Living System Negative Entropy Reliability, Old Trees and a Fifth Law for Thermodynamics on Negative Entropy

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SUMMARY & CONCLUSIONS

Physics of failure laws could start with the Second Law of thermodynamics as it explains aging when written as

"The spontaneous irreversible degradation processes causing aging that take place in a system interacting with its environment will do so in order to go towards thermodynamic equilibrium with its environment increasing entropy"

Often in thermodynamics we can think of replacing the word aging with disorder or entropy increase. Yet it might be said we are at a loss according to the Second Law when we try and explain why living systems allow for spontaneous growth and repair, because in this case entropy is decreasing. In life forms, negative entropy eventually gives way to aging or entropy increase. For living system reliability, understanding aging, requires an additional knowledge of order, repair and growth, a new type of physics of non failure. The concept of spontaneous clearly applies to disorder in the Second Law, yet living systems uncontrollably spontaneously grow and repair, creating order.

However, to make matters even more complicated, Mother Nature has created one living system that seems capable of a type of perpetual spontaneous negative entropy. This life form is trees where in some cases reported to 9000 years old. Such longevity is beyond ones human comprehension.

It becomes apparent in our assessment, that the Second Law has shortcomings and a Fifth Law of Thermodynamics is proposed for repair and growth. We will see that the Carnot cycle instrumental in the second law is modified for living system so that appropriate efficiencies can accurately be measured.

Lastly we describe atomic weapons and global warming. In these extreme cases, degradation can be so severe negative reproductive entropy is unattainable. Extreme degradation will likely have cascade effects, so that many systems can become irreproducible in the environment. Such events need to be defined and identified in today's modern age in thermodynamic terms, which we introduce in this paper.

1. INTRODUCTION - BASIC SPONTANEOUS NEGATIVE ENTROPY GROWTH & REPAIR

To aid the reader, a summary of the key thermodynamic concepts and article notation is provided in the Appendix.

Entropy is the thermodynamic term for disorder, so negative entropy indicates order. While devices and systems that we use every day will not spontaneously repair themselves (become ordered), living systems have this capability. Growth (increase order) requires negative entropy change

$$\Delta S_N<0 \tag{1}$$

Here S is entropy and subscript N for negative entropy. This is performed with available work and matter. However, creating order cause disorder to the environment (waste) and the overall entropy change is positive (i.e., more disorder is created than order) in keeping with the Second Law that entropy must increase in irreversible processes so entropy generated is positive

$$\Delta S_{Generated} = \Delta S_{Environment} + \Delta S_{N\,System\,Growth} > 0 \tag{2}$$

Furthermore, most living systems that sustain an injury, will try and repair the damage creating a spontaneous amount of negative entropy equal to or greater than the entropy damage (due to injury) [1]

$$\left|\Delta S_{\text{Repair}}\right| \geq \left|\Delta S_{\text{Damage}}\right| \tag{3}$$

(where entropy damage causes system damage or internal irreversibility, as compared to non entropy damage flow). The equal sign indicates a highly efficient repair process where the inequality represents an inefficient repair process [1].

A living system seeks to balance damage with repair

$$\Delta S_{damage} \geq 0,\ \Delta S_{N\ System\text{-}Repair} \leq 0,$$
$$\text{so}\ \ \Delta S_{damage} + \Delta S_{N\ System\text{-}Repair} \approx 0 \tag{4}$$

improving its reliability. Therefore, the systems change in entropy has essentially decreased; its free energy (which equates to the ability to do useful work) has increased. However, by the Second Law the repair process generates at least this same amount of entropy damage or greater to the environment often in the form of pollution.

2. AN OBVIOUS QUESTION

The question is, why does repair occur? If work is available, by the Second Law, we expect entropy to be maximize and spontaneous disrepair to be more favorable in order to decrease the system's free energy F and come to environmental equilibrium

$$\Delta S_{\text{System-Disrepair}} \geq 0, \quad \Delta F_{\text{System}} < 0 \tag{5}$$

For say a subsystem the entropy in disorder $S_{disorder}$

$$dS_{Generated damage} = dS_{Environment\ d} + dS_{Sub-System disorder} > 0 \tag{6}$$

While disorder and repair include negative entropy S_N

$$dS_{Generated repair} = dS_{GDisorder} + dS_{environment\ R} + dS_{N\,Sub-System\,Repair} > 0, \quad where\, dS_N < 0 \tag{7}$$

We know that for the negative entropy of the Sub-system

$$dS_{Sub-System disorder} > dS_{NSub-System\_Repair} \tag{8}$$

For the subsystem, disorder is larger, but overall it at first seems disorder plus repair created more entropy. However, if no sub-system repair is ever made, the consequences will eventually harm the full system and maximum disorder is created, that is

$$dS_{System no repairs} > dS_{System with repairs made} \tag{9}$$

Therefore the question is why does repair occur, let the system degrade faster, which is more favorable by the Second Law. We see survival and reliability play a role. This is not included in the Second Law which can be misleading without some new law on living systems reliability.

Negative entropy was first introduced by Erwin Schrödinger in a non technical field in his 1944 popular-science book *What is Life* [2]. Schrödinger uses it to identify the propensity of the living system to want to organize, which is contrary to the Second Law. That is, for most of us, we like to build houses, build cities, and organize our way of life. This is also observed in lower life forms.

In the book, *Principles of Biochemistry*, Lehninger [3] argues that the order produced within cells as they grow and divide is more than compensated for by the disorder they create in their surroundings in the course of growth and division. In short, according to Lehninger, "living organisms preserve their internal order by taking from their surroundings free energy, in the form of nutrients or sunlight, and returning to their surroundings an equal amount of energy as heat and entropy. However, in his argument the preference for order is still not justified.

3. REPAIR OF SYSTEMS

The problem of organization in living systems increasing despite the Second Law is known as the Schrödinger paradox [2, 4].

Systems are frequent opened for repair by man. Consider a repair to a system that requires a certain amount of heat entropy $\frac{-\delta Q_{\text{Repair}}}{T}$ where δQ is the change in heat needed for repair at temperature T. This is the repair entropy equivalent. A simple example is a failed solder joint. The repair amount of heat entropy reflow to the solder joint is [1]

$$dS_G = dS_{Generated} = dS_{Environment} - \left.\frac{\delta Q}{T}\right)_{Sys-repair} \tag{9}$$

The entropy generated in repair is the sum of the environmental entropy and heat needed for repair. By the Second Law $\Delta S_{Generated} \geq 0$ so we have from Eq. 9

$$TdS_{Environment} \geq \delta Q)_{Sys-repair} \tag{10}$$

Therefore, the repair process generates equal or more disorganized energy to the environment than the amount of organized energy needed for the repair process taking a toll on the environment by the Second Law.

Now it is second nature why this repair takes place to fix the solder joint so the system will operate again in its prior thermodynamic state. The system in a sense had become inefficient; the repair then restores the efficiency of the system to operate in its environment.

The fact that man tends to fix a broken closed system, supplying energy for the repair process, is not a reasonable conclusion of the Second Law. It does not violate the Second Law, but why create order, why not let things fall apart?

4. A REPAIR SUBSYSTEM

In repair, time is not reversed; repair is done by removing the damaged area and re-grows the cells as close to their original state as nature permits. To be in agreement with the Second Law there still must be a natural tendency "to come to some sort of thermodynamic equilibrium state". Therefore, Mother Nature must use available work to create a "repair subsystem" that encourages negative entropy flow in order for the sub-system to come to a more reliable ordered rather than disordered equilibrium state. A "repair system" takes energy and creates entropy production. In the non equilibrium growth/repair state entropy decrease while free energy increase

$$\frac{d\Delta S_{\text{System-Growth or Repair}}}{dt} < 0, \quad \frac{dF_{\text{System-Growth or Repair}}}{dt} > 0 \tag{11}$$

Repair/growth stops when with a new "thermodynamic equilibrium state" increasing system free energy.

We can hypothesize the repair tendency. At the repair site matter likely diffuse into the area driven both by a concentration gradient and a biological electrical charge across the repair area (see for example Becker, *Body Electric* [5]). A possible over simplified model for negative entropy flow [1] via non equilibrium is

$$-dS_{\text{Repair}} = \left(\frac{1}{T_s} - \frac{1}{T_R}\right) dU + \left(\frac{E_s}{T_s} - \frac{V_R}{T_R}\right) dq + \left(\frac{\mu_s}{T_s} - \frac{\mu_R}{T_R}\right) dn \tag{12}$$

Body uses work to set up an imbalance. Here R is the repair area, s is neighboring area possible skin surface depending on the injury, T= temperature, E, V are voltages, μ is the chemical potential. The energy flow will go from the higher temperature area $T_R > T_s$ so that the repair internal energy increases *dU>0,* for $V_R>E_s$ then *dq>0,* the repair area is charged, and for $\mu_R>\mu_s$, *dn>0,* so matter flows to the repair site. When $T_R=T_s$, $E_s=V_R$, and $\mu_s=\mu_R$, the repair process is completed and we are in new equilibrium state with increase free energy available for useful work. The result is a more organized area.

In this model, the body growth occurs to drive towards an equilibrium situation; the most efficient growth is to arrange matter in the original system state.

We thus have a repair statement for living system repair

Statement 1*: A living system seeks to set up 1) a non equilibrium state that drives repair to equilibrium which has a propensity to 2) order matter in the original state (i.e. prior to disorder) improving reliability.*

5. GROWTH AND SELF-REPAIR DESCRIPTION

Growth and self-repair have similarities since the living system becomes more ordered,

$$\Delta S_{\text{N-Living System}} < 0, \text{ for } 0 < \text{time} < \text{human growth phase} \quad (13)$$

In the case of repair,

$$\Delta S_{\text{N-Living System Repair}} < 0, \text{ for Repair starts} < \text{time} < \text{Repair completed} \quad (14)$$

The exchange of entropies in repair is

$$\Delta S_{Gen} = \Delta S_{Environment} + \Delta S_{Repair} > 0 \quad (15)$$

The total entropy of any repair process increases. This agrees with the Second Law. Since $\Delta S_{\text{Repair}} < 0$, than the damage to the environment must be positive and greater than the negative repair entropy by the Second Law

$$\left|\Delta S_{Environment}\right| \geq \left|\Delta S_{Repair}\right| \quad (16)$$

The daily damage-repair process can be viewed as cyclic, this means that the internal energy *U* needs to be restored to its original state. Damage portion of the cycle is

$$\Delta U_{Change\text{-}due\text{-}to\text{-}damage} = \int_0^{Damage} dU = U_{Damage} - U_{Non\text{-}Damage} \quad (17)$$

In this simplified view, the internal energy change in a damage-repair cycle by the combined First and Second Laws (see Appendix) is [1]

$$\oint dU = \oint \delta W + T\oint dS + \Delta U_{un\text{-}repaired} \geq 0 \quad (18)$$

That is, for perfect repair, the internal energy in the cycle is unchanged and for imperfect repair, yields some inefficiency and permanent change to the internal energy. The unrepaired portion builds up causing aging and living system efficiency η decreases, some repair work *W*, gets wasted, if W_{rev} is work needed for perfect repair, than $W_{irr}=W_{actual}-W_{rev}$ which increases with aging

$$\eta_{System}(t) = \frac{W_{actual}}{W_{actual}+W_{irr}(t)}, \quad W_{irr}(t+\tau) > W_{irr}(t) \quad (19)$$

To be clear here, we provide a second statement

Statement 2: *Living systems in daily use create internal damage. There is propensity to spontaneously repair the damage. However, since repairs are not 100% efficient, damage cumulates over time creating system aging decreasing efficiency. The closer system activity is to a quasi-static process, the less damage is created. Living system reliability is related to repair efficiency.*

Here a quasi-static process is defined as a slow varying process which is known to create less entropy damage. Although quasi-static process cause less damage to a living system, activity is necessary for good health. The figure below is suggested by a heart study [1, 6].

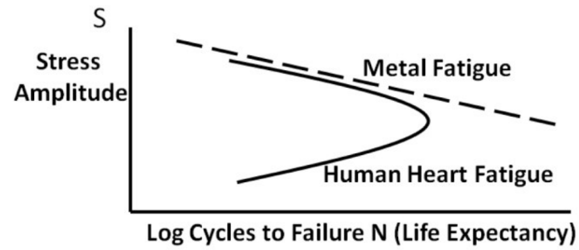

Figure 1 S-N curve of human heart compared to Metal fatigue [1]

Unlike metal fatigue, we see that high and low stresses are not good for the human heart. However, reasonable stress is good. We see that reliability and thus repair efficiency improves with optimum systems stress.

6. LIVING SYSTEM REPAIR WORK AND CARNOT EFFICIENCY

We can make a simplified thermodynamic repair model. The repair process is shown in Figure 2. An injury occurs, after a few hours the entropy is at a maximum where the entropy damage is S_D and the repair area has a temperature rise T_{High} (T_H) due to inflammation and increased blood flow. Repair work is done W_R, and the injury is almost completely repaired, the non repairable entropy is S_{UR}.

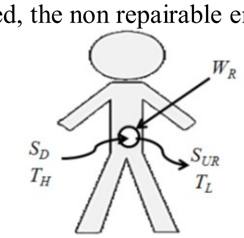

Figure 2 Simplified body repair

The change to the internal energy *ΔU* from repair cycle is due to the unrepaired damage. In this case, from the First and Second Law the minimum repair work is (see Eq. 18 and Appendix A) and Fig. 2

$$W_{R-\min} = T_h S_D - \Delta U_{Damage\text{-}Unrepaired} = T_h S_D - T_L S_{UR} \quad (20)$$

The negative entropy needed for the repair process is

$$S_G = S_D - S_{UR} = -S_R \quad (21)$$

That is, in the case of repair

$$S_D - S_{UR} + S_R = 0 \text{ and } S_{UR} = S_D + S_R \tag{22}$$

So that the minimum work in the repair process is found by combining equations 20 and 22

$$W_{R-\min} = S_D(T_H - T_L) - T_L S_R \tag{23}$$

In the case of perfect repair S_D=-S_R, the minimum repair work is

$$W_{R-\min} = S_D T_H = Q_H \tag{24}$$

where Q_H is the repair heat which can be measured.

The efficiency of living system repair is [1] is

$$\eta_{L-Carnot} = \frac{W_{actual}}{W_{actual} + W_{irreversible}} = \frac{W_{R-\min}}{W_{R-\min} + T_L S_{UR}}$$
$$= 1 - \frac{T_L}{T_H}(1 + \frac{S_R}{S_D}) = 1 - \frac{T_L}{T_H}(1 - f) \tag{25}$$

We use the symbol $\eta_{L\text{-Carnot}}$ for a living system. Here we let S_R=-f S_D a fraction f of S_D , a value between 0 and 1. In the case of perfect repair where S_R=-S_D, f=1 and the efficiency is 1. In the case of no repair f=0, the relation looks like the efficiency of a heat engine $\eta_H \le 1 - \left(\frac{T_{Min}}{T_{Max}}\right)$ with the equality giving the maximum Carnot cycle efficiency. In repair, the human body, behaves somewhat like a heat engine but has better efficiency compared to a Carnot Cycle

$$\eta_{L-Carnot} \ge \eta_{Carnot} \tag{26}$$

Having a higher efficiency than a Carnot cycle actually is not possible for heat engines, a Second Law limit. In a heat engine the entropy into the system equals that out, while in a living system in repair, this is not the case. The repair reduces the entropy, i.e. energy is used to create system order. Yet, the special circumstances of Eq. 26 present more motive for a 5th Law of Thermodynamics. Note that the repair rate term f in Eq. 25 is measurable.

7. REPAIR AGING RATE – AN RC ELECTRICAL MODEL

We can look at the rate of negative repair entropy flow as it relates to entropy damage to within an aging factor *f(t)*

$$\frac{dS_{\text{Damage}}}{dt} = f(t) S_{Damage} \tag{27}$$

Here as aging increases in the living system, we expect that *f(t)* decreases where $0<f(t)<1$ and S_R=-f S_D. Therefore, the rate of change of *f(t)* is some function of the unrepaired entropy damage $S_{UD}(t)$ that builds up over our lifetime and reduces our ability repair a living system and is responsible for the unreliability. If this was not the case and we had perfect repair, we would not age. The model is simple but illustrates a possible reliability aging model. From our experience, *f(t)* must be a slow function of time compared to the repair rate, i.e.

$$\frac{d\Delta S_{Repair}}{dt} >> \frac{df(t)}{dt} \tag{28}$$

Therefore we can write

$$\frac{dS_{\text{Damage}}}{dt} = f(t) S_{Damage} \approx f\, S_{Damage} \tag{29}$$

and treat f as a constant over the repair time period, when we look at the entropy repair rate.

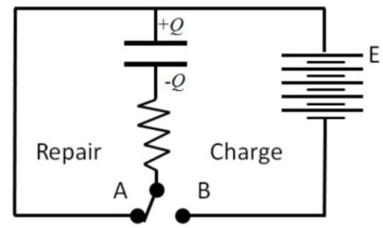

Figure 3 Charge and repair RC Model for the human body

Equation 29 can be compared to the well known RC circuit shown in Figure 3. The notion that the body charges up (switch B) in order to energize the repair area, and then the energy is discharged (switch A) has a similar differential equation given by

$$I = \frac{dQ}{dt} = -\frac{Q_o}{RC} e^{-t/RC} \tag{30}$$

The fractional repair and repair time are *f(t)~1/R(t)C(t)* [1] and *I* is then the entropy current. For *f(t)* to decrease, *R* and *C* would need to increase. Perhaps it makes sense that the internal bodies resistance increase with time as the unrepaired entropy disorder builds up over a lifecycle and we associate entropy production with resistance R. As well C goes as the dielectric constant and if it is leaky, repair current is lost;. However, we see living system reliability has a measurable quantity the repair rate:

> ***Statement 3:*** *Living systems maximum health capability (see Figure 1 apex point) is likely measurable as it is tied to a measurable repair rate.*
> ***Statement 4****: Living systems aging can be measured by its repair or growth rate. This rate decreases with aging time. This decrease should be a good indication of the life span of any living system and a measure of its reliability and negative entropy capability.*

Statement 3 and 4 are supported in the literature [7] as repair time, quantity and quality declines with age.

8. OLD TREES

Of all the living systems, none live longer than trees some estimated to 9000 years. However, unlike most living systems, trees do not repair broken areas but are in a constant growth state. Growth and repair are not so different since growth must occur in repair as time is not reversed, yielding similarities. However, since trees live longer than most living systems, we can observe some of their secrets. First they are environmentally friendly. Their waste product for example, bark serves as a protection, leaves and dead branches fertilize the area. Second and probably most importantly, trees maintain a quasi-static (very slow varying) process of activity so damage is minimize and balanced with growth. This is potentially a key concept in understanding longevity. In thermodynamics a reversible process must be quasi-static in order not to create damage. However, this does not mean that all quasi-static processes are reversible.

If we replace S_R with S_{Growth}=S_G in Eq. 25, we have

$$\eta_{L-Growth} = 1 - \frac{T_L}{T_H}(1 + \frac{S_G}{S_D}) = 1 - \frac{T_L}{T_H}(1 - f) \tag{31}$$

So that if f≅1, the efficiency is ≅100%. Therefore, in the case of healthy trees, efficiency is as high as possible for any living system. A tree that stops growing will die. We see in this highly efficient case living systems utilize available work to create negative entropy reliability flow creating order-disorder balance to obtain high longevity. This selection of survival work rather than destructive use of available work cannot be explained by a Second Law.

9. A PROPOSED FIFTH LAW OF THERMODYNAMICS

We have shown mathematical inconsistencies with the Second Law in Equations 8, 11, 26, and 31, especially with the Carnot efficiency. Note that the first formulation of the second law is credited to the French scientist Sadi Carnot, who in 1824 showed that there is an upper limit to the efficiency of conversion of heat to work, in a heat engine which by itself will not explain living system reliability and we were able to modify it. ***Since repair and growth are spontaneous events, we argue that this is not simply similar to the a Second Law case of adding work to increase efficiency since the type of work is spontaneous, thus specific to living system "natural reliability"(i.e natural aging issues).***

We have provided Statements 1 and 2 that point to Second Law difficulties. Furthermore, we suggest without further proof that living system reliability can be quantified somewhat by measuring it repair rate related to negative entropy [see ref. 7], a specific spontaneous process of growth and repair. Furthermore, living systems utilize available work in a spontaneous way to create negative entropy reliability flow creating order-disorder balance that cannot be quantified with the Second Law as it require a modified Carnot cycle (see Eq. 31).

We see that the Second Law cannot properly quantify living system spontaneous order and reliability which must be tied to repair and growth rates. In terms or reliability science of living systems, we conclude a Fifth Law of Thermodynamics is needed.

The proposed ***Fifth Law of Thermodynamics is a Law of Negative Entropy***:

> ***A living system spontaneous growth/repair rate is dependent on its L-Carnot efficiency.***

In Laymen's terms, the "natural" reliability of a living system is dependent on its spontaneous growth/repair rate. This is a measurable quantity.

Reference 7 is an example of the Fifth law where bone growth in old versus young mice has been measured.

Although this statement of the fifth law looks at first limiting to internal growth and repair, it is more general. Living systems are open and have a propensity to organize their environment by building houses and cities as an example. Thus, living system must organize to survive both internally and externally which creates higher reliability for a living system. We also note that this need to organize creates a demand on natural resources which can be a limiting concern.

10. CRITICAL ENVIRONMENTAL INTERFERENCE

The largest threat to system growth, repair and reproduction is when human nature interferes significantly with Mother Nature tendencies with the use of atomic and chemical weapons which could likely deplete our environment and cause multiple irreproducibilities. This is critical environmental interference. An additional example of such interference is that our environment is also aging as we humans pollute it. Therefore, Mother Nature cannot repair a number of systems like the ice caps and related systems will be affected as the ocean's volume changes. Critical Thermodynamic Interference has consequences that can obviously cascade to many systems.

APPENDIX: BASIC THERMODYNAMICS TO AID THE READER

We provide in this appendix, basic thermodynamics needed for understanding this paper explaining terms and reminding the reader of some key concepts.

The First Law of thermodynamics is one of conservation of energy, system internal energy change dU is partly due to heat δQ added and work δW performed by the system on the environment

$$dU = \delta Q - \delta W \text{ where the work } \delta W = Y dX \tag{A-1}$$

Y is generalized force like stress, dX is generalized displacement like strain. Note we use δQ and δW instead of dQ and dW as they are path dependent quantities.

In this article we talk a lot about entropy S. It may be helpful for the reader to note entropy is a measure of disorder. We also use the term free energy F which is roughly opposite of entropy; it is the capacity for a system to do useful work. We see as entropy increases, the free energy decreases.

The Second Law has many definitions such as the entropy of the universe is increasing. Key to reliability is system damage D, and we term that damage entropy S_D, there is also non damage entropy like adding heat S_{ND} that which increase entropy but may not cause damage, so change in system entropy for any process is

$$\Delta S_{System}=\Delta S_{damage}+\Delta S_{non\text{-}damage} \quad \text{(A-2)}$$

A thermodynamic systems can be simple like a resistor or complex like an assembly or a living system. Systems exchange entropy with the environment so that

$$S_{generated\text{-}by\ Any\ Process}=\Delta S_{total}=\Delta S_{System}+\Delta S_{env}\geq 0 \quad \text{(A-3)}$$

The fact that entropy generated must be greater or equal to zero is a statement of the Second Law. From Eq. A-2

$$\Delta S_{total}=\Delta S_{damage}+\Delta S_{non\text{-}damage}+\Delta S_{env}\geq 0 \quad \text{(A-4)}$$

Then we require

$$\Delta s_{damage}\geq 0 \quad \text{(A-5)}$$

This is perhaps the best reliability statement of the Second Law. A process that does not cause damage so as not to generate entropy is called a reversible process and the Second Law is quantified for this case as

$$\delta Q=TdS \quad \text{(A-5)}$$

We may combine the First and Second Law Equation A-1 and A-5 yielding a combined expression

$$dU=TdS-\delta W=TdS-YdX \quad \text{(A-6)}$$

In the article we describe the term negative entropy S_N. The reader may wish to substitute the term order for it. Negative entropy is a term that applies to living systems since they not only create order but are capable of growth and repair. Repair requires re-order of the disordered entropy damage. So we term this negative entropy. To reorder requires work.

We also talk about work W efficiency η. If all work is 100% efficient it is called reversible work W_{rev}. The actual work W_{actual} minus W_{rev} equals the irreversible work that ($W_{irr}=W_{actual}-W_{rev}$) in this article is work not able to repair damage and relates to efficiency in Eq. 19.

Lastly there is some modeling in repair that uses some of the concepts of a heat engine since injuries create inflammation and heat as part of the repair process via increased blood flow. A heat engine converts heat to work. Since it cannot convert all its heat to work and have perfect efficiency, some unconverted heat is expelled. The analogy is in a living system repair process, the injured area heats up, repair work is done, and due to a lack of efficiency the repair is not 100% somewhat like a heat engine that cannot convert all the heat to work.

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