SMART PROJECTILES: DESIGN GUIDELINES AND DEVELOPMENT PROCESS KEYS TO SUCCESS

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The design of smart projectiles and their components is unique among ordnance design. Because of the unique nature of smart projectile programs, traditional methods of program management must be augmented by a strong understanding of the technical issues. The differences between conventional ammunition programs and smart projectiles are compared. Modeling and simulation techniques, as well as specific technical issues, are discussed. These are an inherent part of any successful smart projectile program. Specifics on **watch items** are given as are suggestions on proper focus of the development effort. The paper is seeded throughout with **lessons learned** from several major smart projectile programs and approached from the perspective of the projectile manager, system developer, and technical staff.

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INTRODUCTION

The design of smart projectiles and their components is unique among ordnance design. Small changes in seemingly unimportant items or processes can result in drastic declines in reliability. This is believed to be due to the complex nature of the item, lack of total understanding of the factors involved in gun launch, and the expediency required to successfully field an item. The adage "no change is a small change" is especially true of gun launched systems that rely on electronics to function properly.

Depending on the political situation, either schedule or cost is the primary constraint in the successful fielding of a weapon system. In wartime, schedule drives the program. In peacetime, cost is paramount. They are related, but usually when one is the driver, the other is in second place. Reliability is always third - that is, until production begins. There is an old relation between these thee variables in the gun launch business, which, like Newton's second law and the first law of thermodynamics, has NEVER been disproven. It is as follows

$$\text{Short Schedule + Low Cost = Low Reliability}$$

$$\text{Low Cost + High Reliability = Long Schedule} \tag{1}$$

$$\text{High Reliability + Short Schedule = High Cost}$$

Normally, the first option is always taken. This is not meant to say that the highest reliability for a given cost and schedule isn't attempted. On the contrary, great pains are taken to insure the highest reliability and, historically, cost does get traded for reliability to some degree at some point in a program. The issue usually is that small or infrequent problems are often neglected because the cause of the problem is not understood or it is (usually erroneously) believed that the problem itself is not big enough to prevent the item from meeting its reliability requirements. On every program the authors have worked on, this is always incorrect. Once again there is an adage that "there is never enough time or money to do it right, but there is always enough time and money to do it over." At least one program the authors worked on was terminated because it "did it over" one too many times. In development we accept reliability levels of around 60 to 70% and always say reliability growth through initial production will get us the desired 85 to 90% reliability. It is likely that we need to set our goals higher in development and not always be on the cusp of not meeting required reliability thresholds in production.

This paper attempts to describe the experiences and lessons learned of the authors on smart projectile program. It is believed that this paper contains the most practical set of guidelines to be successful in an engineering development of a smart projectile. These lessons cost the United States taxpayer large sums of money and should never be repeated - there will be enough new lessons to be learned in the future. At the U.S. Army Research, Development and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey there are two customers: the soldier and the taxpayer. To satisfy both, programs must be handled in the most cost effective manner and that is why these lessons learned are so critical.

WHAT IS DIFFERENT ABOUT SMART PROJECTILES?

Smart projectile programs are different from traditional ordnance programs in a number of ways. It is these differences that make this type of program more challenging than either a conventional projectile program or a missile program. It must be stressed that some of these characteristics are present in all programs; however, it is only in smart projectile programs that all of them are in play simultaneously.

Large Launch Loads

Large launch loads present a challenging problem for the engineer. These loads vary from 1,000 to 30,000 g in axial amplitude with a frequency content that has been arguably measured to date up to 50,000 Hz. It is this unforgiving combination of amplitude and frequency that make the design so challenging. An important misconception (that will be dispelled later) is that design for high inertial loading will mean success. Time and again it has been heard that "so and so part has been tested up to 100,000 g and has survived." Then, when said part is subjected to a 10,000-g gun launch, it fails. This is due to two things - the frequency content in the loading and the structural support received during launch. It is a grave mistake to mount a structure in a centrifuge with more rigidity than it will have during a gun launch and thus qualify a component to a g level. The dynamic response of the structure will win every time. More about centrifuge testing as an acceptance tool will be said later.

High Frequency Content

The gun-launch loading generated high frequencies through two mechanisms - balloting and set-forward (ref. 1). Balloting is the metal-to-metal contact of the projectile bourrelets on the gun tube brought about by tube curvature and the propensity of a projectile to spin about its principal axis. Set forward is the unspringing of the projectile as it leaves the muzzle of the weapon as described in reference 1. In both cases, frequencies have been observed on accelerometers well above 50 kHz; however, recent debates on the validity of the data at that high level are still ongoing. All agree that 20 to 30 kHz is reasonable, yet accelerometers experience unexplained failures in numerous tests that is believed to be due to a resonance excitation. This problem is very challenging as the instrumentation simply does not work reliably up to the frequency levels believed to be present in a gun launch. These frequencies are difficult to measure and therefore difficult to design out. Most importantly, the only way to date that one can obtain both the frequency and the loading levels are to fire a test article in a gun. Thus, a failure diagnosis is extremely expensive.

Stochastic Behavior of a Gun

The behavior of a given projectile/gun/propellant combination is stochastic. Good examples of this behavior are detailed in references 2 and 3. One of the challenges with smart projectile design is the a priori understanding of how a particular launch structure will behave when subjected to launch accelerations that vary, not only occasion to occasion, but also due to ambient temperature and tube wear condition. To date, it has been impossible to predict the launch accelerations with sufficient accuracy such that multiple round reliability is assured. The process usually involves development of a representative launch structure and testing several projectiles at various charges, in different tube conditions at various temperatures. This usually occurs in the first year of a contract so all parties are locked in to what they presume to be the launch loads only to find out that they were incorrect. As we shall see, the proper specification

of a system can minimize this effect. It is extremely difficult to account for the stochastic nature of the loading without resorting to statistics. Unfortunately, when the statistics are used with small numbers of firings and standard deviations are calculated, the loads appear to the inexperienced and extremely high. Eventually, loads are experienced that approach the levels predicted by the statistical analyses, but by that time it is too late to alter the design.

Expensive Prototypes

Smart projectiles are expensive. Their prototypes, being manufactured primarily before production lines are set up or optimized, are even more expensive. When instrumentation is added as a diagnostic, it is not uncommon for a single projectile to cost $120,000. This severely limits the amount of testing that can be done during the development phase of a program. For a program to be successful, instrumentation must be used, but often projectiles are fired without sufficient instrumentation to save money. It usually results in spending much more time and money later. The expense of test articles is problematic because of all the variables noted in the previous paragraph. Programs usually result to firing one or two instrumented projectiles at the corners of a test matrix. Sometimes this will work, but in some cases especially if a design id novel, the corners are estimated by engineering judgment. Several times on the Excalibur program this was insufficient. Another factor leading to the high cost of smart projectile development hardware if the large number of design configurations needed to successfully understand the behavior of the structure. With up to 30 or more design configurations per test (as compared to the one or two configurations when developing traditional projectiles), there is no learning and very little manufacturing repetition of a single design. This adds to the unit cost of smart munitions development projectiles.

Complex, Lightweight Structures

Smart projectiles usually contain a large number of parts. These parts are designed to be as light as possible yet successfully carry the launch loads. They include complex electronics which must be designed in light of the load that will be applies (ref 4). Because these systems are so intricate, there is rarely room the redundancy. This means that tens of miracles need to happen for a system to work. This presents problems for many reasons. In the early stages of a program, failures tend to be masked by failures that occur earlier in the sequence of miracles. Thus, many - sometimes more challenging - failures don't occur or are not diagnosed immediately resulting in what looks like test failure after test failure. Though modeling helps, the in-depth understanding of the interrelationship between failures is usually elusive and is missed in specification of boundary conditions. Also, modeling is normally done so as to increase run times. To enable faster run times, the program relies on the modelers judgment as to what is necessary in the analysis and what is not (refs. 5 and 6). Failures often occur even after a structure is modeled to an engineer's best ability. This is not a say that the model is useless. On the contrary, without the modeling, these programs are never successful. The statement simply means that a judicious application of modeling and testing is necessary for success. The sequence of fixing some failures and either unmasking or causing others is known as pushing on the balloon and is characteristic of highly complex, gun launched structures.

The complexity of the design and the number of functions it must perform is another factor which makes prototype testing so expensive and also leads to real problems when tying to diagnose failures. One of the real issues is that the experiment itself is both hard to design and gather data from. The data would be really useful when the desired outcome doesn't occur. Tests too often are expected to succeed and, when they don't we haven't gathered the data to effectively diagnose the problem.

Extreme Temperature Operation

The temperature extremes experienced by ordnance varies from -60° to +165°F. While this temperature range doesn't affect the metallic components very much [except through coefficient of thermal expansion (CTE) mismatches], it plays havoc with all elastomeric and potting materials. It was found on the SADARM program that 30 temperature cycles were sufficient to destroy the potted electronics. While this can easily be modeled, the challenge is to find the time and the funding to characterize the materials in question over the temperature range, both for strength as well as CTE. Many times projectiles that have been successfully fired at ambient temperatures experience failures at hot and/or cold. This is nearly always due to two things - strength changes in the non-metallic materials at temperature and thermal mismatched applying a pre-loading which is exacerbated by the launch loading.

Currently, there is a debate about why we specify and test to -60°F when many designs fired in a gun at that temperature would break up. It might make sense to specify the cold temperature closer the minimum operating temperature of the gun. Cold temperature seems to be the environment where we experience most failures in many designs. If this were accounted for early enough in a design, it might be able to be overcome.

The environmental issue is a dilemma in its own right; the difference between being able to survive environments and then later being able to reliably used as well as the ability to actually operate in any environment. Many times we have to make a judgment on what environment extreme is truly correct. Design criteria for safety always have a significant margin because of this uncertainty.

Extreme Handling Criteria

During the design phase of any projectile program, the design team usually gets wrapped up in the analysis and design of the projectile for gun launch survivability. The assumption usually made is that if the projectile can survive gun launch, rough handling loads will be much less severe. The real issue here is that vibration loading of the projectile, whether it is mounted in a vehicle ready rack or palletized, is low level over a much longer time. Nearly every program experiences joint failures in vibration because it is ignored in the design phase. Another area that is problematic is drop test and airdrop survivability. These are both historically difficult to model and it is only recently that acceleration loads in an airdrop, which because of its use as a resupply method requires the projectile to operate safely with no decrease in reliability, has been measured. Although drop tests are usually considered during a design, the testing doesn't occur until later in the development cycle, which can be a problem. It is usually the case where the stresses and loads on components within a complex projectile are almost always different (higher) than forces applied directly to the projectile. This is because the design and mounting and assembly in many instances locates them in cantilevered supported positions that amplify the forcing functions and are subject to harmonic frequencies in vibration. Instrumentation to measure these forces is problematic, although modeling techniques offer more success.

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Rugged Environmental Issues

Projectiles traditionally must be able to be stored outside of a container and vehicle for long periods of time. More and more end users are agreeing that smart projectiles should have protective containers; the requirement simply gets pushed onto the container designers. Leaving a projectile (containerized or not) outside in all weather is a challenging requirement. All of the statements made previously with regard to CTE mismatches are valid, but in addition dirt, sand, moisture, etc. all work their way into joints that may have opened. Additionally, there is usually a requirement for nuclear, biological, and chemical (NBC) decontamination that makes the joint design challenging.

Fracture Control

Throughout the Vietnam War, several projectile designs suffered in-bore detonations due to the presence of cracks in the metal structure generated during manufacturing and/or rough handling. This has led the U.S. Army to develop 100% non-destructive inspection techniques for all projectiles that contain a high explosive (HE) fill. The process involves performing a structural analysis followed by a critical crack analysis. The critical crack analysis uses fracture mechanics techniques to predict a maximum flaw size that will not propagate under setback loading. This data is then used to develop a critical crack map and standard for ultrasonic inspection, which delineates zones where cracks of a certain size may be present. Many times contractors who are new to the ballistic design field must be taught how to perform these analyses and inspections. Since many contractors are unaware of these requirements, it usually is not planned for in the contract proposal and must be added in later (usually after heated discussions).

Perception of Low Cost

The perception that a smart projectile will be low cost is difficult to overcome. Historically, projectiles have had so much design margin because the analytic tools used in their design were so crude. With modern numerical techniques, the designs have much smaller margins because anywhere another feature can be squeezed into a design it is. Customers, rightly so, want the most they can get out of a projectile design. The fact that design of these items is so complex and currently the quantities purchased are so small leads to very high costs. Additionally, production line discipline must be rigidly enforced because every component must be exactly the same as what was previously tested in order to account for the stochastic launch loading conditions. One of the biggest challenges to reliability is the use of commercial-off-the-shelf (COTS) electronics. The use of these devices is essential to keep the cost of the projectile reasonable; however, by leveraging commonality with the rest of the electronics industry control of the component design is lost. One of the biggest cost drivers is the lot failure of projectiles because some electronics manufacturer changed their process to make their item a fraction of a penny cheaper. This is always done without informing their customers who are unaware the change was made until months into a failure investigation and probably exists throughout the entire supply chain. It is important to detect these failures early to avoid significant and costly rework. In many of these cases, the government is not a major customer and often the change that affects us (such as high G loading) is NOT a consideration for the other 99% of customers. Therefore, it remains the responsibility of the Government and the prime contractor to remain diligent in using COTS items. The government most likely needs independent testing and analysis to validate continuing acceptable performance to our requirements.

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Expense of Testing

When test quantities are limited because of the expense of an item, the tests that do occur need to be highly instrumented. This drives the cost of the tests up and also requires that instrumentation be available and reliable. Many times the instrumentation is of high reliability; however, that reliability is not 100%, so some data loss must be anticipated. This is because the instrumentation was designed using the same analytical tools as the projectile itself and with it electronics suffers from the same drawbacks. Many programs have made use of parachute soft recovery system, but these are inherently unreliable and they require significant alterations of the projectile structure such that the dynamic response of the projectile is significantly different from the tactical item. Recently, a soft catch system (ref. 7) was installed at ARDEC whereby a projectile is fired into a long tube and exchanges momentum with a water mass. Though this testing requires a structural change so that the projectile nose is strengthened, it has been shown to be less severe than the dynamic changes required for a parachute system. The other drawback of this device is that deployable fins cannot be used in it unless they are below bourrelet diameter.

End to End Test Failure is Difficult to Diagnose

A smart projectile is usually filled with an explosive. Even if it is not, without onboard instrumentation, the projectile impacts the ground, invariably hits something hard and suffers damage which is difficult to differentiate from launch damage. In the extreme case, when a tactical round misbehaves and blows up or, if there is some failure where the timing of the explosion is in question, there is normally no evidence left to diagnose. In these cases failure mechanisms must be inferred, which can lead to painfully long failure investigations, some of which never actually prove the failure was corrected. In these cases the only solution is on board instrumentation and the expense must be accepted.

Controlling Design Definition

The design definition (i.e., the technical data package) of a smart round needs to be controlled from the earliest practical point. Regardless of whether this is done in a system contractor's facility or in a formal government technical data facility, it is important that the government understands and formally controls what is contained in the design. There are several unique aspects and characteristics that are typical of smart munitions and usually not considerations for other conventional munitions. The first of these is that there are usually many proprietary components for which the supplier will resist releasing the detailed configuration. To the maximum extent, this design must be documented since gun qualification of the product is a critical program element. This is compounded by the fact that many components are off the shelf and were never designed to be fired out of a gun. These components only survive gun firing due to the efforts of the designer in mounting them in the projectile. Therefore, it is essential that the internal characteristics (geometry, materials, etc.) are invariant from lot-to-lot and buy to buy. Because of this, once the design is qualified, neither the design nor the components can be changed. The point is that if you don't know the characteristics and features of the components there is no way you can either verify or conduct analysis on it. Even more so this applies to commercial components that the defense industry is not the major user of. The suppliers or their vendors, due to their lack of understanding of the gun launch environment, often feel free to implement changes which, if not identified and re-qualified will show up as failures during lot acceptance testing resulting in an entire supply chain filled with defective

components. Another unique aspect of smart projectile design is that the technology employed in many of the components and assemblies is usually cutting edge and thus subject to a 3 to 5-yr lifecycle, meaning that they will become obsolete and need to be replaced and re-qualified continuously throughout the life of the program. Rigorous configuration control will not eliminate these issues, but will identify what has previously worked and furnish a factual place to start the inevitable redesigns.

To provide the program manager some basis for anticipated configuration management activity the engineering change proposal (ECP)/request for deviation (RFD)/request for waiver (RFW) history for the life of the Copperhead program is furnished in figures 1 and 2. Figure 1 is a plot of ECPs on the Copperhead program over the lifecycle. In this figure, note the increased change in activity after about the fourth year of production. This was due mostly because of parts obsolescence.
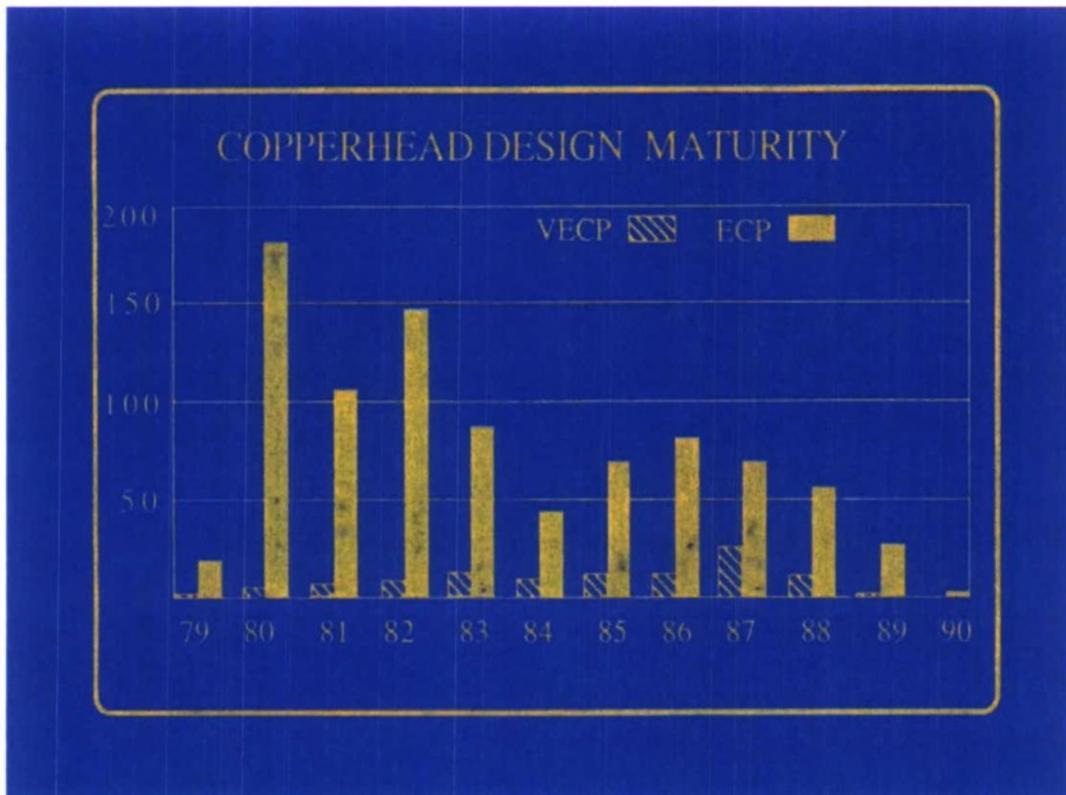
Figure 1
Copperhead lifecycle engineering change activity
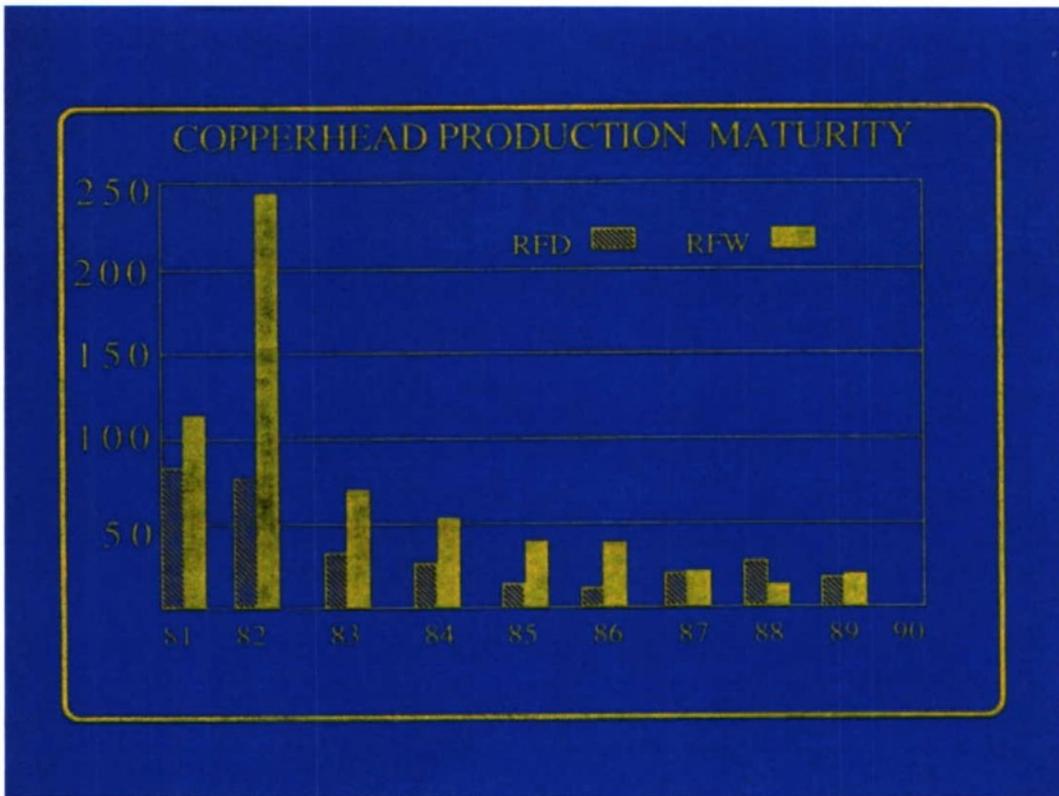
Figure 2
Copperhead lifecycle waiver and deviation activity

All of these difficulties are present in a smart projectile program. While none of them can be completely eliminated, there are methods for limiting their adverse effect on a program. The key to successful programs is then first - to be aware of the issues and second - to take steps that mitigate the risk. In these instances, the risk management process helps only if there are sufficient resources applied to a problem to lower the risk. In many instances, ineffective risk management approaches are taken where these risks are either accepted, have insufficient funding, time is applied to rigorously address the problem, or the risk is incorrectly assumed to be low.

MITIGATION OF THE RISKS

Over the course of the years, the development of technology has brought with it many solutions to the issues discussed in the previous section. When a program is planned and managed properly, the previous issues can be handled and their adverse impact minimized. In this section, we elucidate actions that can save a program thousands, if not millions, of dollars and improve the changes of success.

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Understanding of Gun Launch Loads

The first and foremost requirement for a smart projectile program to be successful is to have a complete understanding of the gun launch loads that he system will create. This is indeed the Holy Grail. This understanding will save huge amounts of time and money on a program. In some cases, this can't be wholly achieved because the dynamics of the projectile itself will be dependent on its unique structure. However, it is vital to program success that some representative, instrumented structure be fired to develop the launch loading across temperature, tube conditions, and charge zone BEFORE design work begins. One of the biggest problems with gun launch programs is that the Army puts a requirement into the solicitation package that states "must be compatible with all current and future gun systems." This statement is absolutely meaningless because compatible says nothing about the design loads that are needed by the engineers to actually design the system and no one except possibly God knows what a future system will even look like. It is imperative that the contracting office either have a launch data available from similar firings or fund the experiment to obtain the proper data. Without this information in the solicitation, much time will be lost either coming up with the loads after program award (and possibly the wrong contractor will be awarded the contract) or a design will be created based on an assumed loading. The latter is the worse of the two scenarios. Once a design is created based on incorrect loads, the tendency is to band-aid the design to make it work rather than scrap it and generate a more robust design – this is the concept of "polishing the turd."

Understanding of the launch loading includes an understanding of the effects of tube wear, temperature, and different propellant configurations, if applicable. This is generally an expensive endeavor. Up-front costs can easily be one of two million dollars. If the up-front costs are not paid, the bill can be (as on the SADARM program) hundreds of millions in repeat tests. One rather effective means of handling this occurred on the Excalibur program. Although it was implemented several years into the program, and therefore not as effective as it might have been, the idea was to create a loads document. This document established the dynamic loading and structural requirements for every subsystem in the projectile. The document was jointly generated by the government and contractor team, leveraging the experience of both. Even though it was established later in the program, it is the author's opinion that this document saved millions in test costs by unifying the design criteria and preventing needless failures.

A common reaction of projectile managers to the extremely high cost of instrumented firings is to tell the engineers to use their best judgment to design the projectile. Another approach is to rely completely on a model of the structure. Neither of these approaches has ever worked. While modeling is essential to program success, without the proper input loads, it is severely limited in its ability to predict reliable projectile function. The result of either of these tacks is failure, which normally follows this sequence: A design is created and falsely validated by some laboratory experiments that are believed to mimic the gun; after this, a flight test with a limited number of projectiles and insufficient instrumentation is completed successfully; this state is followed by a lull where engineering activities move forward in a rather rapid pace; the next phase is that a larger number of projectiles are fired to the updated design and begin to exhibit failures; each failure is fixed and new ones appear; the program either comes to its senses and begins instrumented firings or eventually loses funding and is terminated. This list of programs that followed this model continues to grow: SADARM, X-ROD, STAFF, Excalibur, MRM, etc.

The fact that gun launch loads are stochastic in nature complicated this issue. The probabilistic nature of the loading requires more tests be completed at each condition than would be the case in a deterministic case. The minimum practical number appears to be three tests at each condition. While this number is not statistically satisfying, it has some history of successful application as in the SADARM and Excalibur programs. Three firings always gave some appreciation of data scatter, while at the same time minimizing test costs.

The criticality of the understanding of gun launch loads prior to program start is never evident until several years into the program. It is essential that the launch loads, static and dynamic effects, be fully understood before design activities begin the earnest.

Realistic Schedules and Expectations

Many program issues are brought on by unrealistic (i.e., **success** oriented) schedules and expectations. Despite all of the rhetoric generated by program management courses and schools, it is extremely rare to find a program with a realistic schedule. Aggressive schedules can and should always be pursued; however, normally a schedule is developed that is unrealistically optimistic. As the schedule gets compressed because of slippages due to real events, smart decisions become less frequent. Tests that were independent of one another begin to get combined, hardware with known failures gets tested because it is already built, instrumentation gets removed from the testing because it takes too long to do and costs too much, and the designers are forced to make decisions to adapt hardware and squeak by. Once this process begins, it is extremely difficult to arrest and, like smoking, the adverse effects are as slow as they are inevitable. They result in the fostering of designs that are not very robust and will eventually fail to meet the reliability requirements.

This is probably the most difficult problem to combat from a program management perspective. It is usually caused by the desire to meet an urgent requirement. While urgent requirements must be met, it is very important to let people know when it cannot be done. It probably does more harm to the soldiers and taxpayers to spend all of the time and money on a program that won't work. This is not to say that challenging schedules shouldn't be taken, on the contrary, the mission of the design team is to do the **impossible**. Acknowledgment that the schedule is difficult must be made and realistic planning must be maintained. If a highly aggressive schedule is embarked upon it must be managed to avoid rushing around when a slip occurs. This management by panic must be controlled by rapid and disciplined failure investigations, sound redesign efforts, and avoiding decisions based solely on getting back on track.

Slippage events are generally of two types: production related and design related. In this sense a production related slippage is the inability to build hardware on time for a particular test event. A design slippage is a test failure. A production related slippage is very difficult to control and correct. Historically, once hardware is late, it is late. Occasionally, overtime and expedited shipping can alleviate some of the slippage, but there is a danger here. When a design is complex, many times in a rush to get items build, discipline is sacrificed. This results in failures which are no brainers or hardware built to wrong configuration or revision level. The probability of this problem is greatly increased by the large number of configurations and the high frequency of changes during development of smart projectiles. Examples of these types of failures are lack of excessive application of or insufficient curing of adhesives missing inspections or components improper torque, etc. If these are to be avoided visibility of the manufacturing process is essential.

For a design related slippage, it is essential that the best design fix be implemented as soon as a failure occurs, because if a sub-optimal fix is implemented, the margin may be insufficient and failures will reoccur later in the program. The reason for this is that only statistically significant failures occur in small test samples. After a fix is implemented, the frequency may be reduced to a level that will only be seen after a large number of firings. Many times a fix is chosen on the basis of schedule. This is usually bad. Rework of components to meet schedule is far more risky than building new hardware. Many times components or their underlying assemblies are damaged when they are removed or reworked. Cables get cut or abraded, parts are damaged when epoxy is removed; the list goes on and on. A program manager must always understand that band-aid solutions will almost always cost them more time and money in the future than fixing it right the first time.

Use of Modeling

All of the project management schools use the buzz words **modeling** and **simulation** to describe general activities involving computational analysis of everything from structural dynamics to force on force effectiveness computations. Many times programs only model things because they are supposed to **by the book**, not because they see any real value in it. In these cases, the minimum modeling of the design is done (or none at all) and the program relies on testing to develop the item. This always results in excessive costs in the long run. In every failure investigation, the authors have been involved in, once the modeling is completed properly, issues with the design become obvious and corrective actions become relatively easy to evaluate. The only time modeling becomes useless is when the loading conditions are not well understood. Thus, modeling without understanding the loading correctly is strictly limited.

There are challenges with modeling activities. The concept that modeling is inexpensive is a fallacy. Modeling costs a great deal of money. This money is required for gathering loading data, obtaining good materials properties, instrumenting test hardware, and actually building and running the models. In the long run, it is much cheaper and quicker than the test-fix-test approach. When a program manager looks at modeling costs, their first thought is to reduce the amount done. This always backfires. The modeling should be limited to that which will drive design decisions, but decreasing the budget simply because it looks expensive leads to later problems. This leads to the second challenge - coordinating all of the modeling activities. This is always a challenge because of the numerous disciplines involved and the large number of twists and turns that develop as models lead the designers one way or another. Keeping the modeling team focused on the final goal and stressing the need for models that are good enough should be the job of a **modeling Czar** whose mission is to coordinate all of the models with the design activities across the various organizations. This is never an easy job because modeling teams have a tendency to get wrapped up in details that can many times bring an otherwise useful analysis to a halt. The key is to appoint a **Czar** who can recognize when to cut the solution off at the 80 to 90% accuracy point.

Modeling has to be done rapidly. Many programs have failed because the build of hardware went forward faster than the modeling activities to meet an unrealistic schedule. Thus, the modeling must pace the hardware build and therefore must be done as quickly and accurately as possible. This is usually accomplished by giving the modeling task to the organization that has the most experience in the specific area. Inexperience required excessive time to be lost as the learning curve is climbed and maximizes the possibility of errors. The challenge associated with this is that some organizations (both Government and contractor) are quite headstrong and must get over the fact that there are others that may be better at particular analysis than them.

Meetings

Face to face and teleconference meetings are an important part of any program. It is always better to have personnel meet face to face than use the phone or communicate via email. It is the only way people can be assured that they are all on the same page. That said, the use of group meetings should be minimized. Meeting with large groups of people require significant amounts of time. It is the authors opinion that an optimum meeting schedule consists of a daily meeting of ½-hr in length with the entire team to get any issues out on the table and one weekly 1-hr meeting to discuss overall program issues. Time spent beyond this is usually wasted. If more time is needed on a particular issue/subject that does not involve the entire group, the meeting chairman should suggest the interested parties continue the discussions OUTSIDE the main meeting. Of course, there are exceptions such as design reviews, failure investigations, etc.

Design Reviews

Design reviews are an important part of smart projectile programs and should be treated as such. Many times, however, they are simply rushed in order to meet a schedule and the result is an ineffective review. The review needs to be focused and well organized. There are many items that are overlooked during a review that need particular attention in smart projectile programs. One such item is a comparison of drawing tolerances to design calculations or models. In many programs, either particular calculations or models are so sensitive to certain parameters that a particular tolerance being at one end of its allowable range has implications to system reliability. It is obvious that every tolerance cannot be examined in this manner, but the engineering staff should at least have ranked all of the features prior to the review and gave some indication of which ones are most important. If possible, all of the major, minor, and critical characteristics should be identified. Another item that should be checked at design reviews is that all of the changes that were made in the design were accounted for by modeling or calculations. Many times designers will make a change, assume it is small, and forego additional calculations. This usually causes problems unless the change is so minor that they are unnecessary.

It is important that all teams be represented at these design reviews. For example, many times the test personnel notice recurring issues at tests that go unreported or are documented and forgotten about. These can be important indicators of design weaknesses that eventually blossom into full fledged failures and of course all issues should be assigned to specific individuals along with required due dates.

Classification of Characteristics

As will be described in a subsequent section, classification of characteristics into minor, major, and critical safety categories is an important part of a projectile design. Many times contractors, especially those not familiar with projectile programs, accept contracts without knowledge of this process and both sides are rudely surprised when the requirements for 100% automated inspection on safety critical characteristics comes up. For true success, the contractors should be made aware of the requirement that 100% automated inspection will be required on all characteristics that, if out of specification, can potentially cause damage to the weapon or injury to the gun crew.

In several instances some characteristics fell into a gray area between safety critical and major. Also, some characteristics simply do not lend themselves to automated inspection. In cases like this the characteristics were many times labeled **special** and either given a 200% manual inspection - that is inspected twice, each time by a different person - or inspected 100% by some semi-automatic means.

DESIGN WATCH ITEMS

Many attributes and technologies used in smart projectile design occur repetitively. In some of these cases, the design rules are straight forward. In some cases, the same problems occur on every program. This section is intended to highlight areas where problems have occurred and are known to reoccur and provide some means of anticipating and managing the issues.

Cables

Cabling is a necessary part of a smart projectile design. In many instances, critical electronic components are separated from one another by significant distances and most of the time the only means of electrically joining these components is through cabling. The issue with cables generally stems from the fact that they are flexible and their mass, under gun launch, and spin loading is to large and badly distributed for them to support themselves. Therefore, structural adhesives are relied on to secure the cables to stiffer structural members. This attachment method is very sensitive to production variations and each issue and its remedy, in turn, shall be addressed.

Cable Bending

Often in a design, it is necessary forced the cables to bend over structural components. This can cause failure of electronics through cutting and/or over extension in gun launch, vibration, or even thermal cycling. The only way that these bends can be successful is if the bend is gradual enough (this is unfortunately very subjective and cable dependent) and when the surface over which the bend takes place is properly radi used. Chamfers generally are insufficient because the edges can cut through a cable during vibration or at launch. Additionally, sufficient clearance needs to be present to avoid outright cutting of the cable. The use of templates for routing of cables insures that each is routed with the same slack and removes much of the variability.

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Cable Bonding

Long, free floating runs of cables must be avoided because of the inherent weakness of the cable in supporting its own weight. To avoid this, the cables must be attached somehow to more rigid members (keeping in mind that NOTHING is truly rigid in a gun launch). This attachment commonly uses structural epoxy. Application of the epoxy is the key to its success. It must be within its documented shelf life. There should be work instructions to the operated with pictures of what too much epoxy looks like and what too little epoxy looks like. This is to prevent over application that results in too much mass added to the cable or too little application that results in insufficient strength. Since epoxies are usually applied by eye, this is a key operation. This surface must be free of contaminants and sufficiently abraded to provide a good bonding surface. If either of these conditions are not met, the strength of the bond will be degraded.

Rework Near Cables

Rework, in the vicinity of cables must be avoided at all costs. Many times tooling nicks that are not visible or obvious result in cable breakage or corrosion. If rework must be performed, adequate protection to all cabling must be provided for and close inspection of the cables (not just electrical checks) must be implemented.

Connectors

In the Copperhead projectile, the team eliminated the use of almost all electrical connectors with a process called thermal compression bonding. This process involved the use of high temperature and pressure anvils to literally weld the copper conductors of ribbon cable to each other. This simple but elegant process resulted in three major positive elements: it saved a large amount of hardware costs (connectors are extremely expensive); it eliminated the concern of the shelf life of connectors maintaining continuity in storage over an extended period of time; and by providing a pigtail in production, it allowed for test of the item through the bond, which cannot be done using connectors. The pigtails were then trimmed off after test and before final assembly. This best practice process has not been continued to the detriment of subsequent items.

Potting

Potting is commonly used to encapsulate electronic packages for their protection and structural support during gun launch. There are many issues associated with potting, and if it can be avoided in a gun launched system it should be. This is because failures in a factory acceptance test almost always result in scrapping a potted assembly. When it must be used, the following issues must be dealt with.

Unknown Material Properties

Many times manufacturers list material properties at optimum conditions. Other times there is no data. Potting materials used in gun launch applications invariably carry some load. The way the load is transmitted through the potting is greatly dependent upon its material properties. If these are unknown, the design will generally fail at some point. It is generally recommended that when potting must be used that they be confined to simple geometries near the centerline of the projectile to minimize strain gradients.

Variation in Material Properties over Temperature or Strain Rate

This is a serious problem because many times the material properties at even room temperature are unknown or depend upon the mixing of two or more ingredients. The only solution is to create dog bones of material when a batch is prepared and test it in an independent lab. This usually only has to be performed once at all of the appropriate strain rates and temperature. After the material is initially characterized, it is usually sufficient to test every lot at room temperature only. The design should then be modeled with the potting fired at temperature extremes.

Temperature Cycling

Hard potting usually fails electronics when subjected to thermal cycling due to a CTE mismatch. This can be mitigated somewhat through use of either a softer material or the addition of a conformal coat to the electronic boards and components to absorb some of the movement. This can be problematic if too soft a material is used, the geometry is complicated, or the conformal layer is too thick or thin. A good test of a design is to see if it survives, on its own, 30 cycles from +160°C to -45°C. If it survives this with full functionality and no cracking or separation (irrespective of functionality), there is a good chance that the design is robust. If it fails, changes must be made.

Bar Coding and Stickers

One of the issues that comes' up with potting is that it can be somewhat sticky. There is then a tendency for organizations to attempt to use it like an adhesive. Experience tells us that when we would like the potting to adhere to a surface it most certainly will not, and when we would like it to release reliably it will stick better than the strongest epoxy. Many electronics have identification stickers or bar codes attached to them. These labels form places where the potting will either stick or release (whichever is least favorable to the design). Cleaning of surfaces to be potted is essential for some amount of repeatability. Success has been achieved with grit blasting of surfaces and the application of a primer material.

Geometry

If potting must be used keep the geometry VERY simple. The best results have been achieved in fuzing (through FAR from perfect results), where the potting is confined in a structural can, on the projectile centerline in a right circular cylindrical geometry.

Modeling

ALWAYS model the potting in both the softest and hardest configurations and both with no adhesion and total adhesion. This is four modeling cases. If certain critical (to reliability or safety) components are present, it is sometimes useful to model these with and without adhesion locally as well.

Critical Crack Analysis

Over the years there have been many incidents in qualified, fielded projectiles where either cracks induced in heat treatment or generated by rough handling have caused catastrophic failures (ref. 8). Many times contractors new to ordnance as well as inexperience program managers within the Government are unaware that a design can fail by an inherent flaw that will not be screened out by visual inspection methods or standard quality checks. It is because of this potentially catastrophic behavior in materials that a critical crack analysis is performed and proper inspection methods must be established. This is not a negligible expense both on the analytical side as well as the recurring inspection costs and must be addressed early in a program.

Successful and cost effective designs involve the use of materials with good fracture toughness. Fracture toughness is a property of the material and its processing that determines the propensity of a crack to propagate after it is initiated. The greater the fracture toughness, the more resistant the material is to propagation of the crack. The fracture toughness is only half of the story. The other half requires the stress in the part to be known. Generally, a trade off is made to balance the maximum stress with the lowest allowable fracture toughness of the material. Current analysis techniques involved determining the maximum stress in the material in several zones. Once these zones are determined, critical flaw calculations are made to determine the maximum allowable crack size in that particular zone. A standard is then made out of a representative part in the state at which the inspections will be performed. Cracks are machined in each zone in the longitudinal and transverse or whichever applicable direction is needed by electro-discharge machining (EDM). These cracks are generally one-fourth of the critical crack size. The standard is then used to set a threshold in an automatic inspection process.

In some cases, it is impossible to automatically inspect the part. In these cases, 200% inspection is used with magnetic particle or dye penetrant methods. The danger of these methods is that they are only capable of detecting surface flaws and are subject to human interpretation. This is thought to be better than doing nothing but still involves some risk. These inspections should always be performed after heat treatment of the material since this is the most likely place in the production process that cracks will be induced. On many aluminum parts this can be at the bar level, but on steel parts it should definitely be immediately after the final heat treatment before protective finishes are applied.

The best design practice involves performing a critical crack analysis using the worst properties available. This is true for both mechanical strength parameters such as yield strength, tensile strength, and % elongation as well as fracture toughness. Always remember the two go hand in hand. The stress analysis is always performed dynamically at PIMP +5% loading with the worst case balloting loads. Many contractors will push to use nominal fracture toughness or textbook values. This should be avoided at all costs because variations in production processes and suppliers invariably causes the analysis to be redone again and again due to material coming in with fracture toughness below these values. The results ends up being rejected material anyway. It is best to do the work up front and get the design robust than fall into the false sense that yield is going to increase nominal values are specified in the TDP.

Heat Treatment

Heat treatment of materials is the largest contributor to the materials behavior under launch and impact loads. NEVER use hardness testing as a measure of material properties. Its value is only useful to determine whether a part was heat treated or not. Heat treatment of finished metal parts can be very tricky. In general, the more complicated the heat treatment, the more likely there will be a problem. Locations within the ovens or cooling container make a huge difference in whether a part will be accepted or not. Because of this, mechanical test specimens should be taken out of actual parts from various locations within an oven for every oven batch. If actual parts cannon be used, coupons made to represent the material geometry as closely as practical should be used and located at various locations within the oven.

Changes to a heat treat supplier should be tracked diligently. When a new heat treat supplier is brought online, a new qualification should be done. In every program in this author's career, a change in heat treatment to save a few dollars ended up costing hundreds of thousands and the original supplier was used anyway.

Hydrogen embrittlement needs special mention. This is the propensity of a steel to become brittle when exposed to hydrogen over time. It is exacerbated by stress applied to the component (like a bolt pre-load). Without proper heat treatment, it can be experienced in structural housings, but even more important is the avoidance of hydrogen embrittlement in fasteners and screws and bolts. In one program, it became so important that a special test per lot of material was ordered because of failures. The only way to totally eliminate it is to have detailed control of the heat treating process.

Friction Dependent Designs

Many times either intentionally a design becomes dependent upon friction. These designs must be avoided at all costs, but when they can't there are some things that can be done to minimize the risk.

Friction coefficients vary greatly in the literature as well as in design concepts. Under the influence of gun launch, there is a tendency for surfaces to deform so that classical coefficient of friction can either increase or decrease. If the surface flattens or gets smoother, the coefficient generally decreases. If the surfaces nest, the coefficient increases. Although the normal force may be tremendous sometimes it is simply insufficient to prevent motion of the surfaces. Cold welding, which is the tendency of two very flat surfaces to lock together if pressed, has never been proven to work in a gun to date. Different material combinations have different, and most often unknown, friction coefficients. Corrosion changes the friction coefficient over time. Rate of loading affects the friction coefficient by either increasing or decreasing it, depending on the two materials in contact.

To deal with this, all applicable analyses performed on a projectile should be run twice. One run is to be done with a zero coefficient of friction, the other with an unrealistically high value (or surfaces glued together). Over many programs, it is difficult to reliably maintain a friction coefficient and the only means known at the time of this writing to inspect it are either visual or with a profilometer. Both methods are inadequate and costly to implement. This is even more problematic if the friction coefficient is a safety critical characteristic.

Past programs have specified certain knurling dimensions, surface roughness, and the requirement for a surface to be clean and dry. In practice, however, problems arose when lubricants or even adhesives were used near these surfaces as they tended to find their way onto the friction surfaces and, under the influence of gun launch loading, drop the friction coefficient. If the friction coefficient must be relied upon then its effects and variation must be understood. Testing as close to the applicable loads and rates must be done and a distribution must be established. Finally, proper inspections must be in place at the production facility to assure that the variation falls within the design limits.

Flexure of Printed Circuit Cards

Smart munitions require electronics in the form of components attached to printed circuit cards. The design of the printed circuit cards must be such that they are robust enough to survive some flexure and reliably operate. In general, the deflection and curvature of the circuit cards must be limited so that the internal connections such as via do not fracture and so that the components soldered on to the cards do not disconnect by either solder pad lifting or component fracture. The use of ball grid array (BGA) technology has actually helped this problem as the solder ball seem to be more structurally robust than their wire bonded counterparts. In practice, there is debate about whether board curvature or deflection is the attributes that cause failure. Many successful designs have resulted when defections were limited to 0.005 in. Additionally, hole patterns and component layouts have to be considered to avoid creating a critical stress plane in the circuit card. This may seem extreme, but it is known to work. Regardless of the failure criterion chosen, it is generally a bad idea to allow any structural load to pass through the circuit card. This is because, whether potted or not, the electrical connections in the circuit card itself as well as between the circuit card and discreet components are not designed with load carrying capability in mind. Supporting circuit cards with more rigid structures allows the load to pass around the card and to the other load carrying structures in the design. When a design is such that it allows circuit cards to be populated on one side only, it is desirable to back the circuit card with a relatively stiff yet vibrationally absorptive material such as felt or an epoxy impregnated felt.

Design of Structural Joints

Structural joints are a necessary evil of a smart projectile. Normally these joints are simply threaded, but other designs such as mason jar connections, pinned joints, turnbuckles, spline fits, etc. have been used. The most critical parameter in the design is joint compliance and preload condition. These are interrelated. Joint compliance is the propensity of the joint to open and close during dynamic loading. This opening and closing usually generates high frequency loads into the projectile, which invariably gets transmitted to the electronics. Preloading of these joints can mitigate to some degree both the amplitude and frequency of the loading, but it is usually impossible to preload a joint enough to eliminate the shocks altogether. This is exacerbated by the fact that under different temperature conditions, the joints will have different characteristics due to thermal expansion effects. Another item that must be considered in the joint design is how it will behave under tactical and logistic vibration. This is important enough to warrant a section in its own right and will be discussed later.

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Since threading is the most common practice, it is important to understand the design constraints. In this, the reader is referred to reference 9. Although this reference deals specifically with buttress threads, the equations work for all types of threads. After the design is complete, the most important aspect of assuring the joint behaves properly is the inspection of the threads. In this respect, the normal procedure of using go/no-go gauges is insufficient. If the joint is meant to carry a tensile load (which it is in set forward), it is necessary to check thread form on 100% of the parts. This is because, through the years, on every program that this procedure was not implemented on in the author's memory, eventually a part gets through where it passed go/no-go and failed in tensile loading because it was either double cut, had enough material to fool the gauge user, or with malformed in such a way that the full load carrying capacity of the joint was not realized. Figure 4 shows a picture from the M898 SADARM program as a classic example.
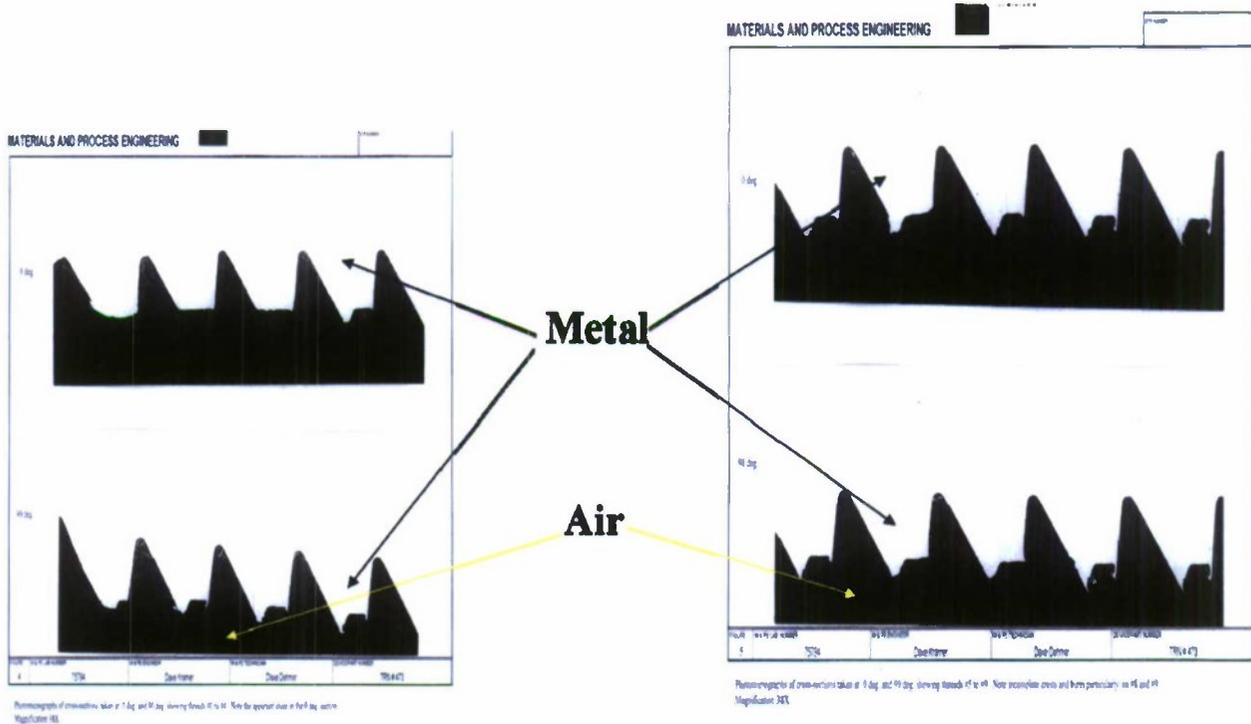

Figure 4
Failed threads on SADARM taken by ATK, Hopkins, Minnesota

Once again the joint design can be accomplished if modeled properly. Success has been achieved by modeling the threads as axially symmetric grooves. The lack of a helix does not seem to affect the analysis enough to require the additional complexity to be included. In order to eliminate the need for thread from inspection, it has been proposed that threads be modeled with the tips cut off to the pitch diameter. At the time of this writing, this technique has not been proven but is in progress. After a joint has been successfully modeled, it is always wise to do some static characterization to validate the model in an instrumented test fixture.

Propellant Gas Leakage

Propellant gas leakage past an obturator or rotating band can have bad consequences. The blow-by will generally force the projectile to one side of the gun tube. Depending on the lateral flexibility of the projectile, the projectile will obturate circumferentially to a large degree, leaving the pressure trapped on one side and causing an in-bore yaw or balloting. Extreme leakage can force the side of a weak projectile in and cause it to buckle akin to pushing ones finger into the side of an aluminum soda can. Another possibility is for the propellant gas to leak into joints, fastener holes, or weak spots in the projectile.

The design of a projectile should be such that it can handle some amount of blow by loading. The challenge is in the specification of the blow by load itself. This has been an area of current work and the current method is to position pressure taps in the side of a gun tube and fire at number of projectiles. With known acceleration-time data (either from accelerometers on the projectile or using an interior ballistics simulation), the pressure transducer data can be mapped back only the projectile once the velocity past the transducer is obtained from the integrated acceleration time trace. It is usually obvious from the pressure transducer data when the leading edge of the obturator or rotating band passes the gauge location, so in essence the mapping is performed backwards onto the projectile body. After several of these pressure maps are obtained, a three sigma upper limit is determined and this becomes the requirement. This may seem like putting the cart before the horse, but it is unfortunately, the only method known at the time of this writing. In the preliminary design phase, the design team should use a pressure map requirement from a similar projectile. The requirement would then be validated after the test is completed and altered if necessary.

Once the blow by requirement is validated, analyses need to be done that include the blow by loading. Experience with the Excalibur program (ref. 10) has shown that the application of this pressure on a 90-deg sector of the circumference, ramping the load linearly down to zero over 45 deg on each edge (so, in essence 180 deg has some load on it) adequately predicts the behavior of the blow by. If the structure does not fail, the aforementioned yielding criteria, the design is acceptable.

Joints leakage is difficult to model computationally. This is due to the fact that fluid elements are necessary to model the behavior of the gas in the joint. Not only are these gaps small, thus run times become monstrous due to the small elements required, they tend to dilate or close completely under pressure and that causes numerical issues. No joint is too small for gas to enter. It is always amazing to examine hardware and find that the propellant gases got into the most minute of spaces. With the cautions previously mentioned on wet processes in place, every joint that will be exposed to gun gases must be sealed by either an O-ring, gasket, or adhesive. Even in the case of O-rings, caution must be exercised to make certain the seal is not compromised during assembly. Use of lubricants for O-rings must be carefully controlled. Another item that must be carefully controlled with either gaskets or O-rings is the surface finish of the seating surfaces.

Transportation Vibration

The design of a projectile to survive transportation vibration is usually an afterthought. Generally, the reasoning behind this is that if the projectile is rugged enough to survive gun launch, it will survive transportation vibration without an issue. This is nearly always incorrect. The reason stems from the fact that transportation vibration has a completely different frequency content than gun launch and the duration is much longer. It is one of the most difficult things to design against, especially because of the way it is normally specified in the requirements specification - that is with a shock response spectrum (SRS) plot. There is, at the time of this

writing, no means to the author's knowledge of how to take an SRS plot and determine if a threaded joint will rotate. This is an issue with the method of specification. Most of the damage incurred in tactical (and logistical) vibration is because of fasteners and projectile joints backing out. Preloading solves part of it, but usually some form of thread locking compound is required. The thread locking compounds that are the most difficult to remove work the best. Other damage had been attributed to non-tactical mounting or errors in the manner in which the SRS was generated.

The SRS is either generated by placing an accelerometer on the vehicle, somewhere near where the projectile will be stored or placed on a projectile in the storage location. Either method has issues. If the accelerometers are mounted on the vehicle itself, they result in an SRS that is representative of the input to the projectile. They take no account of the mounting structure and can lead to answers that can be surprisingly bad. This will either be because the compliance of the mounting structure greatly influences the frequency at which the projectile vibrates or because the physical means of retaining the projectile in its location have compliance and can loosen as time passes. If an actual projectile is used, it will generally have a very different stiffness and center of gravity location than the new design the SRS is being recorded for. This will also result in an incorrect response. These inaccuracies are generally accepted because, as was stated earlier, the data generated has minimal usefulness.

The only way to avoid issues in transportation vibration is to take the prototype of the proposed projectile design and place it on a table that can vibrate in multiple axes simultaneously, or if this is not available, a single axis table will suffice, and mount it in an exact replica of the mounting hardware in the proposed vehicle. Once this is accomplished, the table should be vibrated by programming in the SRS from the vehicular mounted accelerometer (or better yet using the raw data). Joints on the projectile should be marked so that movement can be detected and the projectile should be instrumented with accelerometers in critical areas to obtain the transfer function data so that the test need not be repeated as the design evolves. After the data is collected and any corrective actions implemented, it should be documented and a smaller subset completed before qualification of the design to assure that nothing has changed. It is only in this manner that the headaches of failures of a design at the eleventh hour can be avoided. The Copperhead projectile is a good example of this very issue. During development the reliability of the projectile was approximately 32%. Much of this was attributed to transportation vibration. The transportation vibration issues had to be addressed during initial production prior to first article inspection on the compressed schedule.

Critical Safety Characteristics

One of the most important considerations in a projectile design is safety. For many years the U.S. Army has used a system that breaks items down into three characteristics: minor, major, and critical. In simple terms, a minor characteristic is one where the fit or assembly may be affected, a major characteristic is one where reliability of the item may be affected, and a critical safety characteristics I s feature where in and of itself, if the requirement on the drawing is not met, there is a possibility that the weapon may be damaged or personnel injured. The determination of classification of features is always hotly debated. This is because as a general rule, critical safety characteristics must be identified in an automatic fashion and not subject to human interpretation. When there is no other alternative, 100% inspection performed by two different people at two different times has been substituted and this gets extremely expensive.

Items historically that have been determined to be critical characteristics are the four major mechanical properties (yield strength, ultimate tensile strength, % elongation, and fracture toughness) of any part located in the structural load path, threaded joints in the structural load path that can either compress due to setback or are required to hold in tension during set-forward (muzzle exit), cracks or voids in the explosive that may be compressed and adiabatically heat during launch and features of fuzing components that may initiate or even arm during launch or rough handling.

Over the years of dealing with these components, it has been found that modeling can be used to make an informed decision about whether a feature should be a critical characteristic. For the mechanical properties, it is somewhat straight forward in that one can model the structure with the mechanical properties in the worst case condition specified on the drawings at the safety loading of PIMP +5%. If the structure survives then the properties are valid. If there is a way to determine the 1:1,000,000 lower limit of the mechanical properties and the structure still works, one might consider removing the material properties as a critical characteristic. This is a very restrictive condition that has never been able to be met in the author's experience. As a result, we require an independent laboratory to perform mechanical testing on each lot of material because, over the years, regardless of the credibility of the manufacturer, non-conforming product slips in. It is recommended NEVER to use a manufacturer's data sheet or a certification from the manufacturer as verification that the mechanical properties have been met-use an independent laboratory.

To use modeling to determine if geometric features are critical characteristics requires a bit more judgment. On some features, such as radii, a method of determining the criticality is to replace the radius in question with a sharp corner in the model. If the structure survives, then the lower limit of the radius is not critical. Usually the upper limit of a radius is not an issue, but if it is, replace the radius with one that is so out of tolerance that the mating component will not fit or it will be readily noticeable. If the structure still works, then the upper limit of the radius is not critical. For feature such as blind hole depths, it is typical to punch the hole all the way through on the one hand and not have the hole present at all on the other. If both cases are acceptable when subjected to the safety loading, then that feature is not safety critical. With cylindrical walls, it is typical to run the structure at a wall thickness that it breaks through in an obvious area or is so thin that the mating parts will just drop out (or so thick that they don't go together). With respect to threads, running them so that they are cut below the pitch diameter usually works if the design holds together under both set back and set forward loads. This is because a no-go gage should pick up a thread cut below pitch diameter. Also, double cutting the threads in the model is advised.

Modeling gaps that occur between load carrying surfaces due to thread helical or true position tolerancing is a bit tricky. This is usually a safety critical characteristic and is normally inspected through the inability of a feeler gage of a given thickness (usually 0.001 in.) to penetrate a joint to some depth over some circumferential dimension (usually 60 to 90 deg). In order to model this feature from a strength perspective it is recommended that parts be assembled in the model with a gap of half a thread pitch (achieved by misorienting the axis of the joint in the model) and running it as the safety loading. If the design survives, the gap should not be considered a safety critical. The reason half a thread pitch was chosen is that a gap of this size should be visually obvious to the technician assembling the projectile (NOT necessarily to a soldier in combat).

The presence of pins, loctite, or any goo that would allow a leak path into the projectile is a poor design practice. Unfortunately, sometimes there is no other way to get a projectile design to work. When this is the case, some form of automated inspection must be used to assure the presence of the proper material and also care must be taken to assure that the shelf life of the goo is not exceeded and compatible primers and surfaces are present. Gun gas gets into places that are difficult to image.

It is difficult to describe all of the situations that may develop in an engineering design although with the previous guidance, one should be able to use a model to cover any situation.

Base Gaps and Voids in the Explosive

Base gaps and voids in the explosive fill of a projectile can cause in-bore detonations under certain conditions during gun launch. The physics behind these detonations is believed to be that of a near adiabatic compression. Explosives are generally weak wax-, clay-, or plastic-like material. They are structurally weak and fairly good insulators of heat. When a bubble in the explosive or a bubble near a wall occurs it tends to collapse rapidly under setback or set forward. Because the event happens so rapidly, there is little time for heat transfer to take place and the air is compressed under nearly adiabatic conditions. The heat generated in the now collapsed bubble can be sufficient to ignite the explosive in the tube. This condition can be exacerbated by increased temperature (and usually a corresponding increased sensitivity) in the explosive fill. Based on experience on the SADARM program, it appears that a nearly spherical bubble will be more sensitive than a planar gap. This is believed to be due to the shock heating during the compression of the bubble. The temperature rise in the bubble, included shock effects, can usually be modeled fairly accurately. What cannot be modeled will at the time of this writing is the response of the explosive to this heating. The only recourse, therefore, is to test the material.

A most conservative test is one where the test fixture is rigid and the bubble is forced, under an impulsive load, to collapse (ref. 11). Less conservatism is achieved when the test sample is allowed to fly freely (ref. 12); however, this is probably the more realistic of the two methods. Many laboratories such as ARDEC, Army Research Laboratory, and Defense Research Establishment Valcartier of Canada have testers that can accommodate tests of this nature.

Realistic Test Conditions

In all laboratory tests, it is important to replicate, as best as one can, the conditions under which components will operate. In centrifuge testing it is vitally important that the compliance of supporting structures be replicated for valid test conditions. In electronics component testing, the use of the actual device that will power the electronics is recommended. This is because electronic component performance might be different under conditions of a laboratory power supply than it will under the actual tactical voltage and current. In all cases an exact replication of the tactical conditions should be the goal.

Design Margin

Once the loading on the projectile is characterized, the design must include some design margin to account for process variations during production, multiple reworks, excessive test times due to retest, etc. Although no number is generally agreed to as a universal, a 25% margin to worst case operating conditions is not unreasonable and in some cases may not even be sufficient. A 25% margin was used for qualification of the Copperhead electronics with success.

Design margin is also inextricably linked to producibility. In a design where the margin is low, there tends to be tighter controls on dimensional and performance characteristics. This gives rise to closer scrutiny of production through higher levels of inspection (i.e., 100% inspection). Designs with lower margins tend to be more expensive in production as inspection costs increase and rejection rates rise.

Redundancy

Nearly always in a projectile system cost as well as space claims are carefully controlled. These factors conspire to make redundancy seem inappropriate. The designers and program managers must, however, carefully consider redundancy as a means to increase reliability. Many times, certain components with an inherently low reliability must be used because no other design is available. In these instances, redundancy is certainly warranted. This is especially true if the cost of the offending device is low compared to the overall cost of the projectile. Typical examples are pyrotechnic devices or even system batteries. In the case of Copperhead, removing connectors (discussed earlier) and incorporating a dual starter for the battery were key elements in a reliability growth from 67% to 90%. This reliability stayed through production and was verified during stockpile surveillance testing. Always consider redundancy from a cost basis, weighing the impact of a reliability failure against the cost of the redundant component.

Focus on Reliability

Many times programs are initiated to obtain an improvement in performance of a system over current capabilities. In these instances, leadership tends to focus on performance gains over reliability. It cannot be stressed enough that reliability is as important as performance and it is even linked to performance directly. For instance, a system that kills its target 99% of the time, but only functions properly 50% of the time, is probably worse than a system that kills its target 50% of the time and works 99% of the time. A prime example of this was the M898 SADARM program, where the contractor leadership was primarily focused on performance and only late in the program did reliability enter into the picture. Reliability must be considered from program inception.

It is important to understand the time required for the reliability of a system to grow through steady production. On the Excalibur program, there was no reliability growth phase since the design was needed in theater as soon as possible. This resulted in a somewhat low reliability of fielded units that was eventually corrected, but only after a great deal of effort was expanded in shipping personnel and projectiles in and out of theater. On the positive side, the early fielding was successful and probably saved the program. It was successful because the user was told that the early fielded rounds would have limited capability and agreed to a somewhat lower reliability figure due to the urgent need. A different situation occurred in the Copperhead program and this is illustrated in figures 2 and 3, which plots number of waiver and deviations versus time. These waivers and deviations are an indication of improvements to the reliability.

CONCLUSIONS

The design of projectiles containing electronics is a costly and complicated task. There are many areas where the inexperienced program manager may believe savings can be achieved. In some cases this is true, in most cases it is not. Proper planning of a development program is the key to success. Contractor experience, in general, is very useful, but it has its limitations. This is especially true of contractors who are not experienced in projectile design proper. The issues set forth in this document are nearly always experienced in a projectile program, the degree to which is design dependent. The steps laid out in this document are always followed. Sometimes this is due to good planning, sometimes because of issues that arise because the planning was flawed. It is best to plan for all of these items and executed them as part of an integrated schedule rather than force them in as cost overruns and under an unnecessarily accelerated schedule at a later point in the program.

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