Felix Wankel in 1929, its usage has had some applications to date starting with a working model by NSU Motorenwerke AG in 1959. A number of firms such as Porsche, Mercedes Benz, among others developed this concept, but Mazda introduced its version for mass markets on a sustained basis in 1967. They continued to market it until 2002 thereby proving it as an economical and technically feasible alternative to reciprocating engines.⁹ They discontinued utilizing the Wankel because it offered less fuel efficiency, in the typical passenger car environment, than a reciprocating engine.¹⁰ That being the case, let's assume during the remainder of this article that this alternative will meet the structural requirements for a ceramic engine.

With this assumption in mind, the following figures will show the intake, compression, ignition and exhaust cycles of the Wankel engine. As these stages occur, its torque output is directed by a cog assembly leading to a stable cogwheel that is connected to a propeller shaft. Note how the triangular piston revolves smoothly in a simultaneously lateral and circular (or eccentric) motion that has none of the violence of the reciprocal engine.

As the cycles are followed, you can see the engine can have either a spark plug or it could be designed for a two-stroke diesel engine. The latter option is really preferable from a reliability standpoint because neither an electrical distributor nor valves would be needed. As the piston passes the intake port, fuel is sucked into the cylinder's vacuum. Later, during the higher pressured exhaust cycle when the exhaust port is opened, the fumes are expelled.

What does this mean? The elimination of valves, cogs and timing chains; in short, less to maintain because the reliability problem has been eliminated. Also, another source of energy waste has been eliminated to further enhance power output from a given input of fuel.

Conclusion

In summary, this article proposes the idea that an application of ceramic materials to a tested Wankel design might offer a new way of producing reliable engines that offer increased power output and decreased maintenance requirements. These engines would be easily adaptable, initially, to such uses as generators and long haul trucks, which could deliver power at constant rpms and avoid the problems of less torque and fuel efficiency under heavy loads where reciprocal

⁹ Wankel Engine - Wikipedia. http://en.wikipedia.org/wiki/Wankel_engine. 19 October 2012.

¹⁰ The Last Mazda Wankel. <http://jalopnik.com/5921410/the-last-mazda-wankel-engine-has-been-built>. 29 October 2012.

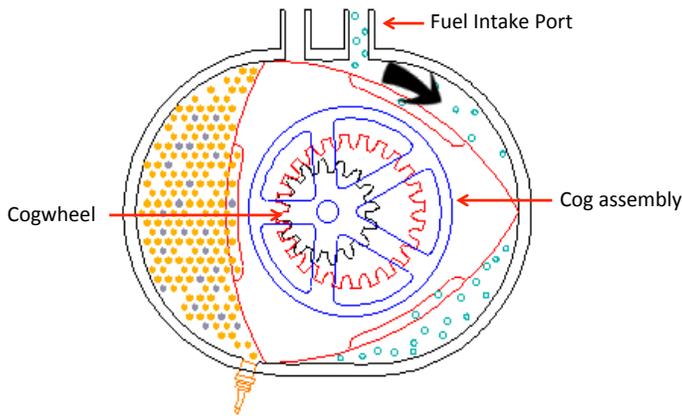


FIGURE 4 - INTAKE CYCLE

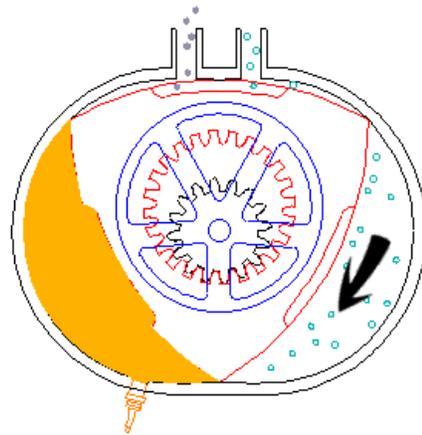


FIGURE 5 - COMPRESSION CYCLE

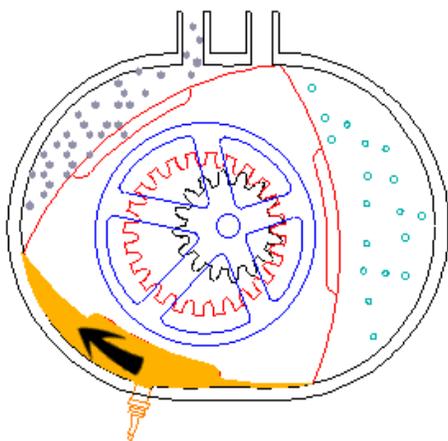


FIGURE 6 - IGNITION/POWER CYCLE

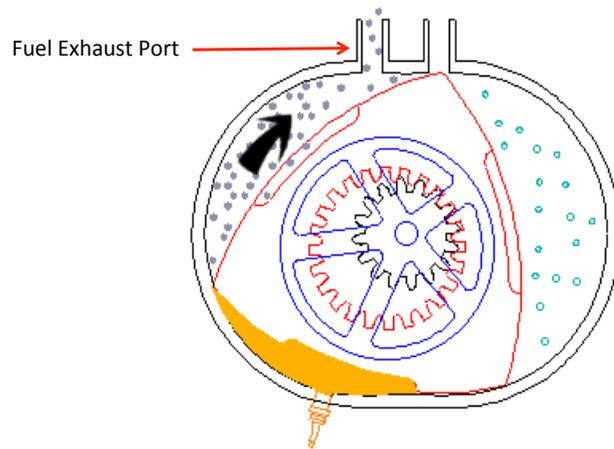


FIGURE 7 - EXHAUST CYCLE¹³

engines have an advantage. Specifically, in 1968, General Motors chose to use a large displacement engine for its Vega. They did so because it provided good low speed torque that would support slow city driving well. Two years later, GM experimented with a Wankel engine but as reported by the *Motor Trend* article, *The '75 Vega Rotary* "[M]ileage will be in the 16-18 mpg range. Compared to the normal piston [engine] Vega's 20 to 26 mpg, the whole rotary deal begins to look just a little less attractive, with what the price of gasoline skyrocketing..."¹¹ [By contrast, with generators and long haul trucks, steady higher speed ranges around 75% of maximum power would achieve much better results for rotary engines in terms of torque and fuel efficiency.¹² Of course, further research and development could expand the usage of this technology.

11 Wikipedia. "The Chevrolet Vega." http://en.wikipedia.org/wiki/Chevrolet_Vega. 29 October 2012.
 12 35 MPG RX-8. <http://www.rotaryeng.net/RX8-TC-eng3.html>. 29 October 2012.
 13 Wankel Engine. <http://search.aol.com/>

About the Author

Dr. Lloyd H. Muller is a logistician with over thirty-five years of experience in all realms of the discipline. He has been involved with all forms of transportation ranging from operating school bus systems to developing and directing strategic sea and airlift requirements for military operations. Management of petroleum, munitions, aviation supply and maintenance has also been among his responsibilities. His planning of logistical requirements and applications for worldwide contingencies led to the development of an automated real time system that managed all of the logistics resources in the Mediterranean during Operation Desert Storm. This system became a prototype for Air Force application. His last assignment was Deputy Commander of 16th Air Force, and he retired as a colonel.

Because of his extensive knowledge of logistics and almost twenty years of applying them in international environments, he has been involved in many diplomatic negotiations that gained significant benefits for both the United States and many of

the nations in Europe. Most recently, in behalf of the Defense Institution Reform Initiative (DIRI) Program, he assisted the Romanian Ministry of National Defence in developing their logistics plans.

Dr. Muller is also widely versed in the academic elements of logistics. Bringing his wealth of practical experience to education, he has taught at numerous universities located both in the United States and in foreign countries. He has written numerous articles and books on many aspects of the discipline. Among the universities where he has taught are the University of Maryland, Emery Riddle Aeronautical University, La Verne University and Middle East Technical University in Ankara Turkey. He has also been a logistics instructor for the United States Navy. Currently, he is an associate professor of logistics for Florida Institute of Technology. Besides these duties, Dr. Muller is a Past President of SOLE, The International Society of Logistics.

INTRODUCTION EXPERIMENTATION AT TEAM CORPORATION USING SINGLE AND MULTIPLE-AXIS VIBRATION: A COMPARISON IN TIME TO FAILURE

Chris Peterson

Abstract

This article is a test report based on data taken while running an experiment at Team Corporation (Team) on the Tensor, a shaker capable of both single axis and multi-axis vibration (Figure 1). The hypothesis for this test was that shaking on X, Y, and Z at the same time would have a different failure rate—presumably shorter—than anything calculated by the results of using the times to failures of the single axes.

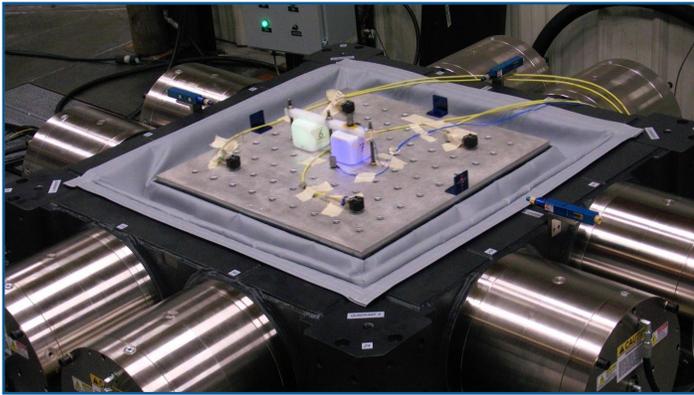


FIGURE 1 - TEST SET UP ON TENSOR

To make the results more traceable only one failure mechanism was looked at; the reaction of the LED. That does not by any means presume that an LED failure would be the only failure found. Other types would be expected. However, if the test was stopped as soon as any failure (or weakness) at all was found then all it would really show would be the likely first failure on each single axis. The idea was traceability on one particular failure mechanism.

The Test Team

I designed the experiment, representing H&H Environmental Systems, Inc., (H&H) and oversaw all testing. Joel Hoksbergen did the majority of the fixturing work and took care of the Tensor while Chon Mech ran the software, both gentlemen working for Team. (Both of them helped in the lab with the test set up, ensuring the equipment ran smoothly.)

Single Axis vs. Multi-Axis Vibration

Most test labs that run vibration have single axis shakers. In some cases they can be rotated so that a Z-axis shaker can change directions to be an X- or Y-axis shaker. Often this means a new fixture needs to be designed.

Combining shakers without a full understanding of what you are doing can lead to destroying the shakers. On a piece of equipment like the Tensor the same fixture can be used; a number of actuators are put into play. Therefore, when doing a test on an item that needs to be shaken in three exclusive orthogonal axes you can go right from one test to the next without ever moving the test item. You also have the choice of combining axes.

The Test Items

Twelve clocks were purchased from Amazon.com by H&H and shipped in advance to Team. (Figure 2)



FIGURE 2 - PACKAGE FOR MOODICARE CLOCK

The name of the clock is "Moodicare," described as a "glowing LED color change digital alarm clock." It was designed to soothe and relieve pressure and stress brought about by living in a fast-paced society. It goes through a cycle of seven different colors based on studies showing those light and color changes can have a soothing effect; these clocks were not built to be able to withstand this type of testing. (Figure 3)



FIGURE 3 - CLOCK WITH BATTERIES INSTALLED

Besides displaying time, the clock face presents a symbol showing whether the alarm is on or off, the date, month and day, and the temperature (user selectable between °F and °C). It comes with two AG13 watch style batteries for powering the clock. The user must add four AAA batteries to power the LED. (New AAA batteries were used for each test.)

The weight of the unit with all batteries loaded is 139 grams (4.9 oz). The external dimensions are 79 x 79 x 78 mm (3.1" x 3.1" x 3.0").

One item was used for comparison purposes only (a control unit) so that it would be easier to see if there were any changes to the units under test. It can be difficult to recognize faded numbers on an LCD unless two units are compared.

One unit was pulled apart so that the components could be identified, and was then later tested that way. It was decided to test a second unit that way, also. (Figure 4)

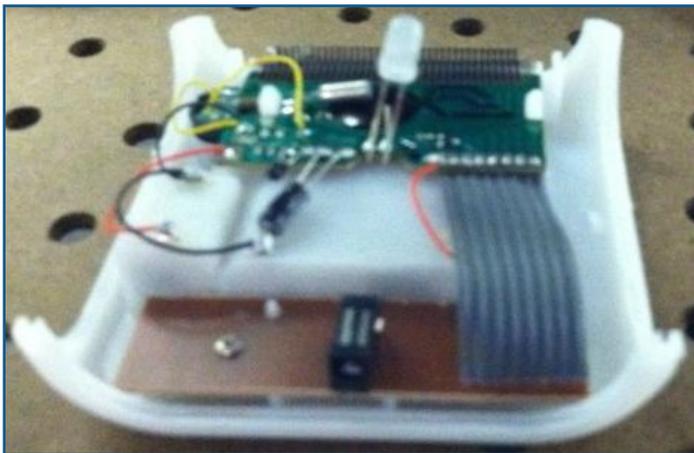


FIGURE 4 - BASE UNIT OF CLOCK

Each test unit was labeled with a piece of masking tape with a hand written number for tracking which test they went through. They were numbered 1 through 11 and C for the control unit.

The Choice of Test Items

While a digital alarm clock that changes colors to “improve mood” would not typically be carried in a military vehicle there were several reasons for using this as a test item.

1. Easily available
2. Non-proprietary
3. Inexpensive
4. A number of failure modes to look for:
 - a. The clock can be measured against other time keeping equipment to see if the timer slips
 - b. The LCD could blink, be partially visible, or go completely blank
 - c. The LED could flicker, lock into one color, blink on only once in a while, or completely stop

- d. There could be structural damage including cracks, flaking, wires loosening, etc.

5. Easy to fixture (a cube)

If defense hardware would have been used then there would be much less of a possibility of sharing results. Many of the components are similar to what would be seen in the field; an LED, an LCD, a circuit board, wiring, etc. Therefore the general findings should be applicable to similarly crafted items.

That being said, it is important to note that the test findings are for this particular unit. If something like a vehicle radio or an aircraft radar detection system would have been tested the times to failure and failure mechanisms would be different. However, I believe that the same basic findings would hold true.

The Test Facility (Shaker)

A Team Tensor 18kN was used. The Tensor is a “fully contained multi-axis vibration test system capable of precise control of all six degrees of freedom through a 5 kHz bandwidth. The system can reproduce real world vibration environments by simultaneously exciting all three linear translations as well as all three rotations.” The goal is replication of real-world vibration environments in all 6 DoF.

Figure 5 shows the side view of the Tensor through the control room window. The computer monitor seen in the bottom right hand corner was from the unit controlling the shaker. The large cylinders on the side are the Y actuators, and on the right hand side you can see one of the X actuators. The clock is mounted in the center of the table for the test.

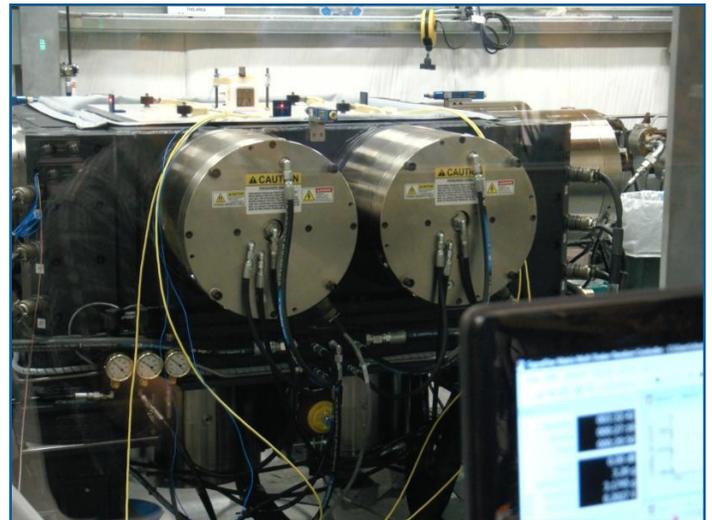


FIGURE 5 - SIDE VIEW OF THE TENSOR WITH TEST ITEM MOUNTED

The Tensor couples electrodynamic shakers to the moving element with hydrostatic bearings. It uses dynamic control of all six degrees of freedom to precisely reproduce the desired response.

In Figure 6, you can see two of the four X actuators (the other two being exactly opposite them), the four Y actuators on the sides, and the front two of the Z actuators on the bottom. The red panel

behind it is the power unit. The small blue plates attached to three sides of the table have target markings, and a laser pointer aimed at them allows for centering of the table before the testing begins.

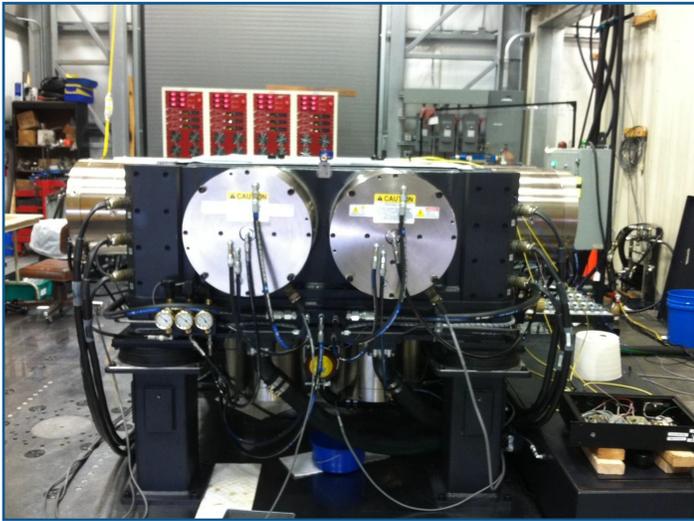


FIGURE 6 - FRONT VIEW OF TENSOR WITH POWER CABINET BEHIND

The Tensor unit has 12 single axis shakers, 4 in each of the X, Y and Z axes. For X and Y the shakers are paired directly opposite of each other. The shaker is capable of vibration in the following axes:

X – longitudinal

Y – transverse

Z – vertical

Roll is the rotation about X controlled by Z

Pitch is rotation about Y controlled by Z

Yaw is rotation about Z controlled by X and Y

Even controlling to a single axis on this unit is considered to be 6DoF because the other axes are being controlled to a very small level. (The shakers in the other axes are minimizing cross-axis motion.)

The Vibration Fixture

Fixturing was kept lightweight and simple. A piece of UHMW (Ultra High Molecular Weight) plastic was used as a cross bar held in place by two threaded rods with nuts. These were screwed down into table inserts next to each test item.

During the first test the clock moved because the nuts had come loose. A different configuration with the nuts was used and no further slippage was found.

Figure 7 shows how the fixture was modified to hold both a full assembly (clock) and a sub-assembly (base unit) at the same time for the comparative testing. A piece of the UHMW plastic was placed on the table itself with a metal plate that would hold down the edge of the base so that it would not wiggle free during the testing. While it was firmly in place no wear was seen on the base after testing which proves that it was not torqued down too tightly. While the metal piece comes very close to the components, it actually only touches the base.

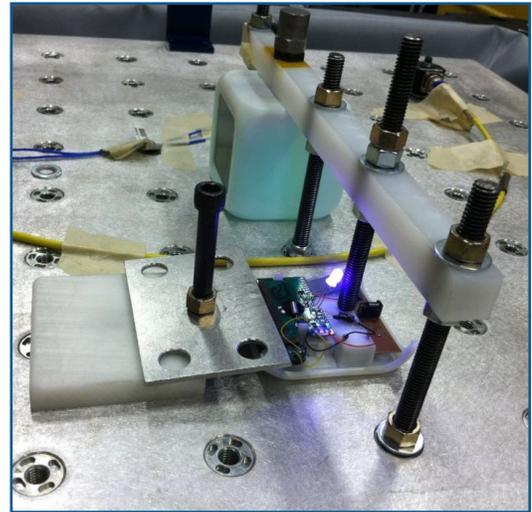


FIGURE 7 - FIXTURING OF FULL ASSEMBLY AND SUBASSEMBLY

Note that the response accelerometer is mounted on the fixture directly over the clock. It was not possible to affix it directly to the clock itself. The LED on the base was checked during the testing to verify that it never touched the threaded rod which would have skewed the test results.

Sensors

The accelerometers were from PCB Piezoelectronics. (Figure 8)



FIGURE 8 - PCB ACCELEROMETER FOR RESPONSE AND REFERENCE

The calibration is good through next February. Four Wilcoxon Research model number 993A tri-axial accelerometers for control were used for control, one near each corner of the table. A PCB single axis accelerometer was mounted in the Z axis on the fixture directly above the test item and a second PCB was mounted on the table nearby. We named the sensors “Response” and “Reference.” The control was from the four corner accelerometers so was done by input. “Response” was only to get a general idea of what the test item was seeing and “Reference” was to get the measurement of the table right next to the item.

Software

The software was written by Data Physics. It is called SignalStar Matrix, and the hardware for data acquisition and control is Abacus.

26 channels were used; 12 input for the tri-axial accelerometers, 12 output which are teed from the drives to amplifiers and the Abacus units, 1 input channel for the “response” accelerometer and 1 input channel for the “reference” accel. The operating system was Windows Vista. The data acquisition was at 0.625 Hz. All six axes and the rotational were controlled even if only one axis was excited.

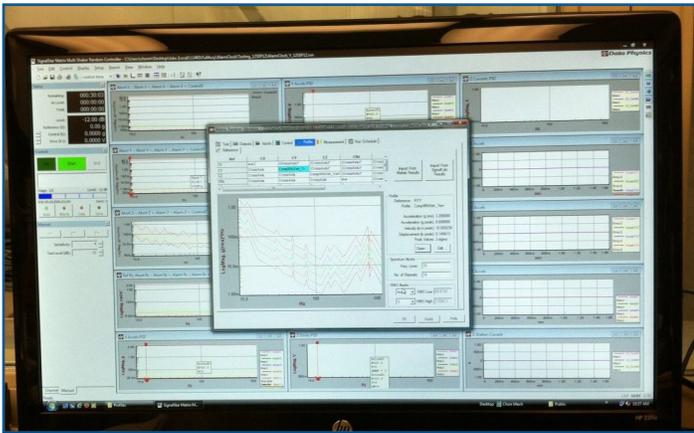


FIGURE 9 - SCREEN SHOT OF SOFTWARE WHILE TEST IS RUNNING

15 graphs show data at the same time and any of them can be opened (see Figure 9) to get a closer look at the data. The original profile is shown as well as the data from all of the accelerometers.

Test Lab Conditions

The lab was not temperature conditioned. The weather was nice and the outer door was sometimes open but it seemed to have no effect on the test. Temperatures ranged from approximately 71-80 °F. No humidity reading was taken. Before each test was started the table was leveled as indicated by whether the lasers were shining into the targets.

A pre-test was run at various levels. For the single axis tests and tri-axial without rotation it was -12 dB for 1 minute, -9 dB for 30 seconds, -6 dB for 30 seconds, then -3 dB for 30 seconds. For the tri-axial tests with rotation it was -12 dB for 5 minutes, -9 dB for 2.5 minutes, -6 dB for 30 seconds and -3 dB for 30 seconds.

Limitations

The main limitation was time. I had two and a half days to complete as many tests as possible so I needed to put a two and one half hour cap on each test. I would have preferred to have had the time to test to complete failure. Therefore, the first item to show signs of wear became what was used as the main failure mechanism.

The Test Set Up

Each clock had two feet and two push buttons on the opposite edge. (That was the manufacturer’s form of snooze button; by pressing anywhere on the top of the clock the buttons would depress and both allow you to “snooze” and the

LED would start its light pattern if it was not in the full ON position.) Because of these natural isolators we chose to mount the clocks upside down for the test for better contact with the table. (Figure 10)

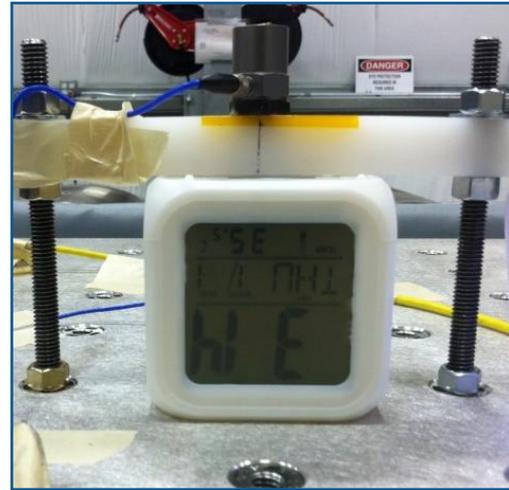


FIGURE 10 - FIXTURING SET UP FOR SINGLE CLOCK

Figure 10 also shows a close up of the fixturing with the “Response” accelerometer mounted just above the clock and the legs can also be seen. The “Reference” accelerometer is mounted just behind the test item. (The blue cable to it can be seen in the background.) Accelerometer cables were taped down during testing.

Mounting Configurations for Each Test

Items with the same color were tested together. (Table 1) Unit 5 was removed at 2.5 minutes and replaced because of LCD failure which was assumed to be close to an “out of box” failure. However, once the vibration was stopped the LCD started working again with no problems.

Types of Failures

One of the unexpected findings was that there was more than one failure mode for the LEDs. Not only would they flicker, and for two of the items completely go out, but another mode was that the colors would stop cycling through all seven colors. Red was the first color of the cycle, and when wear started to occur there would be times when two or three colors would cycle and then default back to red, then red only. Once in a great while it might change to green (the second color in the cycle) but immediately go back to red.

An unexpected failure was that the plastic of the case around the LCD screen would start to powder. This did not happen in every single test, but in the tests where it did there was a different powder pattern for different axes. In many cases there was also powdering on the AAA batteries. (Figures 11 & 12)

Another failure was the LCD screen. There were times when half of it would go blank, or stripes of it would blank out. In more than one case it went completely blank. With Unit 5

Test Sample Number	Axis	Notes
1	X	Mounted upside down
2	X, Y, and Z combined	Mounted upside down
3	Z	Mounted upside down, center of table
4	Z	Base of unit only, cover removed, right side up, slightly to the side
5	X, Y, and Z, combined with rotation	Mounted upside down
6	X, Y, and Z, combined with rotation	Mounted right side up
7	X, Y, and Z, combined with rotation	Mounted upside down
8	X, Y, and Z, combined with rotation	Mounted upside down, center of table
9	X, Y, and Z, combined with rotation	Mounted upside down, slightly to the side
10	Y	Mounted upside down
11	Y	Base only, mounted right side up
C	Control	No Test

TABLE I



FIGURE 11 - POWDERING OF CASE



FIGURE 12 - POWDERING ON BATTERIES

the screen went blank after just 2.5 minutes of vibration but once it was removed from the table the LCD worked fine and continued work afterward.

Test Schedule

The test schedule used was a modification of the ground vehicle vibration profile from MIL-STD-810G which was based on measured data. It was provided by Skip Connon of Aberdeen Proving Grounds, and our thanks go to him for his help. In his words, “the schedules were a higher frequency version of the Composite Wheeled Vehicle schedule from 810G to comply with the displacement limitations.” (See Figure on next page)

The only thing that was modified from this profile for the test was the displacement since the Tensor has low displacement. The acceleration factors were all met.

Test Interruption

There were times when the testing was paused either for facility adjustments or to get a closer look at the item(s) under test. The guidance from MIL-STD-810G on test interruptions was used and at no time was there an over test situation. (Figure 13, following page)

Rationale Behind Testing More Than One Item at a Time

Originally the intent was to test one item at a time. However, since there were extra clocks and it was a once in a lifetime opportunity I wanted to make as much out of the tests as possible. We had removed one cover from a clock to see what the internal components were, and I realized that by testing a sub-assembly alongside a full assembly that it would be possible to see if any of the components failed more quickly. (This could be similar to a Qualification test vs. a Design Reliability test). We did, indeed, find that the specific failure we were looking for occurred more

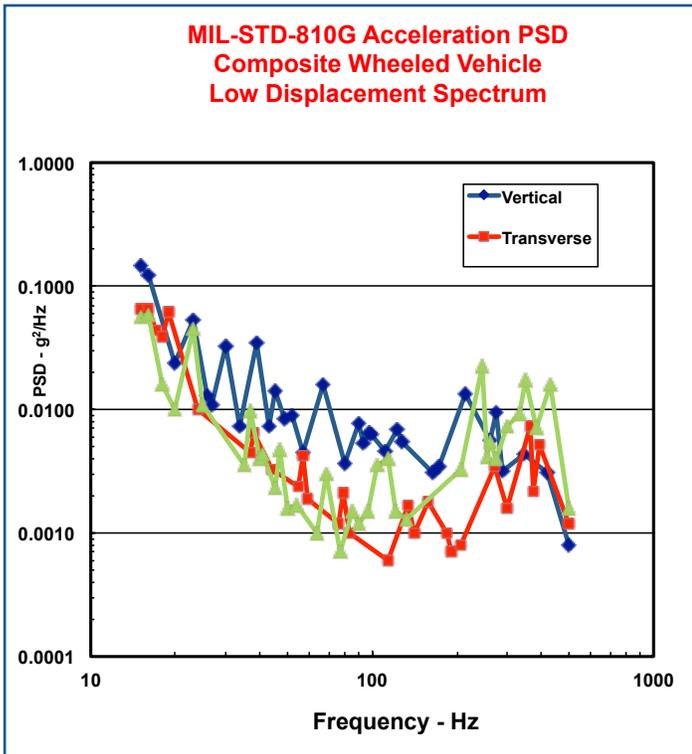


FIGURE 13

quickly at the sub-assembly level in the Z axis test—in roughly half the time—though not at all in the allotted time when we tested on the Y axis only.

In another case I made the decision to have one unit upside down and flush to the table while the other unit was right side up. We found a failure in the upside down unit but the right side up unit didn't seem to show any effects from the testing at all. Because of the two buttons acting as vibration isolators, no sign of failure was ever found in the unit sitting right side up. This gives an important reminder about test orientation. Anything that is shipped, even if in a box marked "This Side Up," has the possibility of ending up in a number of different configurations and one of those could be especially stressful.

In the X, Y, Z with rotation added test where I had two units in the exact same configuration but side by side, one was purposely set directly in the center of the table and one was slightly off to the side. I had been told by Team that I should see more energy in the unit off to the side, and indeed that showed flickering in the LED first. However, the full failure was instantaneous between the two units. That is a good lesson that knowing that something is weakening is still often not a valid indication of how much life is left in it.

One anomaly was found while testing unit #9. We needed to halt the test in order to make a facility adjustment and the LED for #9 had stopped. During the short resting period it started working again and continued to work until the end of the test when it stopped working completely and did not recover. An important lesson to learn from this is that while something might test out perfectly during a bench test it does not mean that it will

necessarily work well while in full operational mode and under environmental stress.

Every one of the clocks kept perfect time throughout the test. Each was started at its default setting, and when testing clocks in the past I've often found the internal timer would reset to the default of 12:00. That did not happen once during this test. (This is not a sign of any weakness of this test; only a side note on what could have been another failure mechanism.)

I needed to leave to catch my flight before the final test (Y axis) was completed. I took the control clock with me and one base (which still worked) to use as examples when I teach. The people at Team took the photo I'd asked for of the remaining ten units after test (Figure 14).



FIGURE 14 - TEN TEST CLOCKS

If you look closely you can see some of the powdering patterns on the cases (first and second units from the left on the top row and the first, second and third units from the left on the bottom row). Some of the LCDs are dimmer than others, and the unit on the bottom right is showing uneven fading. The time showing on the faces each started at the default.

Plotting It Out

This plot is based on time to first flicker in each axis rounded up to the nearest full minutes other than the bar showing when the LCD went completely out at 2.5 minutes on the X-Y-Z with rotation test. Keys to understanding the abbreviations in Figure 15 (See also Table 2):

- *w/rot* - with rotational
- *down* - clock was upside down (default position for all but one test)
- *up* - clock was right side up (done for comparison purposes)
- *center* - with two clocks on the table, this was the one in the center position (default position)
- *side* - clock was to the side of the center (done for comparison purposes)

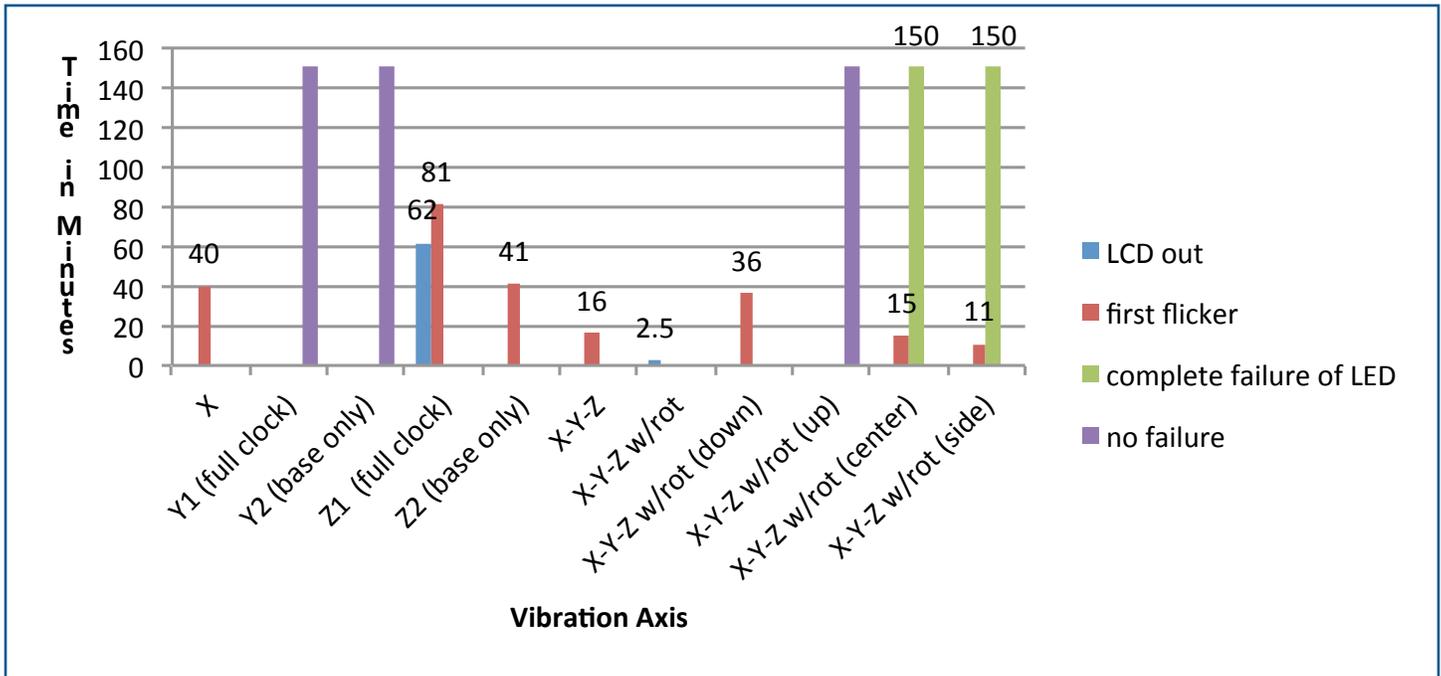


FIGURE 15 - TIME TO FAILURE VS. AXIS

X	40
Y	No flicker found at the end of 150 minutes
Z	81
X,Y, and Z simultaneously	41
X, Y, and Z with rotation	36 minutes for upside down unit (as others were tested), did not fail right side up)
X, Y, and Z with roation	Center of table 15 minutes, slightly off to the side 11 minutes
Time to Failure per Axis - Full Clock Assemblies	
Y	No flicker found at teh end of 150 minutes
Z	41

TABLE 2

Lessons Learned

- The hypothesis behind the test was proven out: using vibration to excite X, Y and Z axes at the same time will not easily correlate to any assumptions made trying to add single axis excitation numbers together.
- Orientation can definitely make a difference.
- Sub-assemblies will show weakness more quickly than full assemblies.
- Different samples using the same test schedule (profile) may have very different times to failure (presumably because of shifts in production).
- The failure being tested for may not be the first failure to occur.
- It takes a team to do the best testing (more than one set of eyes on the test and each with their own area of expertise).
- Testing done as an experiment gives latitude for changes in the initial test plan in order to find data that can be the most useful.
- Some things (such as the beginning of lights flickering) can be seen more quickly through a camera lens than by the human eye.

The Groups Involved

My sincere thanks go to the follow organizations and people for their part in this experiment.

Team Corporation of Burlington, WA was kind enough to allow me to come in and do the experiment. They build a variety of shakers with the Tensor being their newest model. While they have people on staffs that test the shakers to make sure that they are running correctly, they don't have a person who runs actual vibration tests. They allowed the experiment, as well as assigning me two assistants, with the agreement that all data would be freely

shared between us and with the request that I present my findings at Shock and Vibration Exchange (SAVE), no matter what my findings were. They treated me with warmth, respect and were a true joy to work with.

Skip Connon of Aberdeen Proving Ground, MD, an Army testing facility, is the one who provided the vibration schedule. APG does a great deal of ground vehicle vibration testing, and Skip is a member of the MIL-STD-810 Committee and helps to update each Change Notice and Revision as well as other specification work. The seeds of the idea for this experiment came after hearing a report of another vibration experiment that Skip was involved in, and he was the first to hear the idea and give his input. I truly appreciate his guidance.

H&H Environmental Systems, Inc., especially **Howard Cragg**. I do consulting work for H&H and they backed my efforts on this experiment. They supplied the test items, paid my travel, and allowed me to do both the experiment and the follow up reports on my consulting time. Among other things, H&H has a test lab and a training/mentoring program to help people to get the best out of their testing and they wanted to be at the forefront in investigating better ways of running vibration testing.

I'd like to give a special thanks to Norm Green, my strongest backer, who believes in me and thinks of me as his shining star. His faith in me spurs me on to never be afraid to try new things but to be everything I can be. This truly was a group effort and I am very grateful to all involved.

About the Author

Ms. Peterson is a reliability consultant doing the majority of her work for H&H Environmental Systems, Inc. She has been involved with testing since 1990. She is on the MIL-STD-810G editing committee, is Immediate Past President of IEST, is a Board Member of the RMS Partnership, RAMS® committee, and IEEE ASTR, and is in the ISO/IEC WG50. She teaches testing topics around the world and her passion is in helping others to do their testing right—to improve reliability, safety, lower costs, and make all parties the winner.

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