# Reliability Improvement with Physics Based Failure Analytics

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## *Introduction*

This paper will discuss advanced analysis of material failure that assesses how, when, why, and where failure will occur or has occurred. Recognizing that failure is actually a localized process that occurs deep within the material microstructure, physics-based 3D computational methods have been developed to predict lifecycle behavior for the grains of each individual element in a component's material substructure. That analysis is then extended to accurately predict the reliability and lifetime of a component, system, or fleet, before the first component is even built, during operation or after failure. The process involves creating a component's Virtual Twin® and simulating its behavior in a sophisticated software process known as Virtual Life Management®(VLM®).

Economic and time saving advances in product design, manufacture, operation, and maintenance have been achieved with the VLM computer simulation process. The technology models a product's microstructure and service; and performs a simulation that involves considerably reduced time, much lower cost, and higher statistical confidence than traditional physical testing. These simulations produce millions or billions of data points and render statistical confidence levels in the high ninety percent range. Moreover, testing times are reduced by factors of 20 or more and cost saving by a factor of 13 or more.

Figure 1 represents actual data comparing time and costs for traditional physical testing and VLM simulation. The medical stent "test to success" was to demonstrate 90% reliability with 90% confidence over ten years of service (400 million cycles at 50 Hz). The mechanical spring data represents a "test to failure" of five spring sizes, each to five different displacement amplitudes.

***Figure 1***
***Sample: Conventional vs. VLM Physical Testing Comparison***

| | Conventional | VLM | Ratio |
|---|---|---|---|
| Medical Device Test Time | 400 Weeks | 20 Weeks | 20:1 |
| Medical Device Test Cost | $1,000,000 | $80,000 | 13:1 |
| Mechanical Spring Test Time | 50 Weeks | 10 Weeks | 5:1 |
| Mechanical Spring Test Cost | $375,000 | $75.000 | 5:1 |

This advanced simulation analysis can support: a.) All industries[1]; b.) A wide variety of materials[2]; c.) Effects ranging from static loads - to corrosion - to fatigue - to friction –and others. Typical applications are reflected in Figure 2.

[1] VLM methodology has been successfully applied in airline, automotive, electronics, energy, heavy industry and medical device manufacturing; as well as the military and many Federal government agencies.
[2] VLM can be applied to any material that has a granular structure including metal, laminated composite, and hybrid composite structures.

***Figure 2***
***Typical Applications of VLM Advanced Simulation Technology***

| | |
|---|---|
| • Design optimization | • Warranty Claims Mitigation |
| • Life extension analysis | • Durability and Reliability Improvement |
| • Predictive and Forensic Failure Analysis | • Failure Reduction and Prevention. |
| • Operations and Maintenance Optimization | • Other applications |

## *History & Evolution*

Efforts to improve reliability by predicting and preventing failures have evolved over many years. In the most primitive times, things would break without warning, often at a most inconvenient time; resulting in costly impact and perhaps personal injury. Eventually, as science developed, engineered systems and components were created with mathematics-derived and physics-derived mechanical and structural design bases. Such design alone did not optimize reliability, however. Material science evolved causing reliability improvements through enhanced strength of materials. Still, failures continued to occur at random intervals and for a variety of reasons. Ad hoc preventive maintenance practices came along, often in the form of seasoned individuals who applied their experience and intuition to mitigate failure by timely (often premature) replacement or inspection. Operating practices have also improved the reliability of components and equipment. Frequently, sensory indications such as changes in heat, sound, and feel stimulated some form of maintenance action or operating practice change. Such sensory techniques are still employed and are valuable; but they are late indicators of problems or proximate failure…offering information that is often of limited preventive use unless inspection or remedial action can occur in the short term. Tools and techniques such as instrumentation to monitor component vibration and temperature, as well as oil analysis have augmented sensory techniques and proved to be valuable in determining the condition of machinery and components; and contributing to effective lifecycle management.

Throughout the reliability management evolution, engineering and design practices became more sophisticated and effective. Preventive maintenance practices moved beyond intuitive, ad hoc bases and became formal, well-defined programs that drove down failure rates.

Over the last 30 years, engineering disciplines have embraced computerized methods such as Computer Aided Design (CAD), Computer Aided Engineering (CAE), and Computer Aided Manufacturing (CAM). These modern tools have dramatically increased design and manufacturing productivity. But, in the view of some, the analysis of material failure has remained largely wedded to relatively old methods. Today, technology has advanced to a new level. By integrating computational material science, statistical analysis and sound engineering throughout a virtual product life cycle, more accurate and reliable forecasts can be achieved, allowing for better design, more reliable operation and more accurate predictive maintenance.

Consider large industrial facilities that have operated successfully while relying on rigorous and costly preventative maintenance programs, supplemented by corrective maintenance in anticipation of (or realization of) actual component failure. They rely on manufactures' warranty and recommendations for the nature and frequency of preventive maintenance and inspection activities. This has been helpful; but such recommendations are often based on deterministic analysis or engineering judgement with, perhaps conflicting customer and vendor interests. Occasionally these recommendations may even be based on historical failure data with limited consideration to operating modes and environment. Facility operators must rely on this vendor input and the traditional practices mentioned above to fashion reliable operations and maintenance programs.

High risk/ high impact industries (such as in aerospace, medical device, military, and nuclear power) require very accurate, timely and cost-effective means for improving and often ensuring reliability. If an operator or manufacturer desires a high degree of confidence in equipment reliability; or if a regulator dictates it, extensive testing and certification can be accommodated at the expense of time and money. In such industries, reliability is often increased by incorporating multiple redundancies to back up sub-system or component failures. Redundancy provides added assurance of system operational reliability; but it does not affect component or subsystem failure propensity.

Laboratory or shop testing of many identical products is expensive and slow; and worse, inaccuracies lead to costly overdesign with large safety factors. This overdesign often leads to products that are larger, heavier, more expensive and less competitive…and perhaps, in actual deployment, only marginally more reliable. Consider that automobile door hinges that are cycled numerous [maybe millions] of times at a test facility to determine when a hinge will fail. Sometimes the tests must be conducted in a variety of environments to replicate multiple lifecycle conditions. The results of this physical testing are then ascribed to all door hinges in the specific car design.

In another method of prognosticating product life, historical product failure data is obtained from physical operators. Mean time to failure is statistically determined and used as a basis for further analysis, to predict the future life of similar products, and to recommend inspection and replacement timeframes. Clearly, this historical approach is reactive and does not necessarily address the reliability of a production batch that occurs after the analyzed group. There may be indirect, low confidence correlation with subsequent production runs; however, inconsistencies in the production process or factors such as operating and maintenance practices or environmental conditions may not be considered.

The following section addresses the next step on the reliability improvement continuum.

## *Disruptive Breakthrough Technology*

Advances in computational computing systems, computer aided design and the creation of a material microstructure genome has facilitated the confluence of material process analysis, mechanical/structural analysis, statistical analysis, finite element analysis, and probabilistic assessment software… resulting in the VLM technology. VLM is a computational simulation that accurately and efficiently predicts the real world physics of **how, when, why and where** damage occurs and products wear-out and fail. VLM technology is built on three fundamental principles:

1. Durability is not a function of applied stress, alone, but rather a combination of that stress and the material's reaction to it. [3]
2. The materials used to build complex components and systems are not homogenous.

[3] A manufactured component is really an assembly of millions of individual material grains of minute size that have been formed together to make up its microstructure. The process of manufacturing creates a variety of material microstructure complexities within each product coming off the assembly line. In the field, as products are flown, driven, pushed, pulled, heated, cooled, or exercised in any combination of ways, stress is imparted on the product and absorbed throughout its material microstructure. Computational software like Finite Element Analysis (FEA) predicts how this energy is distributed in unequal patterns. However, it's well known that not all product failures occur at the highest stress areas, nor do they originate at the global component level where FEA is applied.

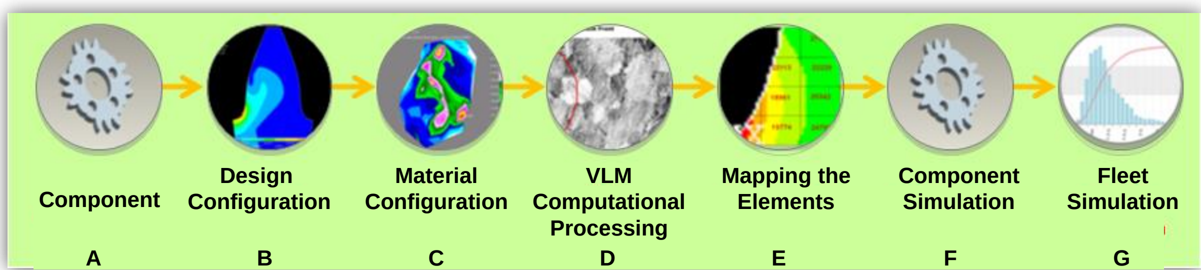
3. Computer cycles are shorter and cheaper than physical testing cycles or prototyping.

Using these ideas as a foundation, VLM technology creates a computational framework that accurately accounts for a material's a.) reaction to the stress imparted upon it; b.) its variability, c.) the various damage mechanisms, d.) its geometry, and e.) the conditions of its usage over time. VLM models material at its fundamental level: its microstructure. Simulating microstructure is important since it plays the key role in determining when, where and how failures are initiated and propagated. In addition to simulating every grain within the microstructural arrangement, VLM also simulates the effects of voids, inclusions, defects, grain boundaries, etc…. in short, all the various features that are derived from real world processing, to determine how they, too, will react to the stress energy imparted upon them. Cloud computing enables the VLM technology to conduct hundreds of billions of simulations in processing times measured in hours rather than months or years. The simulation addresses each individual grain in the component's material microstructure and computationally integrates the results into product, population and fleet-level reliability and life estimates. Therefore, in VLM analysis, the probability of degradation is predicted for every simulated grain; and component durability is derived by aggregating the results of those millions of grain degradation simulations.

The VLM state of the art reliability analysis and assurance tool has been used in a number of industries for over fifteen years. It is a technology that has been proven time and time again in real life applications. The patented VLM predictive analytics and reliability services explain "Why, How, When and Where" product damage will occur over time and what can be done to mitigate the situation and improve reliability. VLM has helped companies resolve in-service product performance and reliability issues related to cyclic fatigue, wear and corrosion; reduce operational downtime, conversion costs, and capital expense; and accelerate product development and time to market for new products.

A complex set of sub processes and iterations make up the VLM approach. Figure 3 depicts the steps involved in creating a component and fleet failure analysis.

***Figure 3***
***Graphical Representation of VLM Process***




A: Schematic representation of a gear e.g. CAD drawing
B: The stress in a gear tooth
C: Finite elements further divided into the granular structure.
D: The initiation and propagation of externally induced defects is established
E: The granular situation is mapped to the finite element
F: Individual elements are aggregated and analyzed at the component level
G: Component data is aggregated and analyzed at the fleet level.

## *Applications and Case Studies*

There are numerous proven and cost-effective VLM applications in various industries, spanning the early specification and design process, through manufacturing and shop testing, and continuing through the entire life cycle of a component.

For example: in a time where coal plants are called upon for cycling duty, the value of reliable and independent forecast data for boiler tube or high energy piping cycling impacts would be valuable. In addition independent analysis of inspection and overhaul recommendations based on the number of gas turbine starts could be valuable in scheduling outages in the face of high demand for electricity. VLM can analyze the effects of cycling with a higher level of certainty than current methods…and in a more time and cost effective manner.

For operating systems, the VLM analysis can usually be performed in a non-intrusive manner with no down time. Failure or degradation forecasts as well as O&M improvement recommendations for chronic problems with components such as bearings, gears, shafts, fan or turbine blades, bellows, seals, nozzles, or other components can be developed. The VLM analysis has a history of extending the life of components, optimizing maintenance practices, and resolving design problems of such components; often saving time by a factor of 20 or more and cost by a factor of 15 or more.

Figure 4 represents a sample of actual savings that were realized using VLM technology.

***Figure 4***
***Actual VLM Results***

| Company | Successes Achieved With VLM Technology |
|---|---|
| **Airline Company** | $4 M/yr saved on bearings with simple lube changes[4] |
| **Large Engine Manufacturer** | $5 M saved from $150K investment |
| **Medical Device Company** | 50% Reduction in testing time.[5] |
| **Oil & Gas Co.** | $12 M /yr saved on equipment leasing |
| **Fortune 500 Co.** | $3 M saved in manufacturing line maintenance |
| **Fortune 100 Co.** | $250 K/month on machining efficiencies |
| **US Army** | Tank Vehicle Maintenance Optimization |
| **Auto Manufacturer** | Early Adopter using VLM software since 2001 |

[4] FAA has approved use of VLM analysis on first stage turbine engine blade repair and for Auxiliary Power Unit bearing maintenance and operational protocol.
[5] The Food and Drug Administration (FDA) is studying the use of VLM to quickly and accurately evaluate the efficacy and safety associated with medical device applications.

## *Turbine Blades*[i]

As an example, a leading cost of engine repair in commercial airlines is the replacement of the first stage engine blades. The leading edge of the blades erodes with time; lowering engine efficiency and increasing fuel consumption. Each new blade costs tens of thousands of dollars and each engine requires several dozen replacement blades. A set of replacement blades can thus cost half a million dollars. VLR was employed by a blade manufacturer to assess the fatigue durability of an innovative blade repair process that involved cutting out the eroded leading edge and electron beam (EB) welding in a replacement leading edge. The cost of the blade repair was less than 10% of the cost of a new blade. A VLM computational microstructural durability analysis was performed on the original replacement blade and on the EB repaired blade. The EB repaired blade was predicted to have the same durability as a new blade. A limited number of physical tests were performed to verify the predictions.

In addition, the EB repaired leading edge material was optimized for erosion resistance. Although the erosion optimized material would not be advisable for the entire blade, judicious application to the leading edge allowed this repaired blade to have the same fatigue durability but better erosion resistance than a new blade. The computational durability analysis was used to support FAA approval. Today, the blade vendor is the only company in the world to receive FAA DER (Designated Engineering Representative) approval for chord restoration on a first stage fan blades such as leading edge replacement.

There are indeed differences between commercial airline applications and other industries; however, the process and value proposition is much the same: to take advantage of all available information and computational durability analysis for the purpose of decreasing maintenance cost and increase availability of the system. VEXTEC has worked with commercial airlines, their suppliers and regulators to assess the acceptability of replacement parts.

## *Bearings*[ii]

Availability is another cost driver in the commercial airline business. Airlines do not have spare aircraft. When an aircraft must be grounded for unexpected maintenance, there is a ripple effect throughout the system. This is especially true for wide-body long-range aircraft because smaller aircraft cannot replace them. A major airline used VLM to assess the durability of a replacement main bearing for the Boeing 777 auxiliary power unit. The 777 fleet was experiencing three to four unexpected bearing failures per year at a cost of $1M per incident.

A computational microstructural durability analysis was performed on the failed bearing and a replacement bearing. It was found that the replacement bearing would not decrease the number of incidents. The computational durability analysis of the original bearing was expanded to assess changes in operating protocol and lubricants. **A combination of a new operating protocol and a different lubricant was found to reduce the number of incidents.** The computational durability analysis was used to support FAA certification of the changes and no incidents have occurred since the changes were instituted.

## *Piping*

An oil and gas company wanted to assess two different grades of steel pipe; the more expensive, higher grade, pipe would cost $12M more per year. A computational durability simulation was performed and found that the high grade steel had significantly better properties for the typical highly polished tests specimens, but for the "as-used" i.e., slightly corroded surface that existed in real pipes, the different steel grades had essentially the same durability.

## *Turbocharger*

An automotive turbocharger manufacturer wanted to replace an expensive, directionally solidified, grain material process with an inexpensive equiaxed grain process. Initial testing showed that a highly controlled equiaxed process would produce a product with equal if not better durability. A VLM computational durability simulation was performed on the product microstructure that would result from the more realistic and less controlled full production process. It was found that the production process would generate a product with significantly reduced durability.

## *Medical Devices*[iii]

Medical device companies invest heavily in extensive test programs before they apply for FDA certification. One major medical device vendor was performing development tests on an airway stent with nitinol material provided by two different suppliers. Both suppliers performed equally well in cyclic fatigue test with a limited number of specimens. VLM durability simulation on a large population of stents with the two different materials found that each supplier had the same average cyclic lifetime but one material had significantly higher minimum (-3 sigma) cyclic lifetime. This allowed the engineers to perform certification testing on the material with the best minimum properties greatly reducing test time and test cost of evaluating two materials.

## *Closing*

VLM simulation has provided significant value for a variety of materials and in numerous applications, including:

- Predicting **how, when, why,** and **where** damage occurs and products wear-out and fail
- Designing products with less expensive metals, alloys, or composites
- Avoiding excessive and costly factors of safety and redundancies
- Reducing or eliminating physical testing
- Accelerating new product time to market
- Reducing failures during operation
- Reducing warranty claims and financial accruals
- Obtaining credible forensic failure analysis
- Assessing plant life extension factors
- Optimizing operation and maintenance costs


## *Keywords*

- Asset Reliability
- Best Practices
- Cost Savings
- Equipment Failure
- Equipment Reliability
- Failure Analysis
- Life Extension
- Life Cycle Improvement
- Maintenance Optimization
- Operations Optimization
- Root Cause Failure Analysis
- Warranty Risk Reduction
- Time to Market
- Component Testing
- Design Optimization

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[iii] Ref : S. Kulkarni, G. Krishnan, C. Clerc, K. Merdan and R. Tryon, “Using Probabilistic Computational Durability Modeling and Simulation to Create a Virtual Design of Experiments Based on Limited Laboratory Tests,” J. Med. Devices 7(4), 2013.