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DFR - Moving from 4 Traditional to 33 Innovative Ways to Improve Reliability

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ABSTRACT

Problem: *The traditional four (4) methods for improving reliability; 1) High design safety margin, 2) Reduction in component count or system architectural complexity, 3) Redundancy, and 4) Back-up capability, are often ignored or perceived as being excessively costly in weight, space claim as well as money.*

Solution 1: *Discussed here are the practical and very cost effective methods for achieving improved reliability by Functional Interface Stress Hardening (FISHtm or FISHingtm). The Author has been able to apply FISH to eliminate 70-92% of unscheduled equipment downtime, within 30-60 days, for more than 30 of the Fortune 500 and many other large companies which utilize automation controls, computers, power electronics and hydraulic control systems.*

Solution 2: *From Structured Innovation the 33 DFR Methods & R-TRIZ Tool can be used to grow or improve reliability, via rapid innovation. The R-TRIZ tool) is provided so that users can instantly select the best 2, 3 or 4 of these 33 Principles for eliminating the PoF, thus solving any given reliability constraint or problem.*

Reliability is the key driver of minimal warranty support costs. Reliability is a key driver trustworthy design, product reputation and expanding market share. Reliability is key to bottom line profitability. DFR is likewise essential to supporting missions of the US Army.

INTRODUCTION

The reliability and Design for Reliability (DFR) guidelines, discussed, here, are based on established design principles and rapid innovation methods for failure avoidance. These guidelines can move you, your design team and your organization from one which simply tracks, charts, and reports reliability, to one that engages meaningful Design for Reliability (DFR) activities and initiates powerful but inexpensive corrective actions; resulting in maximum equipment availability and reliability. Your organization can thus be one that achieves and exceeds reliability requirements and improves product image and sales, due to a product reputation for reliability and quality. The 4 traditional methods for improving reliability are discussed in some detail:

1. Design margin improvement
2. Component complexity reduction
3. Redundancy
4. Back-up capability

Functional Interface Stress Hardening; Cushioning, Lubricating, Insulating and Cooling (FISH-CLIC) explains how to make design margin improvements cost effectively.

The traditioinal 4 methods are then expanded, from 4 to 33 methods or ways, by providing the 33 DFR Principles which apply to reliability from "TRIZ structured innovation methodology", introduced into the USA in 1998. A working knowledge is provided for use of the R-TRIZ tool, an easy to use reference table, so that users can instantly select the best one or two DFR principles, applicable from over 200,000 patents, for solving their immediate reliability problem.

1.0 MANAGE FAILURE RATE FROM STRESS vs. STRENGTH INTERFERENCE

Component design reliability is improved by increasing safety margin. Safety margin is increased by reducing interference or overlap of each applied stress and the component's strength distributions. Figure 1. The probability of failure is shown in the figure below, where the red, left stress distribution exceeds or overlaps the strength distribution curve. The larger area of overlap, the larger probability of failure, and the higher failure occurrence rate to be expected. Optimization of component design safety margin can be obtained through specific stress reduction efforts and/or improved material strength enhancements.

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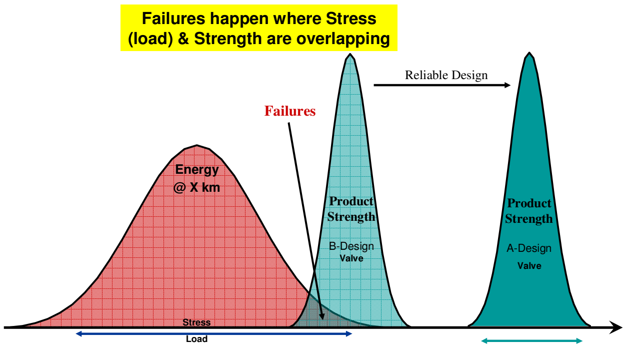

Figure 1 Stress vs. Strength Curves

The life expectancy profile, Figure 2, a.k.a. reliability "bath-tub" shape curve, plots hazard or instantaneous failure rate versus time. Understanding and mitigating the causes of failure at each phase of this curve, will help to minimize early life failures, lower the magnitude of useful life failures, and shift wear-out failure occurrence further to the right.

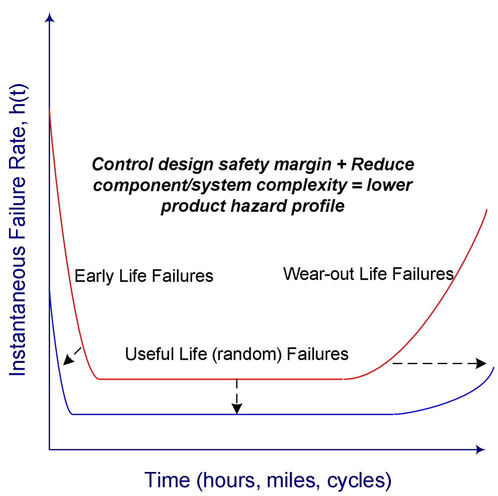

Figure 2 A Product's Normal Failure Profile (Reliability Bath-tub Shaped Curve)

1.1 Four General Design Guidelines

There are four (4) traditional strategic approaches to achieve the reliability growth or improvement, outlined above. These are applied to the material/hardware or to functional interfaces responsible for generating or inducing the stress applied to material/hardware being negatively affected by the stress:

a). Increase average material strength. Use stronger material with geometric or integral modifications which:

1. adds strength,
2. decreases stress concentration points, or
3. provides material surface mitigation.

b). Decrease material strength variation – by improving material processing controls or apply tighter screening tests to remove infant mortality failures, achieve higher quality level, and gain higher levels of component maturity, reliability and reduce part-to-part variation.

c). Decrease the applied average and peak stress to the material, by limiting stresses on parts, via: 1. part stress de-rating, 2. interface stress hardening, suppression, cushioning, lubrication, isolating, insulating, cooling or conditioning; 3. protection or removal of material from stress concentration points, or 4) structural thermal cooling.

d). Decrease the applied stress variation to the material, by applying limitations to use conditions such as; filter stress, harden or implement barrier(s) from stress i.e.: steel case hardening, aluminum anodizing, epoxy coating, painting, insulating, adding a hydraulic accumulator as a barrier against hammering or surges, or adding electrical "surge protection," etc.

1.2 How to Apply FISH to Improve Reliability

To demonstrate the power of and quickly explain the applicable methodology for approaches "c." and "d." (above), for improving reliability, this author coined the acronym, FISH-CLIC, in 2003.

By remembering the acronym FISH, one is reminded that most things in life, and things man-made, fail at Functional Interfaces, because of Stress (FIS). And, what is needed to achieve or improve reliability is to simply "Harden" FIS(H) or protect components from root-cause stresses, coming through various interfaces. Approaches c) and d), above, explain how this "Hardening" or protecting can be accomplished (without component redesign).

To make more memory accessible, the various concepts in c) and d), an expanded acronym serves well; FISH-CLIC. Now, the various means of reducing failure rate are included: (F)unctional (I)nterface (S)tress (H)ardening, via. surface (H)ardening or by (C)ushioning, (L)ubricating, (I)nsulating or Isolating, or by (C)ooling or Conditioning (FISH-CLIC). By reducing stress on components, via their Interfaces, failure rate is dramatically reduced. Manufacturing and IT companies applying FISH methods on fielded equipment have reduced failure rates by 70-92%, meaning reliability (MTBF) jumped by 500 – 1,250%. Guidelines c) and d) are extremely powerful to achieve reliability growth. One simply must "go FISH" to achieve Reliability.

1.3 Improving Design Safety

Margin Related to section 1.1.a - d., the measurement of an estimated design safety margin (DSM) can be calculated for each specific functional area that is influenced by the applied magnitude of stress and the part or system strength. This safety margin, "s" can be calculated using a ratio of the applied stress mean and the material strength mean:

Estimated Safety Margin, DSM = $\mu strength/\mu stress$

where: DSM = design safety margin, exists when s>0
$\mu strength$ = material mean strength parameter
$\mu stress$ = applied mean stress parameter

Higher safety margin ratio suggests an estimated greater reliability, but the actual DSM must consider lowering the Interference or overlapping of stress and strength distributions.

The Interference area "I" which influences failure instances, where stress exceeds the strength, is more completely defined by the overlap of these stress and strength distributions, based on their statistical mean and variance parameters. A large gap between the tail of the stress distribution upper limit and the strength distribution lower limit would correspond to the optimal amount of design safety margin (DSM). Actual DSM corresponds to the probability of failure and is a function of the difference between both probability density functions (pdf) for the stress and strength distributions. A calculation for the probability of failure or unreliability, regardless of the specific stress and strength statistical distribution type, is defined as follows:

$$I = 1 - P(X>Y)$$

where: I = interference (probability of failure)
X = random variable for strength
Y = random variable for stress

Interference for a "normally distributed" random variable for stress and strength, assuming population variances are unknown and not equal:

$$I = 1 - \Phi\ (\mu strength-\mu stress)/[(\sigma 2strength - \sigma 2stress)1/2]$$

where: Φ = standard normal CDF
$\mu strength$ = mean variable for strength
$\mu stress$ = mean variable for stress
$\sigma 2strength$ = variance variable for strength
$\sigma 2stress$ = variance variable for stress

1.5 *Calculating Reliability from Stress-Strength Interference*

Interference calculations as a function of the specific physical parameter (i.e. pressure, voltage, vibration, heat, etc.) for different stress and strength distributions can be performed once the distribution types; normal, lognormal, Weibull, etc. for the random variables are defined. The mathematical difference in the stress and strength probability density functions can be calculated to approximate the Interference or probability of failure, as a function of the stress-strength physical parameter, x (see figure below):

$$I(t) = 1 - [fstrength(x) - fstress(y)]$$

where:
I = interference (probability of failure) or proportion of the stress distribution that overlaps the strength distribution, as a function of physical parameter, x

fstress(y) = probability density function for the stress distribution as a function of physical parameter, x (based on a stress usage profile – frequency of applied stress)

fstrength(x) = probability density function for the strength distribution as a function of physical parameter, x (based on construction variability)

Stress and strength pdf may be represented by different parametric distributions each with specific input statistics (mean, variance and shape parameter).

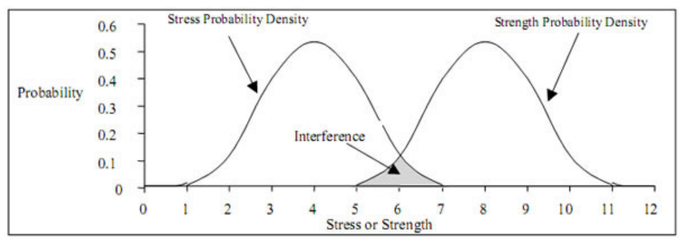

Figure 3 Interference of Stress vs Strength

To determine the life expectancy as a function of time t one can use the inverse power model for mechanical or thermal fatigue physics of failure mechanisms:

$$Life\ (s) = 1/K(s)^n$$

$$\ln(Life) = -\ln(K) - n \ln(s)$$

where:
Life (s) = time until the part exhibits failure based on the stress induced physics of failure mechanism(s)
K = the intercept of the S-N curve (applied stress – time or cycle of operation to failure) to be found experimentally from testing parts at different stress levels and recording time to failure
n = slope of the S-N curve from experimental step-stress data (see Figure 3)

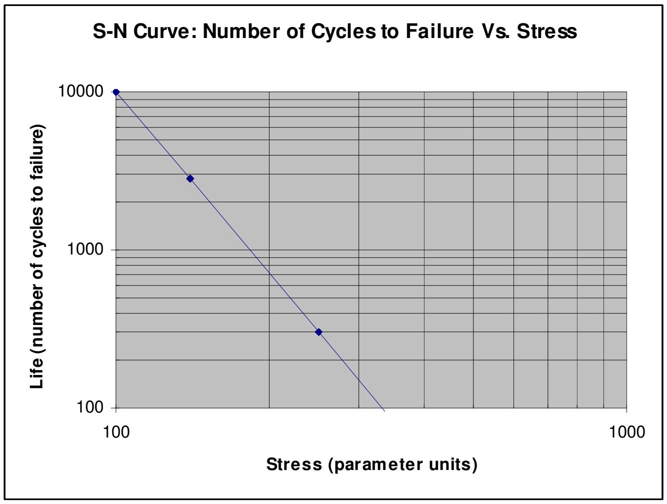

Figure 4 Stress vs. Cycles to Failure

Other basic life-stress models can be used to address other physics of failure mechanisms for a part as a function of time. Thus, the four (4) traditional reliability methods have been discussed;

1. design margin improvement,
2. component complexity reduction,
3. redundancy and
4. back-up capability.

Redundancy and back-up capability, one might argue, "is not really a method of increasing reliability. Rather, these increase "effective reliability." More failures will occur, as there are more components, the back-up parts, have been added to the system, along with their probability of failure.

Yet, "effective reliability" is improved, meaning the system is kept functioning when a failure does occur, yielding effective reliability.

The goal should always be to design the most cost effective system which will meet or exceeding the Customers functional reliability requirements. Therefore, in Part 2.0, we will take a first time look at lessons learned, from the 33 TRIZ, structured innovation, DFR principles. These are 33 approaches, or design principles, extracted from more than 200,000 patents, to solve reliability problems.

2.0 APPLYING THE 33 DFR PRINCIPLES FROM R-TRIZ STURCTURED INNOVATION

It is most appropriate, then, in a comprehensive DFR discussion or guideline, that Part 2 focus on the 33 DFR principles or approaches, which can be extracted from TRIZ, and which can be used to mitigate or redesign for reliability. These 33 DFR principles are not mutually exclusive from the four (4) traditional principles discussed above. In some cases these 33 DFR principles simply help shift paradigm, to more rapidly and cost effectively implement one of the 4 traditional methods. In other cases just one or two of the 33 principles can be applied to completely remove the reliability constraint, conflict, problem, or failure mode. In such cases the 4 traditional methods are no longer needed. The DFR principle facilitates an innovative redesign solution which not only eliminates critical failure modes, but also increases reliability with decreased weight, decreased cost, decreased part count, increased manufacturability, safety, etc..

2.1 R-TRIZ Tool for Rapid DFR Solutions

An easy to use DFR tool was created to quickly identify the best DFR principle(s) to apply, by identifying the conflicting design parameter, in left-hand column. Figure 5.

Reliability is one of 39 Design Parameters identified by Genrich Altshuller in his TRIZ study of over 200,000 patents. Therefore, the DFR tool was built by simply extracting all information from the Reliability column-27, in Altshuller's complex TRIZ Matrix, to form a simple Reliability solutions look-up table.

2.2 TRIZ – The Origin and Power of TRIZ

A Russian acronym meaning Theory for Inventive Problem Solving, was developed by Genrich Altshuller (1926 – 1999). Some now refer to Altshuller's work as structured innovation. Altshuller studied, sorted and classified over 200,000 patents to determine how inventors are able to solve the thousands of problems that the rest of us simply stare at. He discovered that the technical contradiction or problem solved in any given patent, was solved using one or two of only 40 design principles. Across all these patents, he also discovered the problems to be solved could be expressed as a conflict between two or more of only "39 design parameters", a.k.a. design characteristics. Since establishment of the USA TRIZ Association and the American TRIZ Institute in 1999, these 39 Parameters and 40 Principles have been verified across some 400,000 patents, without need for additional Parameters or solution Principles.

Therefore, the first Guideline for DFR might be to have every reliability engineer and every design engineer memorize these 40 principles and learn when to use each? Applying these 40 principles to ones next design, should save time and improve the design, or facilitate another patentable break-through. One can, at least, more quickly and completely eliminate design constraints and achieve reliability while improving functionality and quality. The engineer need not memorize all 40 Principles, nor know when to use them, because the structure and process of TRIZ guides him quickly to the right solution Principles for any given technical contradiction, or problem.

Extracting all Reliability information from TRIZ yields the R-TRIZ Tool, below. Use this straight forward extraction of the 39 Parameters with their general Reliability solutions.

When a design parameter or characteristic (left column) is in conflict with or negatively impacts **Reliability**, use these **TRIZ** Principles or Approaches (right-hand 4 Columns) to **Reclaim Reliability.**					
Param #	**Select Parameter or Characteristic restricting or impacting Reliability** (below):	**DFR TRIZ Solutions** Approach-1	Approach-2	Approach-3	Approach-4
1	Weight of a mobile object	1	3	11	27
2	Weight of a statioinary object	10	28	8	3
3	Length of a mobile object	10	14	29	40
4	Length of a stationary object	15	29	28	
5	Area of a mobile object	29	9		
6	Area of a stationary object	32	35	40	4
7	Volume of a mobile object	14	1	40	11
8	Volume of a stationary object	2	35	16	
9	Speed	11	35	27	28
10	Force	3	35	13	21
11	Pressure / Stress / Tension	10	13	19	35
12	Shape	10	40	16	
13	Stability of the object's composition	(No help. Increasing stability should increase reliability)			
14	Strength	11	3		
15	Duration of action of a moving object	11	2	13	
16	Duration of action of a stationary object	34	27	6	40
17	Temperature	19	35	3	10
18	Brightness (Illumination Intensity)	(No help)			
19	Energy spent by moving object	19	21	11	27
20	Energy spent by stationary object	10	36	23	
21	Power	19	24	26	31
22	Loss of Energy	11	10	35	
23	Loss of substance	10	29	39	35
24	Loss of information	10	28	23	
25	Loss of time	10	30	4	
26	Amount or Quantity of Substance	18	3	28	40
27	Reliability				
28	Accuracy of measurement	5	11	1	23
29	Accuracy of manufacturing	11	32	1	
30	Harmful factors acting on an object from outsi	27	24	2	40
31	Harmful factors developed by an object	24	2	40	39
32	Manufacturability				
33	Convenience of use (Ease of operation)	17	27	8	40
34	Repairability (Maintainability) Ease of Repair	11	10	1	16
35	Adaptability or versatility	35	13	8	24
36	Complexity of a device	13	35	1	
37	Complexity of control (difficulty detecting or me	27	40	28	8
38	Level of automation	11	27	32	
39	Capacity / Productivity	1	35	10	38

Figure 5: R-TRIZ Tool yields 3 or 4 best approaches to solve any reliability problem

2.3 Innovate Reliability with "33 DFR Principles

The 33 Principles applicable to DfR and called out in the R-TRIZ Tool, under "DFR TRIZ Solutions" are here listed:

1. Segmentation

• Divide an object into independent parts.

• Make an object sectional

2. Extraction, Separation, Removal, Segregation

• Extract the "disturbing" part or property from an object.

• Extract only the necessary part or property from an object.

3. Local Quality

• Transition from homogeneous to heterogeneous structure of an object or outside environment (action).

• Different parts of an object should carry out different functions and/or placed under conditions that are most favorable for its operation

4. Asymmetry

• Replace symmetrical forms with asymmetrical form(s).

• Increase its degree of asymmetry.

5. Combining, Integration, Merging

• Consolidate in space homogeneous objects, or objects destined for contiguous operation.

6. Universality, Multi-functionality

• An object can perform several different functions; therefore, other elements can be removed.

8. Counterweight, Levitation

• Compensate for the weight of an object by combining it with another object that provides a lifting force.

9. Preliminary anti-action, Prior counteraction

• Preload counter-tension to an object to compensate excessive and undesirable stress.

10. Prior action

• Perform required changes to an object completely or partially in advance. (PM or CBM or replace before mission)

• Place objects in advance so that they can go into action immediately from the most convenient location. (spare parts locally ready)

11. Cushion in advance (FISH-CLIC), or compensate before.

• Cushion by installing or replacing cushioning, shock absorbing, or shielding

13. Inversion, The other way around

• Instead of the direct action dictated by a problem, implement an opposite action (i.e., cooling instead of heating).

• Turn an object upside-down, inside-out or inverted.

14. Spheroidality, Curvilinearity

• Replace linear parts with curved parts, flat surfaces with spherical surfaces, and cube shapes with ball shapes.

• Use rollers, balls, spirals. Use rotational motion.

15. Dynamicity / Optimization

• Characteristics of an object or outside environment, must be altered to provide optimal performance at each stage of an operation. Or, if an object is immobile, make it mobile, or flexible. Make it interchangeable.

16. Partial or excessive action

• If it is difficult to obtain 100% of a desired effect, achieve more or less of the desired effect.

17. Moving to a new dimension

• Transition one-dimensional movement, or placement, of objects into two-dimensional; two-dimensional to three-dimensional, etc.

• Utilize multi-level composition of objects.

• Incline an object, or place it on its side.
18. Mechanical vibration/oscillation
• Utilize oscillation. If oscillation exists, increase its frequency to ultrasonic. Use the frequency of resonance.
19. Periodic action
• Replace a continuous action with a periodic action.
• If the action is already periodic, change its frequency.
• Use pauses between impulses to provide additional action.
21. Rushing through
• Perform harmful operations at a very high speed.
23. Feedback
• Introduce feedback.
• If feedback already exists, change it.
24. Mediator, intermediary
• Use intermediary object to transfer or carry out an action.
26. Copying
• A simplified and inexpensive copy should be used in place of a fragile original or an object that is inconvenient to operate.
• If a visible optical copy is used, replace it with an infrared, ultraviolet or digital copy.
• Replace an object (or system of objects) with their optical or digital image. The image can then be reduced or enlarged.
27. Cheap, disposable objects
• Replace an expensive object which may be compromised by other properties (ie. Longevity or reliability), with a cheap version, or a digital model.
28. Replacement of a mechanical system with 'fields'
• Replace a mechanical system with a magnetic, optical, acoustical, thermal or olfactory system.
29. Pneumatics or hydraulics:
• Replace solid parts of an object with a gas or liqud (use air or water for inflation, or use pneumatic or hydrostatic cushions)
30. Flexible membranes or thin film
• Replace customary constructions with flexible membranes or thin film, or isolate an object from its outside environment with flexible membranes or thin film.
31. Use of porous materials
• Make an object porous, or use supplementary porous elements (inserts, covers)
• If an object is already porous, fill pores in advance with some substance.
32. Changing color or optical properties
• Change the color of an object or its environment.
• Change degree of translucency of an object or its environment.
• Use color additives to observe an object, or process which is difficult to see. Or, employ luminescent or tracers.
34. Rejection and regeneration, Discarding and recovering
• After completing its function, or becoming useless, an element of an object is rejected (discarded, dissolved, evaporated, etc.) or modified during its work process.
35. Transformation of the physical and chemical states of an object, parameter change, changing properties
• Change the physical state of the system, temp or volume.
• Change the concentration, density, or flexibility.
36. Phase transformation
• Using the phenomena of phase change (i.e., a change in volume, the liberation or absorption of heat, etc.)
38. Use strong oxidizers, enriched atmospheres, accelerated oxidation
• Make transition from one level of oxidation to the next higher level: (Ambient air to oxygenated, Oxygenated to oxygen, Oxygenate to ionized oxygen, Ionized oxygen to Ozoned oxygen, Ozoned oxygen to ozone, Ozone to singlet oxygen)
39. Inert environment or atmosphere
• Replace a normal environment with an inert one.
• Introduce a neutral substance or additives into an object.
• Cary out the process in a vacuum.
40. Composite materials
• Replace homogeneous material with composite ones. Find or develop a more ideal (nano-tech) material

Of course one cannot, nor should he, apply all these Approaches on any given design. Nor will any single Principle solve all reliability problems.

However, with the R-TRIZ Table, Figure 5 (above), one can quickly determine which 3 or 4 of these Principles can best solve a particular reliability problem. The user determines which of the 39 Parameters, from the left column of the Table is negatively affecting reliability. A solution can be derived from one or some combination of the Approaches to the right.

These are general design principles or approaches, not a final specific design solution. With the 3 or 4 best general solution principles identified, a specific solution is more easily determined. It may help ones specific design to combine two or three of these approaches, to further improve reliability. TRIZ methodology also suggests, from its patterns of system evolution, that the best move may be to eliminate the problem component or subsystem all together, if its function is not needed. Or, if the function is needed, can the system, or super system, be altered to perform the function of the component being removed?

Identify your current design's reliability problem and see how R-TRIZ would suggest solving the problem. The user should have a solution in less than an hour. Genrich Altshuller often said and demonstrated, "You can wait a hundred years for enlightenment, or you can solve the problem in 15 minutes with these principles."

2.4 Case Study Example

The presentation slides, accompanying this paper, step through one actual example DFR case where the R-TRIZ tool was used, in a 35 minute rapid innovation session, to solve a 5 year standing reliability problem: One of eight catch-and-drag "stops" on a critical set of telescoping rails was failing. The stop in position 3 of the left-hand rail would randomly sheer off the rail. Manufacturing tried adding epoxy under the stops, as they were screwed into place, but this failed to improve reliability. So, before the redesign DFMEA was started, the reliability engineer suggested attacking this one critical seen failure mode with a 30 minute structured innovation/solution session. The R-TRIZ Tool was used. An ideal design concept resulted, which eliminated the failure mode completely, eliminated rail part count by 3 to 1, which cut manufacturing labor hours by better than 3 to 1 and further improved reliability. Actually two improved design concepts were derived. Both were built and both passed all verification testing and were put into limited rate production. Both are being tracked for actual cost and reliability, over time.

By understanding and employing both the 4 traditional ways, including FISH-CLIC, and these 33 innovative ways to design for reliability, rapid and required improvements in reliability, at the component, subsystem and/or system level, should become much more cost effective and become the norm rather than the exception.

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BIOGRAPHY

Howard C Cooper is a Reliability Engineer for General Dynamics, facilitating engineering teams through the Design for Reliability (DFR) process. He is a Design for Six Sigma Black Belt, specialized at facilitating FMEA and TRIZ Structured Innovation. Previous to GDLS he worked DFR at GE Medical Systems and spent 26-years consulting on reliability issues for manufacturing automation controls and computer controlled machine tools. His focus was helping Fortune 500tm companies eliminate 70% - 92% of their unscheduled equipment downtime, in 30-60 days! He coined the phrase, FISH™ (Functional Interface Stress Hardening), to explain how dramatic reliability improvement can be achieved during development and for fielded equipment. His seminar: "How To FISH – Eliminating 70-92% of Your Unscheduled Equipment Downtime in 30-60 Days" is often rated as "most valued seminar of my career" by operations, maintenance and plant engineers, manufacturing and plant managers. Mr. Cooper received a B.S. degree from SUU, in Math and Industrial Technology and did M.S. work in Technical Education at BYU.

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