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Applicability of Industrial Test and Evaluation Practices to Nuclear Weapons

Sharissa Young and Michael W. Moulton
Nuclear Weapon Systems Analysis Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0415

Abstract. This report documents the results of a study to identify governmental or commercial industry test and evaluation (T&E) approaches, practices, and strategies for detecting manufacturing or design defects and predicting or identifying performance degradation that may occur over the life of an engineered system. The industries selected for study were limited to those for which some characteristic of their product share similarity to nuclear weapon (NW) systems. Application of industry paradigms to a governance model for the Sandia National Laboratories (SNL) nuclear weapons (NW) test and evaluation (T&E) program results in some obvious challenges and shortcomings, given the distinct business environments and product requirements involved in the nuclear weapons enterprise. However, an intriguing case can be envisioned whereby some aspects of T&E strategies used by analogous industries can be incorporated into governance models to support increased accountability in a budget constrained environment.

Introduction

Weapons in the U.S. nuclear stockpile are achieving unprecedented ages, exceeding the original service life in many cases. In response, the federal government has begun a series of life extension programs to modernize, remanufacture, and replace components and subsystems within these critical assets. Many challenges are implicit in this reconstruction effort, but opportunities exist to modernize not only the products but also the nuclear weapon (NW) processes and policies that are applied to these weapons. Test and evaluation (T&E) of the fielded products to detect potential defects is one such process that bears examination in light of current opportunities to modernize governance models in today's cost-constrained environment.

While the hardware and technology contained in the NW systems have stayed the same for many decades, the political and economic environments have not. Cost drivers have gained in relative importance and austerity currently plays a large role in business decisions world-wide. This shift has caused many customers to question each element of lifecycle cost and to challenge suppliers to devise more cost-effective ways to deliver the same value. Rather than employing incremental improvements to existing processes, many times introducing an innovative approach can result in significant cost savings without detracting from those product attributes that the customer values.

To identify innovative test and evaluation approaches that may achieve the same customer value for the future stockpile at a lower cost, this paper investigates other governmental and commercial industry practices related to defect identification and performance testing of similar products. Characteristics of NWs important to the T&E effort are first identified to understand what may qualify as an industry analog.

Defining Industry Analogues

To understand the applicability of the approaches used in other industries, the products must share some aspect in common with NWs. There are a number of aspects, or characteristics that are pivotal in defining NWs.

The only characteristic that is consistently predicted among various authors discussing the future of the US nuclear stockpile is that they all predict fewer U.S. NWs. This reduction, both in the numbers and types of weapons, has already begun and has continued for several decades, such that a trend of reduction is well-established. Therefore, U.S. NWs are constrained to relatively small production runs (limited quantities), as compared to commercially mass-produced products.

Similarly, although consensus about the necessary reliability is not achieved by the various authors, most include an assumption that reliability will not be less than the currently high requirements. NWs are by necessity high-reliability systems, using the industry standard definition of mission reliability as having a high degree of confidence in *the ability of an item to perform its required functions for the duration of a specified "mission profile."*[i]

Also implicit in all of the scenarios is the idea of dormancy. No author indicated a belief that NWs will be detonated as fast as they are manufactured. Thus, any engineered products that are considered to be analogous to NWs should be those with low production quantities, high reliability, and some period of dormancy. Over the course of history, many thousands of NWs have sat dormant and on alert, providing a deterrent capability. Therefore, dormancy is included as a characteristic of NWs.

In addition to stockpile composition and quantity scenarios, changes within the weapon hardware and componentry have been posited. As the life extension programs for NWs are performed, some legacy parts are reused while others are manufactured new or remanufactured. Therefore, NWs of the future will likely consist of a combination of old parts joined onto or contained in new parts. The new parts will, by necessity, contain some commercial off-the-shelf (COTS) electronics and use only technologies and materials that are currently available, rather than relying on sunset technologies.

Nuclear weapons are clearly unique in their enormous destructive capability, accompanied by a strong emotional response to the potential scale of devastation. While few other engineered products are comparable to the scale of NWs in this respect, there are products that are capable of causing mass casualties, many of which carry some degree of emotional response to potential defects or failures of these systems. Because this characteristic of NWs is so important, only those engineered products that can cause mass casualties will be considered as an analogue.

Table 1: Characteristics of nuclear Weapons

Small production quantities
High reliability systems
Long periods of dormancy
Contain legacy parts combined with newly manufactured parts
Contain commercially available parts and materials
Cause mass casualties in use or accident scenarios

Provided with these six characteristics of weapons that are assumed more likely to exist in the future stockpile, commercial and other government products that may share one or more of these attributes were considered. Other governmental agencies were considered first. The National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), the Department of Defense, and the U.S. Army Corps of Engineers (USACOE) were identified as having some engineered products that had some traits in common with NWs. These agency products include manned rockets; unmanned space probes; commercial aircraft safety and navigation; strategic and tactical rockets, missiles, and torpedoes; and engineered dams. For these products, failures can be life-threatening and mass casualties can result from accidents or intended use, therefore, high reliability is required to prevent accidents.

Commercial industry practices, where the products offered for purchase are in some way analogous to NW products, were examined next because cost-effective strategies are likely to be more prevalent in commercial industries than in governmental enterprises due to the commercial requirement to achieve profit. Of these industries, the following products were selected for additional study to understand their specific situations and approaches to defect and aging identification: commercial rocket motors, aircraft, electronics, emergency generators, canned foods, and pharmaceuticals. The characteristics of these commercial products as well as the other governmental agency products that were deemed to be common with the NW traits are identified in **Error! Reference source not found.**.

Identifying T&E Strategies Used by Industry

Once identified as a potential analogue, each industry or product type was researched in more depth to understand product aging and defect identification strategies employed. These strategies are discussed in the following paragraphs.

Space Vehicles (NASA). NASA recognizes three types of dormant systems elements: Type A parts that are subject to random failures but otherwise have indefinite non-operating lives (e.g., electronic components), Type B materials and components that degrade at a slow but predictable rate over time (e.g., energetic materials, etc.), and Type C materials and components that have short, limited shelf lives (e.g., batteries, gas generators, etc.).[ii, iii] High-reliability systems that are dormant for a length of time, then are not accessible during use (such as satellites and spacecraft) and rely on strategies to eliminate defects during and prior to production. Examples of these are

Table 2: Industry Analogs to Nuclear Weapons

An	Industry/Agency

		NASA*	Rocket motors	FAA*	Aircraft	Electronics	Dams*	Emergency Generators	WWII Torpedo*	Canned foods, drugs
	Small production quantity	X	X						X	
	High reliability	X	X	X	X	X	X			
	Dormancy	X	X	X		X		X	X	X
	Use of new with legacy parts	X		X	X					
	New (current) materials and COTS parts	X	X	X	X	X		X		X
	Use or failure can cause mass casualties	X	X	X	X	X	X	X	X	X

model-based testing, 100% functional testing at every stage of assembly, and software de-bugging tools. These systems have no T&E, aging, or test program after production. Instead, reliability is an upfront defect prevention cost rather than an after-the-fact defect detection effort. This is also usually a strategy employed by software product companies that can use model-based testing and other QA strategies prior to end use.[iv, v, vi]

Rocket Motors. One rocket motor manufacturer's[vii] aging and T&E program includes a mechanistic and an empirical program, based on the differences between causality and knowledge.[viii] Empirical testing is performed somewhat infrequently on relatively few assets for the sole purpose of either validating the mechanistic model (data match prediction) or identifying the presence of unknown or unknowns that are not described by or contained (accounted for) in the mechanistic model (data fall outside model prediction). ATK has a well-defined methodical process to develop and validate the initial mechanistic model for each product, along with a tailored T&E and aging program to continue to validate the model or identify discrepancies.

The DoD has a SRM sustainment plan that is designed to sustain the SRM industrial base. This plan accomplishes the objectives to maintain SRM design teams, exercise production capabilities, and preserve the option to satisfy new demand for future systems. This goal has been considered when defining the DoD SRM aging and T&E approaches.[ix]

Federal Aviation Administration (FAA). The FAA has a few systems that are unique, dormant, or critical to life/safety with different approaches to T&E for each.

1. LIFE/SAFETY: For the life/safety system that is the tower-to-pilot communication link and ASR-9 radar transmit and receive A and B channels in the control tower, the redundant backup channel is used routinely for additional or continued (but not initial) conversations between the pilot and the tower and the backup radar channel display is also actively used frequently as a matter of course.
2. DORMANT: For the power conditioning system (PCS, a UPS-like battery backup system) built-in test (BIT) data are collected regularly to monitor the performance and a

record of the data collection is documented in logbooks subject to periodic audit inspection. The data from the BIT is reviewed multiple times by several people – the data collection person, the supervisor, the auditor, etc. In addition, an annual load test confirms that the PCS can accommodate the expected emergency loading that may be necessary.

3. UNIQUE: Only one radar dish is used at the FAA control tower for radar approach control, due to cost constraints associated with staging and storing a redundant backup dish. Routine maintenance along with preemptive replacement of parts with a history of wear is performed to ensure continued reliable operation. This includes the automated electronics checks (BITs), draining/refilling the gear box, rotary joint (slip ring) maintenance, and calibration checks. Trends in the diagnostic checks are used to predict maintenance against the key performance parameters listed in the maintenance handbook (65-80.5).[x]

Aircraft. Aircraft aging and T&E strategies include routine inspections, BITs, non-destructive evaluation (NDE), such as eddy current to look for structural weaknesses, routine maintenance, remanufacture of replacement and upgraded components and subsystems that bolt on original airframe. The commercial transportation industry is highly regulated and specified. Componentry and subsystems are designed to be used frequently, be self-monitoring, record diagnostic checks, and send pilot alerts; and this large volume of empirical data is used to develop predictive maintenance models so that parts can be replaced before the predicted failure interval.[xi] However, some aging phenomena are known to occur and their incidence increases with age. Corrosion is a known degradation process that has well-established prevention and inhibiting technologies, but those technologies have decreasing effectiveness over time. Based on replacement cost, many civilian and military aircraft are being used in service much longer than their original design life. Therefore, NDE techniques are becoming even more critical as the cost of system replacement is traded for the cost of increased inspection, maintenance, and subsystem/component modernization. Corrosion mechanisms are well-known and common corrosion areas are similarly recognized by industry experts.[xii]

Electronics. Electronics manufacturing and testing industries employ a variety of methods of T&E and product testing. Defect prevention methods like HALT/HASS (highly accelerated life test/highly accelerated stress screens), and accelerated-life testing as well as product acceptance testing (electrical, optical, etc.) are used initially to identify and discard less reliable parts and ones with latent defects that can be identified by exposure to harsh environmental conditions.[xiii, xiv, xv] Other efforts have been developed to maximize the amount of failure identification and prediction information by subjecting aged field-returned hardware to stress testing and accelerated life reliability testing to encourage latent defects to emerge earlier in the test samples than later in the fielded hardware.[xvi]

Dormant military systems designed with electronic parts and components were initially subjected to frequent handling and testing. However, this procedure was found to induce failures from testing or to erroneously reject compliant assets in as many as 50% of the confidence tests. Therefore, reliability was drastically improved by reducing or eliminating periodic confidence tests. Maintenance, however, was still required in some systems and the maintenance concept varied for products that were designed as a "wooden round"[xvii] versus those dormant military systems that have age-affected, degrading, or known LLCs.

The first type of dormant military system, which includes both the idea of the "total-" and the "quasi-" wooden round, is designed to eliminate the need for confidence testing or inspection, except for periodic inspections of the package to assure integrity. Using the dormant military system design guide, there is 100% burn-in, screening, and preconditioning of both mechanical and electrical parts and subsystems; complete documentation of manufacturing parameters and test results; elimination of BIT points for external testing; and the use of a sealed, inert atmosphere with few interconnection plugs or materials that are sensitive to degradation over storage times. A maintenance theme that is included in this system design guide is the ability to replace limited-life items, if any, without any significant disassembly or test.

The second type of dormant military system design is one that includes the need and ability to perform periodic monitoring/repair/maintenance in the system architecture. This concept is designed to improve the reliability of non-operating equipment by periodically testing items to detect failures so they can be repaired prior to use. The basic assumption is that reliability, performance, or both will degrade according to a known or predictable function over time. Periodic replacement of the part(s) that are the largest contributors to the failing reliability can be repaired or replaced before the overall system reliability falls below the target value, which will elevate the average reliability of the system in a saw-tooth fashion over a longer total service life (see Figure **2**).[xviii]

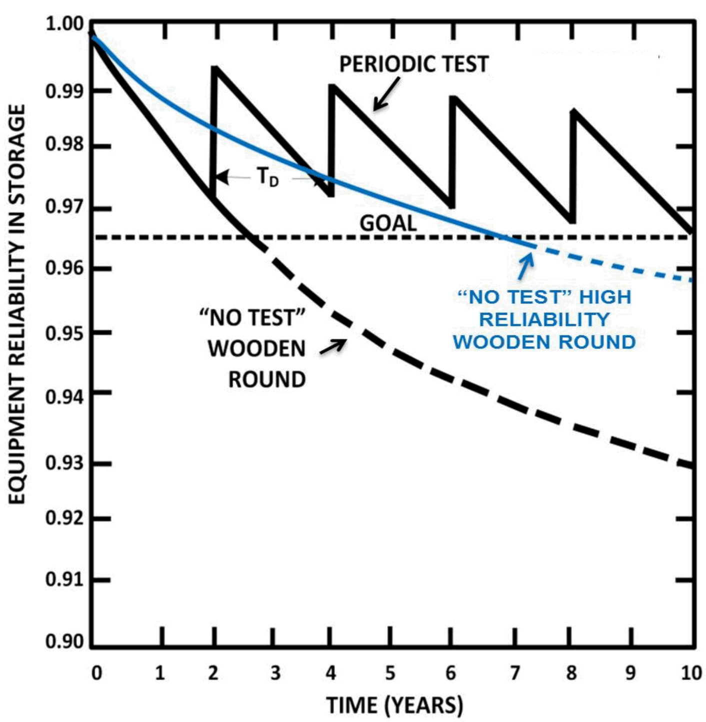

Figure 2: Adapted from Rome Air Development Center, Lockheed Electronics

Fundamental to most of these electronics T&E and aging approaches is the assumption or mandate that failure mechanisms and factors that determine or constrain reliability must be understood and used to devise a strategy, or else the failure rate or life estimates exceed actual product life. The alternative is that the reverse often occurs. A product is over-constrained and the cost to manufacture becomes unnecessarily high.[xix] Common failure modes and mechanisms for semi-conductor devices such as light-emitting diodes and laser diodes are known and well-documented. The time to failure can be predicted statistically when the failure mechanism is known and careful production controls have resulted in a homogeneous product.[xx]

Dams (USACOE). Dam inspection strategies are predicated on the fact that dissection and intrusive information concerning the interior components of the dam are not available and remote methods of NDE must be used to infer the condition of the dams. There are regular annual inspections combined with a more intensive team inspection every five years as part of a dam safety program. There is some ability to perform limited hydraulic/hydrologic analysis, based primarily on environmental elements surrounding the dam. If some indication for additional concern arises, more intrusive subsurface drilling exploration and testing may detect precursors of failure, that is, seepage from under the dams. If dam failure precursors are found, repairs are fairly routine and appear to be effective at extending the service life of the dam. This strategy is predicated on the fact that the engineers and dam inspectors understand the failure mechanisms and that some test or inspection will provide a parametric indication of the presence of this failure mechanism.[xxi, xxii]

Emergency Generators. Emergency generators, such as those used to power hospital life support operations during power outages, experience periods of dormancy but then are required to operate during critical periods. The National Fire Protection Association mandates that commercial building generators be tested both monthly (limited test) as well as undergo more rigorous annual tests. Strategies used are replacing aging generators or performing life extending modernization that also may include BITs and other upgrades to achieve flexibility, ease of maintenance, better operation control, and quick access to precise information (system read-outs from displays and BITs).[xxiii]

WWII Torpedoes. The strategy used to identify and repair defects in Mark 14 submarine torpedoes that failed during actual use after a period of dormant storage included field testing under conditions that most closely approximated actual use. The collaboration between research engineers and the end-user community was cited as necessary in performing the testing that was able to identify a difficult-to-detect defect that severely affected asset performance.[xxiv] As noted by the Foster Panel in 2001, "The magnitude of this challenge is underscored by our past difficulties in fielding new conventional expendable munitions, which, although tested extensively, often have proven to be less reliable in combat than expected."[xxv]

Canned Foods and Pharmaceuticals. The U.S. Food and Drug Administration (FDA) regulates the requirements and testing of food and drug products in the U.S. There is shared motivation between governmental agencies and private industry to ensure that ingestion of consumer products do not result in immediate life-threatening results. However, after long periods of dormancy, neither of these entities certifies the safe use of these consumer products (i.e., canned food and drugs). As evidenced by the recent salmonella [xxvi] meningitis[xxvii] and other food and drug safety events in recent news, bad publicity provides an economic safeguard against many drug- or food-borne pathogens. Coupled with requirements for production and/or pre-production testing or inspection, a strategy of setting expiration dates was employed by the FDA for in an attempt to limit public exposure to food and drug-borne hazards. Although most food expiration dating is voluntary, for prescription and over-the counter medicines the FDA began requiring an expiration date in the late 1970s. "Expiration dates on medical products are a critical part of determining if the product is safe to use and will work as intended."[xxviii] The expiration date is the final day that the manufacturer guarantees the full potency and safety of a medication.[xxix] Safety certifications are given for near-term time limits (typically 12 to 60 months from time of manufacture), even though the product may well be viable long after that date.[xxx] The DoD reportedly saved significant resources by contracting the FDA to perform a Shelf Life Extension Program (SLEP) for some pharmaceutical products.[xxxi] In this way, a life estimate is given that can be extended by collecting stability data on aged products. However, rather than performing costly drug stability testing and maintaining controlled storage environments, many small quantity consumers are advised to simply dispose of expired products by consumer and medical authorities when drug certifications have expired.[xxxii]

In summary, there were five distinct strategies identified by surveying analogous industry practices. Each industry has been identified with one of these five strategies, labeled A through E for ease of reference (Table 1). The aging and T&E strategy employed by the studied industries was adopted as a result of the characteristics of their products. Each of these strategies may have some applicability to NW T&E, at least in some aspect of the T&E operation. At the least, the industry experiences may be able to point out unproductive strategies before substantial resources are directed in those directions.

Table 1: T&E Strategies Used by Industry Analogs to NW.

	T&E Strategy	Industry/Agency								
		NASA	SRMs	FAA	Aircraft	Electronics	Dams	Emergency Generators	Torpedoes	Canned food, drugs
A	Defect prevention, 100% production and acceptance testing, no T&E	X								
B	Mechanistic prediction, sparse empirical data for model validation, and unknowns discovery		X				X			
C	Collect large volumes of data from BIT, monitors, predict failure from empirical data curves, and Repair and Replace/maintenance			X	X	X		X		
D	Make best product given affordability constraints; limit liability with warrantees, expiration dates, certifications									X
E	Empirical test in exact test environments using operations and test SMEs								X	

Governance Models Using Alternative T&E Strategies

This section explores the advantages and challenges inherent with applying each of the five strategies to NWs. None of the strategies identified in the preceding section can be applied wholesale to the NW T&E enterprise; however, some of the strategies may be able to be applied, in whole or in part, to selected SNL NW T&E practices to provide continuing value to the customer in a more cost-effective manner. Therefore, it is instructive to consider how each strategy might be advantageous and what challenges might be faced if SNL adapted them for use.

To begin defining the potential trade spaces that a new approach to SNL T&E must occupy, we need a clear understanding of the valued principles, attributes, and product needs that accompany a responsive governance model. There are a number of themes that constrain the solution space when devising alternate T&E strategies for NWs. These themes include safety, surety, and effectiveness as a nuclear deterrent. [xxxiii] We must carefully consider the effects that potential revisions to the T&E strategy have upon these values.

Strategy A: Defect prevention, 100% production and acceptance testing, no T&E. In considering the first strategy, labeled "A" in Table 1, the industrial application would be to those programs, such as satellites and space vehicles, for which the system hardware is extremely expensive and only a very small number of units are built. Because space flight hardware is generally not available for testing, repairs, or maintenance after being put into service, ease of repair or maintenance is not a design requirement. Instead, architectural modularity and integration are design requirements for these high-reliability products to facilitate acceptance testing at every level of assembly. Because no T&E data are collected after the products are placed into service, the reliability is quantified using design, qualification, and production acceptance data.

The differences between the NASA products and NWs, however, may overwhelm the trade space. After a period of dormancy, NASA products are launched and data regarding their continuing functional state are received regularly, unlike NW products. The need for continuing assurance of the safety and effectiveness of NWs may outweigh the cost-saving aspect of this strategy if no T&E data are collected after each NW unit is produced.

To the extent that design and production defects are able to be eliminated, then only the unknowns (both known and unknown) [xxxiv]would be relevant. Therefore, T&E sampling could focus on aging phenomena from the outset, obviating the need for a Retrofit Evaluation System Test program.[xxxv] The cost of applying a more rigorous defect-prevention strategy could be balanced by a corresponding need to do less T&E, if a convincing argument could be made that fewer T&E samples were truly needed.

Strategy B: Mechanistic prediction, sparse empirical data for model validation, and unknowns discovery. Industrial Strategy B includes the concept of trading greater *a priori* knowledge of a well-characterized material used in the product for more limited T&E testing after the product is fielded. Strategy B differs from Strategy A in that upfront costs arise from a more thorough materials characterization and analysis rather than from extreme defect prevention efforts.

Service life projections are derived from first principles equations describing physical or chemical mechanisms that cause performance degradation over time. Models using the equations governing these mechanisms apply to failures that are either gradual (i.e., performance degradation) or catastrophic over a given time scale. Test data, on the order of two to three samples a year or less, are compared against model predictions. If the actual data comply with the model prediction, then the conclusion is that the system conforms to our understanding of it and the model appears to be accurate. When the test data diverge from the prediction, then the conclusion is that the model does not include an important chemical or physical mechanism that is governing the performance degradation process. The corrective action is to begin an thorough investigation into identifying the mechanism that is controlling the aging process and to understand the initial and boundary conditions related to the omitted aging phenomena, similar to the significant finding investigation process in the NSE.[xxxvi, xxxvii] The model is then updated and a new life estimate results from the mechanistic approach described by Strategy B.

The difference between Strategy B commercial industry products and NWs is that the mechanistic approach is only cost-effective to implement for systems with few components, which use a small number of well-characterized materials. Therefore, this mechanistic approach may be applicable to some of the materials used in NWs if they are well-characterized and likely to be affected by aging processes.

Strategy C: Collect large volumes of data from BIT, monitors, predict failure from empirical data curves, and R&R/maintenance. Strategy C is used primarily for electrical or electro-mechanical systems. Embedded sensors and BIT routines have been seen by some as the "holy grail" of T&E. However, many seemingly insurmountable issues, such as nuclear safety and surety concerns, have precluded their widespread use.[xxxviii] These issues include technical issues such as developing an acceptable mode of transmission for sensor data outside of the weapons, weight and geometry restrictions, and the calibration/reliability of the sensors themselves as well as the more esoteric questions such as whether the act of monitoring changes the property being measured and knowing which properties and locations bear measuring in an embedded NW monitoring system.

Strategy D: Make best product given affordability constraints; limit liability with warrantees, expiration dates, and certifications. Strategy D involves the use of expiration dates and certifications to limit corporate liability. Although liability for U.S. NWs already rests firmly on the federal government, the congressional requirement for annual certification is reminiscent of this strategy. Applying this strategy to SNL NWs offers limited value, except in the recognition that if successful design and production defect prevention efforts were implemented, such as described in Strategy A, then it may become possible to certify a newly refurbished weapon for some finite amount of time. At that point, T&E testing strategies such as previously described might need to be instituted for continuing annual "extensions" to the initial certification, as the stockpile ages beyond the original design life.

Strategy E: Empirical test in exact test environments using operations and test SMEs. Strategy E was applied to a product with known production and/or design issues. If additional funds are not dedicated to defect prevention, then this strategy suggests that more realistic flight testing, which includes both test/measurement and operations personnel, is indicated. From the perspective of an effective deterrent, no amount of laboratory testing at the system or component level will ever equal the demonstrative power of a successful flight test. This is true for both adversaries and for those non-proliferant allies under the US nuclear umbrella. Flight testing reduces much epistemic uncertainty that is difficult to eliminate with absolute confidence via laboratory tests. Although more expensive, the deterrent value of flight tests is unequaled by any statements of confidence or certifications. Applying this strategy to SNL NWs governance models would suggest that the limited T&E resources should be spent on performing more flight tests. Additionally, this strategy forms the basis for integrating design engineers into the core flight testing team, rather than being absent altogether or passive observers.

Summary

Characteristics of future NW systems are difficult to predict with any certainty, but the most likely are those that are already manifested to some degree. Dormancy, low production quantities, use of commercially available parts and materials and high value for safety, security, and reliability are established NW traits that are likely to prevail into the future stockpile.

Identifying industrial products that embody some analogous characteristics to NWs yielded a broad array of product-based enterprises. Governmental and commercial industries in the aerospace field had obvious similarities, but additional areas of engineering such as civil and health-related fields also provided an opportunity to examine T&E practices that may be applicable. Based on the identification of these industries five distinct T&E approaches were identified and considered, with respect to application to NW T&E..

Conclusions

Given the need for a more cost-effective T&E program in the future that retains or improves value to the customer, a governance model for the NW enterprise could be envisioned that may include elements of strategies employed by analogous industries.

Each of the five strategies identified presented advantages and challenges inherent with the application to NW. If an amalgam of the five strategies were applied without regard to existing paradigms, the resulting program may be described by the following steps:

1. Spend more resources early in the design and production process to prevent initial defects.
2. Devote the largest portion of resources to understanding those few mechanisms within a limited number of materials well enough to develop a reasonably accurate first principles model of that system behavior.
3. Include more embedded sensors and BIT routines to collect data, but only on performance-indicating parameters.
4. Certify refurbished systems for the period before known aging mechanisms develop into performance problems then perform periodic demonstration-based and/or model-based recertification thereafter.
5. Perform higher fidelity flight tests.

In this way, a new and effective paradigm for T&E of NWs might be envisioned that provides continuing value in a more cost-effective manner.

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Biography

Sharissa Young is a geologist and materials engineer with 25 years of experience at Sandia National Laboratories and has served as project manager, program integration lead, system test and evaluation engineer during her tenure in the nuclear weapons and environmental remediation fields. She has been a certified systems engineering professional (CSEP) since 2005.

Michael W. Moulton is ____.