Physics of Failure Laws Using Thermodynamic Degradation Science

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SUMMARY AND PURPOSE

This tutorial brings a new perspective as we will use a relatively new approach with Thermodynamics degradation Science. We explain how this energy approach provides different tools to help understanding the degradation process and in developing useful aging laws to analyze important reliability problems. Thermodynamic Degradation Science (TDS) merges the Science of Physics of Failure with thermodynamics.

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Alec Feinberg received his Ph.D. in physics from Northeastern University in 1981. He is the founder of DfRSoft, a software and consulting company where he now works. He is the principal author of the book *Design for Reliability*. Alec has 30 years of experience in the area of reliability physics working in diverse industries including AT&T Bell Labs, TASC, M/A-COM, and Advanced Energy. He has provided reliability engineering services in all areas that include solar, thin film, power electronics, defense, microelectronics, aerospace, wireless electronics, and automotive electrical systems. He has provided training classes in Design for Reliability, Shock and Vibration, HALT, Reliability Growth, Electrostatic Discharge, Dielectric Breakdown, DFMEA, and Thermodynamic Reliability Engineering. Alec has presented numerous technical papers and won the 2003 RAMS Alan O. Plait best tutorial award for the topic *Thermodynamic Reliability Engineering*. Alec is also the author to the new book, Thermodynamic Degradation Science, Physics of Failure, Accelerated Testing, Fatigue and Reliability Applications of which much of this tutorial is based on. Alec is available to provide consulting and to give training classes in Thermodynamic Degradation Science, Design for Reliability, and Shock and Vibration through the author's website at www.dfrsoft.com.

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1. INTRODUCTION (slides 1-12)

Much of the material in this tutorial is based on the authors new book, Thermodynamic Degradation Science, Physics of Failure, Accelerated Testing, Fatigue and Reliability Applications [1]. The reader will find these topics and much more in this reference.

Thermodynamic degradation science is a new and exciting discipline. There are many different ways to approach the science of degradation. Since thermodynamics uses an energy perspective, it is a great way to analyze such problems and develop aging laws. Thermodynamic Degradation Science (TDS) merges the Science of Physics of Failure with thermodynamics [2-6].

When we think of thermodynamic degradation, whether it be for complex systems, devices, or even human aging, we begin to realize that it is all about "order" being converted to "disorder" due to the natural spontaneous tendencies described by the Second Law of thermodynamics to come to equilibrium with the neighboring environment [7,8]. Although most people who study thermodynamics are familiar with its second law, not many think of it as a good explanation of why a product degrades over time. However, we can manipulate and phrase it as [1]:

> *Second law in terms of system thermodynamic degradation: The spontaneous irreversible degradation processes that take place in a system interacting with its environment; will do so in order to go towards thermodynamic equilibrium with its environment.*

We see that the science presents us with a gift, for its second law actually explains the aging processes. Therefore, we can combine the science of degradation with thermodynamics. This tutorial presents the fundamentals aging laws. This science will significantly expand soon and engineers should start to be exposed to this science. Currently there is little ability to learn such methods. There are a lot of new opportunities to enhance and use thermodynamic degradation methods. We should find that prognostics, using a thermodynamic energy approach, should advance our capabilities immensely.

The fact is that in many situations, failure is simply not an option and it can take immense planning to prevent failure. We simply need all the tools we can get to assist us. Thermodynamic degradation science offers new tools, new ways to solve physics of failure problems and new ways to do prognostics and prevent failure.

2. ENTROPY DAMAGE CONCEPT (Slides 13-22)

When building a semiconductor component, manufacturing a steel beam, or simply inflating a bicycle tire, a system is created which interacts with its environment. Left to itself, the interaction between the system and environment degrade the system of interest in accordance with our second law phrasing of device degradation. Thus, the degradation is driven by this tendency of the system/device to come into thermodynamic equilibrium with its environment. The original order created in a manufactured product diminishes in a random manner, and becomes measurable in our macroscopic world.

Associated with the increase in total disorder or entropy is a loss of ability to do useful work. The total energy has not been lost but degraded. The entropy of the aging process is associated with that portion of matter that has become disorganized and is affecting our device's ability to do useful work. The aging process is an interaction of the system and its neighboring environment which can be defined as

- *The system is some sort of volume set apart for study. From an engineering point of view, of concern is the possible aging that can occur to it.*
- *The environment is the neighboring matter, which interacts with the system in such a way as to drive it towards its thermodynamic equilibrium aging state.*
- *This interaction between a system and its environment drives the system towards a thermodynamic equilibrium lowest energy aging state.*

Note that system in thermodynamics can be as simple as a resistor or complex like an assembly.

More precisely [4]:

> *If entropy damage has not increased, then the system has not aged.*

Sometimes it will be helpful to separately talk about entropy into two categories.

Entropy damage is a term that causes system damage, as compared with non damage entropy.

Not all changes in system entropy cause damage. In theory, "damage entropy" is separable in the aging process related to the device (system) such that we can write the entropy of the system [1]

$$\Delta S_{System} = \Delta S_{damage} + \Delta S_{non-damage}$$

For example, a bicycle tire that degraded due to energy loss did not experience damage and can be re-used. Adding heat to a device increased entropy but does not necessarily cause damage. However, the corrosion of the steel beam is permanent damage.

A statement of the second law in terms of entropy damage requires it to always be greater than zero [1,7,8]

$$\Delta S_{damage} \geq 0 \text{ (Statement of the Second Law of Thermodynamics)}$$

For any process, the overall exchange between an isolated system and its neighboring environment requires that the entropy generated be greater than zero for an irreversible process and equal to zero for a reversible process [7].

$$S_{gen-any-Process} = \Delta S_{total} = \Delta S_{System} + \Delta S_{env} \geq 0$$

Combining these we can write[1]

$$S_{gen-any-Process} = \Delta S_{total} = \Delta S_{damage} + \Delta S_{non-damage} + \Delta S_{env} \geq 0$$

Entropy damage can sometimes have a threshold [1]

$$\Delta S_{Damage} > \Delta S_{Threshold}$$

For example, when a wire stretches due to a force on it, the first part is an elastic (non damage) elongation, then at some point it starts to "creep" and damage occurs with permanent deformation called plastic strain.

3. CUMULATIVE ENTROPY DAMAGE (Slides 23-33)

The entropy change of an isolate system is the sum of the entropy changes of its components, and is never less than zero.

The total entropy of a system is equal to the sum of the entropies of the subsystems (or parts), so the entropy change is [7]

$$\Delta S_{System} = \sum_{i}^{N} (\Delta S_{Subsystem})_i$$

This is an important results, it allows us to now define a *Cumulative Entropy Damage Equation [1]*

$$\Delta S_{System-Cum-Damage} = \sum_{i}^{N} (\Delta S_{Subsystem-Damage})_i$$

3.1 Example – Miner's Rule Derivation

Consider cyclic damage occurring in a metal crystal lattice. Let n be the total number of cells having damage entropy $S_{Damage-cell-i}$. We assume equal damage entropy per cell. Consider that we have M total cells of potential damage to failure that would lead to a maximum cumulative damage S_{Max}. Then the cumulative damage entropy can be normalize as [1]

$$Cum\,Damage = \frac{\sum s_{n-Damaged}}{S_{Max}} = \frac{\sum m_{Damaged-cells}}{M} \leq 1$$

If we sum to N, the total number of cycles to failure, where we have n is the number of cycles performed (N>n), then we can write for the ith stress level

$$Damage = \frac{f_1 n_1}{f_1 N_1} + \frac{f_2 n_2}{f_2 N_2} + ... + \frac{f_k n_k}{f_k N_k} = \frac{n_1}{N_1} + \frac{n_2}{N_2}$$
$$+ ... + \frac{n_k}{N_k} = \sum_{i=1}^{K} \frac{n_i}{N_i}$$

This is called Miner's rule [9] for cumulative damage. It is a well known often used method to estimate damage. An example of this is applied to aluminum fatigue is given in Slides 24-25.

3.2 Non Cyclic Applications of Cumulative Damage (Slide 30)

In general, most aging processes cumulate damage over time. Therefore, similar to Miner's Rule, cumulative damage for non cyclic time dependent processes can be generally written [1]

$$Cum\ Damage = \sum_{i=1}^{K} \left(\frac{t_i}{T_i} \right)^P$$

Here as in Miner's cyclic rule, by analogy, t_i is the time of exposure of the i-th stress level and T_i is the total time to cause failure at the i-th stress level. Not all processes age linearly with time as is shown later like in creep on slide 80. Therefore, the exponent *P* has been added for the generalized case where *P* is different from unity (creep ($0<P<1$) and wear ($P=1$) even semiconductor degradation, that is any process where it might make sense to estimate the cumulative damage.

4. NEGATIVE & SPONTANEOUS NEGATIVE ENTROPY – GROWTH & REPAIR (Slides 31-34)

We have talked about disorder, what about order and negative entropy [10]? It takes work to re-order a system that has been disordered. We can measure the amount of re-order needed using a number of metrics, cost, work, energy, or entropy change required. In this case, re-ordering a process would equate to generating negative entropy [1]. We note that, there is no free ride, the overall entropy generated to the universe is positive. For example, even a simple solder repair generated excess heat to the environment and contaminants. This adds a certain amount of disorder to the environment that is necessarily greater than the amount of negative entropy generated.

It is obvious that devices and systems that we use every day will not spontaneously repair themselves. However, Mother Nature has apparently provided life forms with this capability [1]. However, the overall growth or repair process must still generate positive entropy by the second law. Still, in our definition of entropy for a system, we understand spontaneous positive entropy change $\Delta S>0$ as the amount of disorganization that occurs; then why spontaneous negative entropy change?

It is not immediately obvious why spontaneous negative entropy processes would be allowed by the Second Law of Thermodynamics where positive entropy is encouraged forcing equilibrium with the environment [1]

- *Mother Nature likely creates a closed system that encourages growth and repair in order for the system to come to some sort of final growth or repair equilibrium condition*

A full discussion and model details are available in Reference 1 for the interested reader.

5. UNDERSTANDING THERMODYNAMIC WORK AND HOW IT RELATES TO DEGRADATION (Slides 35- 59)

When we manufacture a system, the system has a certain amount of free energy (like potential energy). Prior to aging, our system has a certain portion of its energy that is "available" to do useful work. This is called the thermodynamic free energy. The thermodynamic free energy is the internal energy input of a system minus the energy that cannot be used to create work [8]

$$Work \leq \Delta Free\ Energy\ of\ the\ system$$

The change in the free energy F is related to the entropy S and work W as [1]

$$\delta W = -dF + TdS_{Damage}$$

Since the free energy is the maximum amount of useful work, we term this the reversible work then the equation is effectively describing the actual work, the reversible work and the irreversible work [11], i.e.

$$W_{Actual} = W_{Rev} - W_{irr}$$

We can conclude that the thermodynamic work is perhaps the most directly measurable and practical quantity to use in assessing the system's free energy [1].

As we have describe entropy increase as a measure of disorder, this equates to free energy decrease. For example we can find for a system with no mechanical work *PdV=0* and fixed temperature and volume, the ideal system in contact with a heat reservoir, the relationship is more obvious and is written

$$\Delta S = -\frac{\Delta F}{T}$$

Thus it is clear in this instance that a change in the entropy damage increase is directly linked to a loss of ability to do useful work.

5.1 Relationship Between Work & Damage
(Slides 46-58)

Disorder also equates to decrease in free energy that causes a loss of the ability to do useful work. Since the free energy bounds the useful work $F_i \geq W$, where *Fi* is t he initial free energy. The total work accomplished is

$$Work_{Total} \leq (F_{final} - F_{initial})$$

Then damage is defined more easily using the thermodynamic as the work is easier to measure than free energy decrease or entropy increase. This allows us to write the damage as [1, 2, 3,5]

$$Damage = \frac{\int YdX}{W_{Failure}}$$

$$= \frac{Partial\ work}{Total\ work\ needed\ for\ failure}$$

Work is path dependent as there are many ways to walk up a hill for example. How does aging occur over time? When we talk about work we cannot just look at the end points.

To assess work we can use what we call the conjugate work (an energy approach) to assess damage both cyclic and non cyclic work over time. For example, we know that Work=Force x Distance. The conjugate work variable are for a change in work Y (force) and dx (distance) and we list the most work types in the below table.

We will find that this will also lead to an improved method for determining acceleration factors using a work damage approach. More formally the work can be summed over its path for each ith stress

$$Work = \sum_i \int Y_i dX_i$$

Table Generalized conjugate mechanical work variables [1, 2, 4, 5]

Common Systems δW	Generalized force (Intensive) Y	Generalized Displacement (Extensive) X	Mechanical Work δW=YdX
Gas	Pressure (-P)	Volume (V)	-P dv
Chemical	Chemical Potential (μ)	Molar number of atoms or molecules (N)	μ dN
Spring	Force (f)	Distance (x)	f dx
Mechanical Wire/Bar	Tension (J)	Length (L)	J dl
Mechanical Strain	Stress (σ)	Strain (e)	σ de
Electric Polarization	Polarization (p)	Electric Field (E)	-p de
Capacitance	Voltage (V)	Charge (q)	V dq
Induction	Current (I)	Magnetic flux (Φ)	I dΦ
Magnetic Polarizability	Magnetic Intensity (H)	Magnetization (M)	H dm
Linear System	Velocity (v)	Momentum (m)	v dm
Rotating Fluids	Angular velocity (ω)	Angular momentum (L)	ω dl
General Electrical – Resistive	Power [Voltage (V) x Current (I)]	Time (t)	VI dt

The Cyclic Work that cause damage after each cycle can then be found as [1]

$$Cyclic\ Damage = \frac{\sum_n \oint Y_n dX_n}{W_{Failure}}$$

For example if the work was due to mechanical stress and strain, the total cyclic work is [1]

$$Damage = \frac{\sum_{i=1}^{n} \oint_{Area_i} Sde}{W_{Failure}}$$

This leads again to Miner's rule which can be written with AF as [1, 5]

$$\text{Effective Damage} \approx \frac{n_1}{N_1} + \frac{n_2}{AF_D(1,2)N_1} +$$

$$\frac{n_3}{AF_D(1,3)N_1} + \bullet \bullet \bullet = \sum_{i=1}^{k} \frac{n_i}{AF_D(1,i)N_1}$$

6. SELECTED PHYSICS OF FAILURE MODELS (Slides 60-70)

In this section we develop what we call, the Cumulative Accelerated Stress Test (CAST) equations, that allow one to plan accelerated test times for systems that are exposed to multiple stress environment. As well we determine physics of failure damage equations and acceleration factors for [1, 5, 13]

- Wear, Arrhenius Activation, Corrosion Damage and Rate in Microelectronics - Life Testing, Creep, Thermal Cycle, Cyclic Mechanical Vibration Fatigue

We provide one full example for wear in the tutorial of how to use the thermodynamic work to assess damage, the acceleration factor and obtain the CAST equation. Most common wear model of the softer material between two sliding surfaces is the Archard's wear equation [11, 12]

$$D = \frac{k\,P_W\,l}{AH}$$

Here, d=removed depth of the softer material, P_W=normal load (lbs), l is the sliding distance (feet), H=hardness of the softer material in psi, A=contact area, k=Archard's wear coefficient (dimensionless).

External work goes into creating the wear velocity while some causes wear, the work force x distance [1, 5]

$$w = \int_{x_1}^{x_2} P_F\,dx = \int_{t_1}^{t_2} (C\,P_W)C_2\,\frac{dL}{dt}\,dt$$

$$= C\,C_2\,P_W\,v\,t = k_P\,\frac{kP_W v\,t}{AH}$$

At some time t=τ we may consider that too much damage has occurred in a stress environment we call 1 as compared to stress environment 2. Then we can assess the damage ratio between environments 1 and 2 were 1 has caused failure and 2 failure has not yet occurred [1, 5]

$$\text{Wear Damage} = \frac{w_2}{W_1} = \frac{\left(k_P\,\dfrac{P_{W2}v_2\,t}{HA_2}\right)}{\left(k_P\,\dfrac{P_{W1}v_1\,\tau_1}{HA_1}\right)}$$

$$= \frac{\left(P_{W2}\,\dfrac{v_2\,t}{A_2}\right)}{\left(P_{W1}\,\dfrac{v_1\,\tau_1}{A_1}\right)}$$

Here τ₁ is the time for critical wear failure in stress environment 1. Note for the two environments (1 and 2) the materials are the same so H and k, cancel out. As well we must stay on the same work type to make comparisons between environments, therefore k_P are the same. When failure occurs (the amount of wear is the same for both environments). The thermodynamic work in environment 2 equals that of environment 1 and the damage ratio is 1, $W_{F1} = W_{F2}$. This occurs at time τ₂ in environment 2, so we can then write the wear acceleration factor as [1, 5]

$$AF_{Wear}(2,1) = \frac{\tau_1}{\tau_2} = \left[\frac{\left(P_{W2}\,\dfrac{v_2}{A_2}\right)}{\left(P_{W1}\,\dfrac{v_1}{A_1}\right)}\right]_{DF}$$

If a number of different i stresses are applied along the same work path (Eq. 4-22), the general wear damage ratio can be written by accumulating the thermodynamic damage at each stress level as [1]

$$Damage = \sum_i \left(\frac{t_i}{\tau_i} \right) = \sum_i \left(\frac{t_i}{AF_{Wear}(1,i)\tau_1} \right)$$

This provides not only the damage but also the CAST equation, for when the damage is 1 we have [1]

$$\tau_1 = \sum_i \left(\frac{t_i}{AF_{Wear}(1,i)} \right)$$

An example of how to use these important CAST equations, we exemplify this using a simple example for the Arrhenius Model. In this example, we wish to do an accelerate stress test on a unit at 100°C to equate to 10 years. How many hours do we test for if we have a complex use environment where [18]

❑ The use environment is 20°C for 50% of the time, 40°C for 25% of the time and 60°C for 25% of the time. Here for the Arrhenius model we will use Ea=0.7eV

Solution:
- The acceleration factors are: AF(100°C, 20°C)=380.3, AF(100°C,40°C)=64.8, AF(100°C,60°C)=13.65
- The CAST equation then indicates the test time as
  - t_1=43800/380+21900/65+21900/13.7 =115.2+338+1604.4=2057 Hour of test
- Then we need to perform the accelerated test at 100°C for 2057 hours. This will equate to 10 years of life for this profile

6.1 Numerous Ways a System Can Fail (Slides 71-72)

Often a system has numerous failure mechanisms. We might consider these as discrete states. When a particular state fails, the system may fail. The states may be continuous function with numerous energy states or discrete with relative minimum energy states having different degradation mechanisms. Therefore the free energy can have many states. This is given by what is called the Partition function due to the Boltzmann distribution

The sum often referred to as an ensemble, can have a number of different internal energy states as shown in the figure. The partition function near a true equilibrium state will have the free energy at a minimum, where the partition function will be at a maximum value [8]. However, complex systems can have numerous degradation mechanisms with its own relative minimum free energy state. The probability for a state to be occupied near an equilibrium state is

$$p_i = p_o \exp\left(-\frac{F_i(U,T)}{K_B T} \right)$$

Note the probability is expressed in terms of the systems free energy Fi where in this case the free energy is related to the ith failure mechanism.

6.2 Log(time) Aging Model (Slides 73-76)

In this section we describe a general log(time) parametric aging model that has its origin due to the Arrhenius degradation rate. This parametric model is [3]

$$a = \frac{\Delta P}{P} \cong A \ln[1 + B\,t]$$

Here "*a*" is typically a unitless value, where *a=ΔP/Po*. For example, *ΔP* could be a parameter change that is of concern, such as resistance change, current change, mechanical creep strain change, voltage transistor gain change, and so forth, such that *a* is then the fractional change.

The log(time) aging model is important as numerous degradation mechanisms age in log time such as
- Creep, wear
- Transistor Bipolar Aging Beta degradation
- Transistor FET aging on transconductance
- Crystal frequency drift

6.3 Corrosion and Corrosion Rate in Microelectronics (Slides 77-80)

There are four requirements for corrosion:

- o a metal anode,
- o cathode,
- o electrolyte,
- o and a conductive path

If any one of these is removed, corrosion can be prevented. The corrosion current is proportional to the rate kinetics and this local relative humidity (%RH) as

$$I_{Corr} \propto (\%RH)^M \, K(T)$$

Therefore the acceleration factor for corrosion assessment often used in microelectronics is [17, 19]

$$AF_{TH} = \frac{I_{Stress}}{I_{Use}} = \left(\frac{RH_{Stress}}{RH_{Use}}\right)^M \left(\frac{K(T)_{Stress}}{K(T)_{Use}}\right)$$

$$= AF_H \, AF_T$$

It is common to use the Arrhenius model for AF_T. We provide a numeric example on slide 78.

We also provide in this section physics of failure results for creep, thermal and mechanical cyclic fatigue.

6.4 Heat Engine Cyclic Work (Slides 84-87)

Engine cyclic work is represented illustrated in the thermodynamic work figure of slide 82. The area is the engines work done. Here an engine takes in heat converts it to work and its efficiency is [8]

$$\eta_{Heat\ Engine} = \frac{Net\ Work\ Out}{Total\ Heat\ In} = \frac{W_{out}}{Q_{in}} = 1 - \left(\frac{Q_{out}}{Q_{in}}\right)$$

Alternately this could be an electric engine that takes in a certain amount of electricity and converts it to work in a similar manner. For an electric engine we can substitute charge q for Q or Current I.

A degraded engine takes in heat but performs less work as its free energy is decreased so its efficiency is relative to when the engine was new can be written as [1]

$$\eta(t) = \frac{W_{Degraded-Engine}(Area\,2)}{W_{New-Engine}(Area\,1)} = \frac{\oint_{AREA2} Y\,dX}{\oint_{AREA1} Y\,dX}$$

This is very similar to our damage concept [1].

$$1 - \eta = \frac{\delta W_{irr}(t)}{W_{rev}} \Rightarrow Damage = \frac{\sum W_{actual}(t)}{W_{actua-failure}}$$

7 NOISE - A NEW PHYSICS OF FAILURE TOOL (slides 88-102)

In an aging system, we suspect that disorder in the system can introduce some sort of randomness in an operating system process leading to system noise increase. What we mean by system noise is a disruption of energy flow through for example an operating system. That is the randomness of disorder caused by aging is reflected by energy outputted by an operating system. This disruption of energy flow we suspect is a sign of disorder and increasing entropy. Simply put, if entropy damage increases, so should the system noise in the operating process. Therefore, noise is caused by some sort of disorder in the system. The results is that it causes some sort of variation in the operating process. Noise does not have to be acoustic. It can occur in an electrical signal, voltage output, mechanical vibration etc.

Statistically for discrete and continuous state variable X, the entropy functions in information theory are written [8]

$$Discrete\ X, s(x): \quad S(X) = -\sum_i f(x_i) \log_2 f(x_i)$$

and for the discrete case extended to the continuum [14]

$$Continuous\ X, f(x):$$

$$S(X) = -\int f(x) \log_2 (f(x)) dx = -E\big[\log f(x)\big]$$

Here X is a discrete random variable in the discrete case and a continuous random variable in the continuous case and f is the probability density

function. This above equation is referred to as the differential entropy.

As an example, when we find that a system has Gaussian White noise, the pdf function $f(x)$ is

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right)$$

Then when this function is inserted into the differential entropy equation, the results is given by [14]

$$S(X) = \frac{1}{2}\log(2\pi e \sigma(x)^2)$$

This is a very important finding for system noise degradation analysis [1] especially for complex systems as we will see. Such measurements can be argued to be more on the macroscopic level. However, their origin are likely due to collective microstates which we might argue are on the *mesoscopic* level [1]. We clarify what we mean by mesocopic level on slide 89-91.

However, what we find is that for a Gaussian noise system, the deferential entropy is only a function of its variance. For white noise we note that the expectation value of the mean is zero as it fluctuations around a zero but the variance is non vanishing.

For a white noise system that is degrading by becoming noisier over time, the entropy damage can be measured in a number of ways where the change in the entropy at t_2 relative to t_1 is then [1,15]

$$\Delta S_{Damage} = S_{t2}(X) - S_{t1}(X) = \Delta S(t_2, t_1)$$

$$= \frac{1}{2}\log(\frac{\sigma_{t2}^2}{\sigma_{t1}^2})$$

As and example consider an engine that exhibits a constant PSD (Power Spectral Density) characteristic of $3G_{rms}$ content in the bandwidth from 10 to 500 Hz. After some time the engine becomes degraded and exhibits a constant PSD characteristic of $5G_{rms}$ content in the bandwidth from 10 to 500 Hz

The system noise damage ratio is then [1,15]:

$$\Delta S_{Damage-noise-ratio} = Log(5^2)/Log(3^2) = 1.47$$

Such methods can be extended to complex systems in electronic noise, engine noise, human system noise

7.1 Human Heart Noise (Slide 101)

Here heart rate variability was studied in young, elderly and Congestive Heart Failure (CHF) patients. The tutorial shows noise limit measurements of heart rate variability. We note that heart rate noise limit variability between young and elderly patients are not dramatically different compared to what is occurring in patients with CHF [16]. Although this is not the same system (i.e. different people), such measurements can be compared using noise analysis described in this section. This is further illustrated in the slides showing noise variability in heartbeats of young subjects compared with CHF patients. This is an example of damage entropy comparison in a complex human heart aging system between a good and a failing system observed well prior to catastrophic failure. This reference [16] shows a variation of how damage noise entropy measurements in general can be implemented and would be helpful as a detection method of a system's thermodynamic degradation state.

This concept has broad implication for complex systems. For example, we predict that a side effect of global warming is increased volatility in the weather as our environment ages [1].

8 FINAL THOUGHTS – THEORY OF ORGANIZATION (Slides 103-107)

The Theory of Organization for stability, reliability and quality [1]: For a system, subsystem, component, material or process, in general, the higher the organization, the more likely is the probability of success over time.

Up to this point we have been describing degradation and disorder. In the opposite sense, we can talk about order and preventing disorder as a summary to the concepts in this tutorial. We provide a model with two variables to control disorder: Nmax and the time constant τ. The variable Nmax applies to our everyday notions in design and manufacturing. Reducing the potential for disorder through organization is equivalent to designing for a smaller Nmax. Simplicity, reducing complexity, and structural order can be key for the probability of success for our systems, subsystems, components, materials, and processes. This does not necessarily mean we cannot have complexity. However, we would then need to focus on designing for small time constants τ. As we have seen,

one should seek to maximize the free energy of a system and minimize variability in a system or a process. Processes often relate to the normal distribution; variations in our design and defects in our materials increase the potential for disorder, creating opportunities for entropy damage. Variability is therefore a strong measure of disorder. As we have noted in Chapter 2, variability can promote noise. We know that materials such as crystals and highly repetitive structures such as metals and diamonds (polynomial structures) are often the strongest and most reliable materials. Their redundant structure and designs can minimize the potential for entropy damage for materials and structures. Their free energy, that is, capacity to perform useful work, is higher than for amorphous materials or untidy structures. The tutorial concepts supports the theory of organization to increase our probability of success in preventing degradation, and is a validation in our understanding of how to improve stability, quality, and reliability for our products.

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