Living Systems Negative Entropy Thermodynamics with Growth, Repair, Carnot Cycle Comparisons and the Second Law Paradox

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Abstract

In this paper, we provide insight into understanding living system negative entropy growth and repair processes from a thermodynamic perspective. Living systems are viewed as cyclic from a daily perspective of work, sleep, nutritional consumption, waste, breathing, growth, and repair cycles. We assess growth and repair with an equivalency cyclic work model. In a repair, for example, the free energy of the system is restored close to the original state with some imperfect repair that also occurs. We illustrate this using an equivalent amount of cyclic work by comparing it to a heat engine and assessing its efficiency. Results of modeling suggest a type of living system heat engine and cyclic efficiency that we were able to compare to a Carnot type efficiency for repair and growth processes that are insightful in the thermodynamic framework compared to traditional medical methods. The efficiency is somewhat paradoxical in Second Law treatment as one might expect due to the spontaneous negative entropy nature of growth and repair in living systems compared to the spontaneous entropy nature of disorder in passive systems. We suggest a simple modification of the Second Law in negative entropy terms. We also suggest metrics that can be used to assess a living system's ability to generate negative entropy using the fractional repair and a repair rate function that is comparable to an electric RC circuit charge-discharge model. Results provide new insights on how to approach living system negative entropy thermodynamics.

Key Words: *Negative Entropy, Spontaneous Negative Entropy, Entropy damage, Growth, Repair Rate, Carnot Cycle*

1. Introduction

Negative entropy was first introduced by Erwin Schrödinger (1944) in a non-technical field in the popular-science book, *What is Life*. Schrödinger uses it to identify the propensity of the living system to want to organize, which is contrary to the Second Law and is sometimes referred to as Schrödinger's paradox. 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. Thus, the second law, when it comes to spontaneous order is somewhat controversial among some scientists (Schrödinger, 1944; Schneider et al., 2005). However strictly, the second law applies to closed systems that are adiabatically isolated, i.e. living systems are open. Nevertheless, the concept of spontaneous negative entropy is an interesting aspect that we explore. Furthermore, the concept of closed systems can be very broad when it comes to its deduced application statement that the entropy of the universe is increasing where living systems tend to organize which can add an element of confusion. In this paper, we provide some suggestions that can be helpful on this topic.

In the book, *Principles of Biochemistry*, Lehninger (1993) 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 (1993), "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 spontaneous order (cell growth) is not addressed.

Odum brothers (1955) pioneered work in theoretical ecology. A maximum power principle which Odum considered as a new law in thermodynamics was formulated. In this view, all-natural systems traded off efficiency to maximum power output. Odum working with Pinkerton (1955) claimed that maximum power occurred when the efficiency of energy production was about half of what was theoretically possible. In this paper, we can lend some support to their efficiency claim. According to Odum systems organize and structure themselves naturally to maximize power. The maximize power concept provided a way to interpret evolution which Odum thought that systems that maximized power were selected whereas those that do not are eventually eliminated. The concept also provided information about the rate at which one kind of energy is transformed into another as well as the efficiency of that transformation. Yet as Gillian wrote (1978) that Odum's new law had not yet been validated.

Ilya Prigogine (1955) formulated descriptions of how open systems move far away from thermodynamic equilibrium to express the concept of dissipative structures. Here open systems absorb negentropy and discharge positive entropy outside themselves. In this way, they evolve and move away from thermodynamic equilibrium and can develop orderly and stable stationary states before eventual equilibrium is reached in irreversible processes. Thus orderly and stable systems can arise from disordered systems. By comparison to passive systems that move towards thermodynamic equilibrium. Dissipation is possible if there is a cold sink. The sink is important for negentropy flow.

In this paper, our work is related to these notions. However, our approach is to focus on growth and repair. Furthermore, we look at growth and repair using common traditional thermodynamic language by viewing living system thermodynamics with a cyclic work equivalency method to illustrate efficiencies. We focus mainly on repair in humans and animals. However, much of our approach applies to all living systems with the caveat that not all living systems repair themselves. For example, systems without a nervous system for feedback, such as trees and plants, primarily experience growth. However, growth has strong similarities to repair which we point out in the paper. Because growth and repair are fundamental building blocks for living systems, our result allows for a clarification statement to aid in one's interpretation of the second law for negative entropy. We consider this statement on the second law clarification unique in formulation and interpretation (See Eq. 32).

Interestingly, our results for efficiency of growth and repair lend some support to Odum and Pinkerton's (1955) notion that efficiency is about half of what is theoretically possible. Our results show this by comparison to the Carnot Cycle portion of our formulation (see Eq. 20). Therefore, in this regard, this study may be helpful as a verification to the Odum and Pinkerton's efficiency statement.

Thus our study is unique in thermodynamics with our focus on growth and repair, which after can be considered as the building blocks of living systems. We know that while devices and systems that we use every day will not spontaneously repair themselves (become ordered), living systems have this capability. Growth and/or repair, increase order and this requires an amount of negative entropy change

$$-\Delta S_{N\,System} \leq 0 \tag{1}$$

In this paper, the symbol S applies to entropy, and in the above case when subscripted by N indicates it relates to negentropy. In our case, it is used as a measure of negative entropy in the application for growth and/or repair R. 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 where we can isolate the living system and its neighboring environment. If a passive system and a living system have an equivalent amount of entropy internal disorder, which we often define as entropy damage ΔS_{damage}, then the living system responds with a spontaneous repair on itself (as in humans or animals), the repair processes generate additional positive entropy so

$$\Delta S_{Environment} + (\Delta S_{Living\,System})_{Damage+repair\,process} \geq \Delta S_{Environment} + \Delta S_{Passive\,system\,damage} > 0 \tag{2}$$

Comparing the repair process before and after for a living system

$$\Delta S_{Living\,System\,Unrepaired} > \Delta S_{Living\,System\,Damage\,area\,repaired} > 0 \tag{3}$$

We know from experience, that the that as living systems become older, there is a reduction in energy levels and in the repair rate as well (Johannsen et al., 2008; Goodson et al., 1979; Engeland et al., 2006). In addition the quality of the repair is less complete (Ahe, 2013; Gerstein 1993). For example, repair was perfect, aging would not occur in humans. Due to the living system imperfect repair, some disorder be left in the damaged area. The negative entropy change in the repair process given by $-\Delta S_{N\text{ System-Repair}}$ is not equivalent to perfect repair, leaving a certain amount of disorder remaining. We denote the remaining disorder with the quantity ΔS_{UR} (where UR is for the unrepaired portion) so that

$$\Delta S_{Damage} - \Delta S_{N\text{ System-Repair}} = \Delta S_{UR} = (1-f)\Delta S_{Damage} > 0 \tag{4}$$

where

$$-\Delta S_R = \Delta S_D - \Delta S_{UR},\ then\ \ -\Delta S_R = f\Delta S_D = -\Delta S_{N\,System\ repair} \tag{5}$$

Here f ranges from 0 to1, yielding the fraction of the damage entropy that has been repaired. When f=1, it indicates perfect repair and 0 indicates no repair. As living systems become older, repair becomes less efficient including the quality of the repair. For example, Ahn (2013) found that bone healing in young versus old mice was faster and had a higher quality of the repair. As well, Gerstein et al. (1993) noted similar results of wound healing in humans. Therefore f is likely a slowly varying function of time f(t) and this can be included in Eq. 5, so the living systems ability to generate negative entropy over time decreases and this notion can be included in our formulation so that

$$f(t+\Delta t) < f(t) \quad \text{and} \quad -\Delta S_R(t) = f(t)\Delta S_D = -\Delta S_{N\,System\ repair}(t) \tag{6}$$

However, during the repair process since f is slowly varying with time compared to the time it takes to repair an injury, we can treat f as a constant

$$\frac{dS_R}{dS_{Damage}} = -f > 0, \quad for\ t \approx \text{Repair time} \tag{7}$$

2 Method and Data - Repair in a Subsystem

In living system repair, time is not reversed; repair is done by removing the damaged area and cells are re-grown as close to their original state as nature permits (Johannsen et al., 2008; Goodon et al. 1979; Engeland et al., 2006; Wikipedia). To agree 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 for the sub-system to come to a more reliable ordered rather than a disordered stationary state. A "repaired system" uses energy and creates negative entropy production. In the non-equilibrium growth/repair state entropy decrease while free energy increase

$$\frac{dS_{\text{System-Growth or Repair}}}{dt} < 0, \quad \frac{dF_{\text{System-Growth or Repair}}}{dt} > 0 \tag{8}$$

A repair or growth cycle stops when a new "thermodynamic stationary state" is reached resulting in increases in the living system's free energy.

We can hypothesize the repair tendency to understand how a repair may occur in thermodynamic language. At the repair site, we envision that matter diffuses into the area driven both by a concentration gradient and a biological electrical charge across the repair area (see for example Becker, *Body Electric*, 1985). For example, a common thermodynamic potential model (Feinberg, 2019) for non-equilibrium is

$$-dS_{\text{Repair}} = \left(\frac{1}{T_R} - \frac{1}{T_b}\right)dU + \left(\frac{E_b}{T_b} - \frac{V_R}{T_R}\right)dq + \left(\frac{\mu_b}{T_b} - \frac{\mu_R}{T_R}\right)dn \tag{9}$$

We can think of a living system repair as setting up some similar potential system state for repair. Here the indices R indicates the repair area, b is the neighboring area 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 $T_R>T_b$ so that the repair internal energy increases $dU>0$, for $V_R>E_b$ then $dq>0$, the repair area is charged, and for $\mu_R>\mu_b$, $dn>0$, so matter flows to the repair site. When $T_R=T_b$, $E_b=V_R$, and $\mu_b=\mu_R$, the repair process is completed and we are in a new stationary state occurs with increased free energy available for useful work. The result is a more organized area. An actual repair process is more complex, it may take many such repair cycles to complete. However, the example illustrates from a thermodynamic perspective the concept of how a potential non-equilibrium state may occur in repair to generate negative entropy.

2.1 Growth and Self-Repair Description

Growth and self-repair have similarities since repair consists of removing damage and re-growing cells in the living system (Johannsen et al., 2008; Goodon et al. 1979; Engeland et al., 2006; Wikipedia). In both instances, the system becomes more ordered in the growth or repair phase

$$-\Delta S_{\text{N-Living System Growth}} < 0, \text{ for } 0 < \text{time} < t_{\text{growth}} \qquad (10)$$

In the case of repair,

$$-\Delta S_{\text{N-Living System Repair}} < 0, \text{ starts} < \text{time} < \text{completed} \qquad (11)$$

The exchange of entropies in repair is

$$\Delta S_{Gen} = \Delta S_{Environment} - \Delta S_{\text{Repair}} > 0 \qquad (12)$$

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

$$\left|\Delta S_{Environment}\right| \geq \left|\Delta S_{Repair}\right| \qquad (13)$$

This was recognized by Prigogine (1955) who won the Nobel Prize for discovering the importation of dissipation of energy into chemical systems and increase order in open systems. Macklem (2008) summarized the open system similar to Lehninger (1993) noting that

> "Life is an open thermodynamic system, in which energy is imported as food and oxygen and utilized in a process we call metabolism. Entropy in the form of waste products is exported. As entropy decreases, order must increase. Thus the imported energy is used to create the spontaneous development of self-organized, emergent phenomena."

2.2 Living System Negative Entropy Repair Work Equivalency Cyclic Model

Even with a simplified thermodynamic model as indicated in Eq. 9, growth and repair are complex. However, living systems undergo cyclic aging with periodic daily routines of work, sleep, nutritional consumption, waste, breathing cycles, and so forth. From an energy perspective repair and growth are also cyclic work occurrences. It may take many cycles for a repair or growth to occur. It would be difficult to model the full cyclic changes occurring during growth and repair as even suggested by Eq. 9. The most logical way to try and understand growth and repair is using an energy equivalence approach.

Rather than detail each repair process, for instance, we can make a simplified thermodynamic energy repair model similar to a cyclic heat engine that produces the equivalent work for a repair or growth process needed to increase the required amount of free energy. This can provide from a thermodynamic perspective, reasonable insights. The repair process is shown in Figure I. An injury occurs, after a few hours, the entropy is at a maximum where the entropy damage change has occurred, expressed by the entropy damage quantity ΔS_D , and the repair area has a temperature rise T_{High} (T_H) due to inflammation and increased blood flow (Chanmugam, 2017). Repair work is done ΔW_R, with heat ΔQ exchange between the T_H and T_{Low} (T_L at normal body temperature). We treat T_H and T_L as temperature reservoirs. This is an equivalence model. We can treat cyclic growth and repair in a thermodynamic framework using an equivalent amount of work needed to raise the free energy to its final state with an equivalent repair process due using the needed work output of a heat engine.

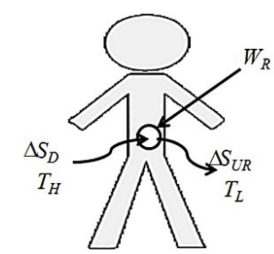

Fig. I Simplified body repair cycle

When the injury is almost completely repaired due to the repair work W_{Repair}, the entropy damage amount is quantified as ΔS_D, and the amount of negative entropy that flows into the site is $-\Delta S_R$. Since living systems are not capable of perfect repair, the amount of entropy that is left is denoted as the unrepaired entropy portion $\Delta S_{Unrepaired}$ (S_{UR}). We can make an equivalency T-S diagram. This is shown in Figure II.

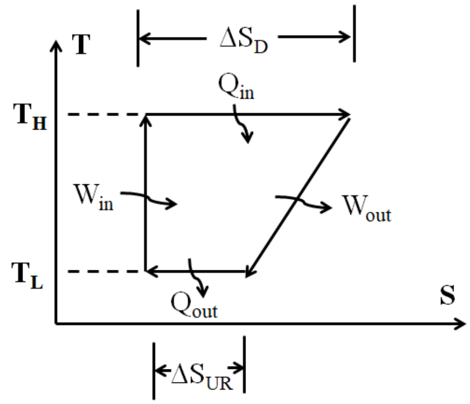

Fig. II Simplified body repair cycle

In this case, the cyclic thermodynamic equivalent repair work in Fig. II is the cyclic area which is simply the area of a trapezoid so that

$$W_{\text{Repair\_out}} = Q_{in} - Q_{out} = \frac{1}{2}\left(\Delta S_D - \Delta S_{UR}\right)\left(T_H - T_L\right) \tag{14}$$

The negative entropy needed for the repair process is

$$-\Delta S_{N-Generated} = \Delta S_D - \Delta S_{UR} = -\Delta S_R \tag{15}$$

So that the minimum work in the repair process is found by combining equations 14 and 15

$$\Delta W_{\text{Repair out}} = \frac{1}{2}\left[\Delta S_D - (\Delta S_D + \Delta S_R)\right](T_H - T_L) = \frac{1}{2}\left(-\Delta S_R\right)(T_H - T_L) = \frac{1}{2} f\left(\Delta S_D\right)(T_H - T_L) \tag{16}$$

From Figure II, Q_{in} is

$$\Delta Q_{in} = \Delta S_D T_H \tag{17}$$

In this equivalency model, the efficiency of a heat engine is given by

$$\eta = \frac{W_{\text{Repair out}}}{Q_{in}} \tag{18}$$

The heat is moving in at the top part of the cycle and the repair work cannot exceed the value found in Eq. 16 so that the following inequalities occur

$$Q_{in} \le \Delta S_D T_H \ \ and \ \ W_{\text{Repair out}} \le \frac{1}{2} f\left(\Delta S_D\right)(T_H - T_L) \tag{19}$$

The efficiency of living system repair from equations 18 and 19 is then

$$\eta_{LS} \leq \frac{\frac{1}{2} f \Delta S_D \left(T_H - T_L\right)}{T_H \Delta S_D} = \frac{1}{2} f \frac{\left(T_H - T_L\right)}{T_H} = \frac{f}{2}(1 - \frac{T_L}{T_H}) \tag{20}$$

We use the symbol η_{LS} for living system efficiency. In the case of growth instead of repair, we can substitute a growth entropy change ΔS_G for ΔS_R in Eq. 16. In Eq. 16 we used the fact that $-\Delta S_R = f \Delta S_D$ (from Eq. 5) with repair fraction *f* times S_D, where f has a value between 0 and 1 as previously defined in Eq. 5. In the case of perfect repair f=1 so that $-\Delta S_R = \Delta S_D$, and the theoretical maximum efficiency of half that of a Carnot cycle's maximum efficiency. In the case of no repair f=0, the efficiency η_{LS} goes to zero. As this is just an equivalency model, it shows that it may take many cycles for a good repair.

Finally, it is noteworthy that the maximum efficiency is found here to be half of what is theoretically possible in growth and repair when compared to the Carnot efficiency in Eq. 20. This lends some possible support to what Odum and Pinkerton (1955) claimed that maximum power occurred when the efficiency of energy production was about half of what was theoretically possible.

2.3 Repair Aging Rate – An RC Electrical Model

Note that the repair fraction *f* in Eq. 5 and 20 is, in theory, measurable and will depend on the living system's aging affecting the repair fraction (Ahn, 2013) and its repair rate $1/\tau$ (Ahn, 2013; Gerstein, 1993) that we now discuss.

We can look at the rate of negative repair entropy current flow I for a repair time τ as it relates to entropy damage to repair f(t) S_D. Here f(t), the fractional repaired and the repair time $\tau(t)$ will change as the living system ages so the amount of damage repaired is reduced and repair times increase over the life of a living system (Ahn, 2013; Gerstein, 1993). We propose a simple repair rate equation for the damaged area with repair capability where

$$I_{\text{Repair}} \tau(t) = f(t) S_D \tag{22}$$

This simply suggests a logical model that the repair current needed over the repair time $\tau(t)$ should go as the amount of fraction of repaired damage. The repair current is $I_{\text{Repair}} = dS_R/dt$. Then we can write this as

$$\frac{dS_R}{dt} = \frac{f(t)}{\tau(t)} S_D \tag{23}$$

We note that $S_R(t) = -f(t) S_D$. However, since f(t) and $\tau(t)$ are slow varying over a living system lifetime compared to the typically short time required for a repair process, we can treat f(t) and $\tau(t)$ as a constant so that $S_R = -f\, S_D$ (see Eq.7). Then, we can write Eq. 23 as

$$\frac{dS_R}{dt} = -\frac{1}{\tau} S_R \tag{24}$$

Then the solution to this differential equation is

$$S_R = S_{R0} e^{-t/\tau} \;\; where \;\; S_{R0} = -f\, S_{D0} \tag{25}$$

Inserting the solution into Eq. 24 yields

$$I_{\text{Repair}} = \frac{dS_R}{dt} = -\frac{S_{R0}}{\tau} e^{-t/\tau} = -\frac{S_R}{\tau} \tag{26}$$

as required. Often in physics, we like to make comparisons to other systems. It is common for example to compare electrical and mechanical systems. For example, a resonance circuit can be compared to a spring system having harmonic oscillations. It is not unusual in the literature that authors have compared living systems to circuits. For example, Becker (1985) in his book, The Body Electric, considered the human body to have internal electrical forces. Odum (1955) was drawn to electrical circuits. During the late 1950s, Odum started to simulate ecosystem dynamics using simple analog computers. He also made simulations to electronic components such as resistors and capacitors, and energy flow similar to circuit currents.

In this case, what comes to mind in Equation 26 is a simple discharge RC circuit. Let consider this for a moment since they have identical differential equations and the time constant also shows a strong analogy. The well-known RC circuit is shown in Figure II. The notion that the body charges up (switch B) to energize the repair area and then energy is discharged (switch A) into the repair process is the analogy that comes to mind.

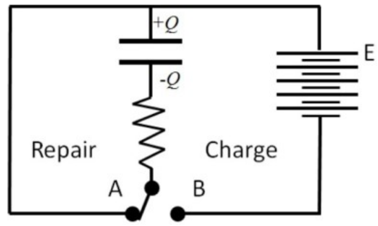

Fig. III Charge and repair RC Model for the human body

Indeed, the solution for the discharge circuit over time presents an identical analogy for Equation 26 where

$$I = \frac{dQ}{dt} = -\frac{Q_o}{RC} e^{-t/RC} \tag{27}$$

Comparing Eq. 26 to 27 we see that

$$\tau \equiv RC \ and \ Q_o \equiv S_{R0} = f\, S_{D0} \tag{28}$$

In this comparison, we can think of the repair area undergoing a type of charging to a value S_{RO} equivalent to the fractional damage to be repaired, $f\ S_{D0}$. The time to 63% of the repair cycle is τ and is similar to the RC time constant in a circuit. We see that the idea of a circuit comparison can be helpful. The capacitor charges to a voltage level with charge Q_0 similar to the negative entropy potential repair flow of $f\ S_{D0}$. This discharge occurs through a circuit resistance, as it takes time to discharge which is comparable to a living system repair time. We now can make a generalized statement. We see that

- a *living system's growth and repair are likely tied to a measurable repair or growth rate*.

Similar to Equation 6 we anticipate

$$\tau(t+\Delta t) > \tau(t) \tag{29}$$

The repair or growth time increases as the living system ages, it takes longer to repair entropy damage. This is an everyday experience in our personal lives. As an example, a University at Pennsylvania by Ahn, (2013) found "young mice produce a more robust healing response (timing, quantity, and quality) than geriatric mice which persisted throughout healing."

Therefore**,** living systems aging can be measured by its repair or growth rate τ and repair fraction f. If we had a perfect repair, for example, f=1, living systems would not age. These will change with aging time where the repair time $\tau(t)$ will increase and the repair fraction f(t) will decrease (Ahn, 2013; Gerstein, 1993). These metrics could likely help as a partial indication of the life span of any living system and a measure of its negative entropy capability. We note from Eq. 23 that repair rate is a function of time as well as f (see Eq. 6). Therefore we conclude

$$\tau(t) = R(t)C(t) \ and \ Q_o = S_{R0} = f(t)\, S_{D0} \tag{30}$$

Then from Eq. 25, we have

$$S_R(t) = -f(t)\, S_{D0} e^{-t/\tau(t)} \tag{31}$$

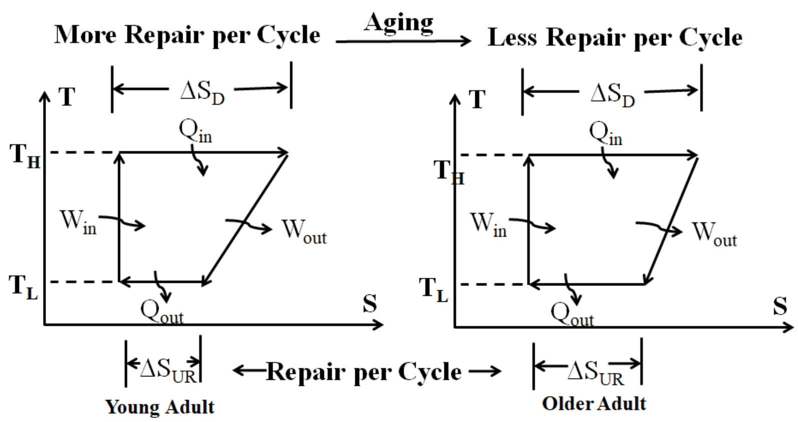

Fig. IV Comparison between repair for young versus older adult where $\Delta S_{UR\ Old\ Adult} > \Delta S_{URYoung\ Adult}$

In our thermodynamic equivalency model, we can illustrate this with a T-S diagram in Fig. IV. Here we conceptualized the repair per cycle for a young versus an older adult where $\Delta S_{UR\ Old\ Adult} > \Delta S_{URYoung\ Adult}$. In this equivalency T-S diagram, it would take an older adult many more repair cycles compared to a young adult, with the same amount of initial damage ΔS_D, to complete a repair (Gerstein et al., 1993; Ahn, 2013). Recall that $\Delta S_{UR}=(1-f)\Delta S_D$.

Measuring young versus old adults' repair rate is likely difficult. However, there are many qualitative examples from our everyday experience. For example, skin wrinkles, athletic performance, loss of hair, and so forth. It would be important from a medical perspective to measure a person's negative entropy capability more precisely. One possible practical measure of a living system's negative entropy production (growth/repair rate capability) for humans or animals may be strongly related to their amino acid levels which change with aging. For example, Canfield (2019) noted, "amino acids in the diet may be a viable approach for delaying aging in humans" and levels of each of the 20 proteogenic amino acids affect aging, aging-related diseases, and the associated signaling pathways." Alanine (an amino acid used to make proteins) levels have been shown to decline with aging in mouse plasma (Houtkooper et al., 2011) and in muscles (Uchitomi et al., 2019).

3. Discussion

In a Carnot engine, the total entropy change is zero, while in a living system in repair, this is not the case. The repair decreases the net living system's entropy (by $-\Delta S_R$ or $-\Delta S_N$) and increases the system's free energy. In the open system, energy is used to create system order (simulated in Eq. 9) and provides η_{LS} efficiency. The process that occurs is 'spontaneous'. One can argue that work was done to the system to accomplish this as it is not isolated to justify a Second Law treatment. Yet, in a Carnot cycle, due to the Second Law, heat flows 'spontaneously' only from higher to lower temperature bodies. Because spontaneous is in nature intimate for the Second Law itself and drives thermodynamic states towards equilibrium, one could state that contradiction occurs, causing a paradoxical situation for living systems. That is, we can't have it both ways. We can contend that when repair or growth occurs, the system is isolated enough to choose the type of work to be performed on the damaged or growth area. Entropy could increase, decrease, or remain unchanged after injury. The spontaneous tendency, however, is negative entropy production. Without this choice, living systems could not exist. This special circumstance results in somewhat of a paradoxical, and presents a difficulty to fully interpret living system growth and repair work due to their 'spontaneous' nature. We suggest a negative entropy statement below that could be helpful for interpreting living system thermodynamics through Eq. 32. One might suggest that these are special circumstances. However, this is not the case as Schrödinger paradox points out as well as Eq. 20 in interpreting negative entropy using the Second Law.

We first suggest a general statement on living system negative entropy from our results. We find

> *A living system's ability to generate negative entropy can be measured by its repair/growth time $\tau(t)$ and fractional repair $f(t)$ efficiency.*

If we redefine Eq. 1 such that $\Delta S_{N\,System} \le 0$, and combine it with 12 and 15 and 31, we find a generalized statement on negative entropy for living systems in application to and resembling the second law

$$\Delta S_{Environment} + \Delta S_{N-Generated}(t) \ge 0 \tag{32}$$

In this case, we arrange a Second Law statement for open living systems' by utilizing its form and interpret it as follows:

> *The equal sign suggests a statement of conservation of entropy between living systems and the environment. Alternately, one might suggest that living systems tend to spontaneously try and conserve entropy with the environment. However, the inequality is a statement of aging and irreversibility. When entropy is not conserved, the living system degrades and aging occurs, and entropy increases. This is time-sensitive and denotes a spontaneous nature as the living system's ability to generate negative entropy degrades over time towards eventual equilibrium.*

This reinforces Lehninger's (1993), and Prigogine (1955) contention 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. However, we note that this statement on the conservation of entropy also addresses the spontaneous nature of living systems that changes with time.

4. Conclusion

It is interesting to look at living systems from a thermodynamic framework. In this paper, we used an energy equivalence cyclic model to look at growth and repair from a thermodynamic perspective. Repair and growth were viewed as cyclic processes which suggested that equivalent work could be modeled with a cyclic heat engine. The efficiency results were similar to a heat engine with maximum efficiency half of that of a Carnot cycle. Results suggested that due to the spontaneous nature of growth and repair that one could argue that a paradox is still appropriate with the second law even though living systems are open which is illustrated by the spontaneous tendency towards repair and growth. That is, living systems are closed enough during repair where the internal spontaneous choice is to grow/repair rather than increase disorder. We suggested a statement through Eq. 32 to help clarify this tendency.

We also provided a repair rate model where analogies were made to an RC circuit and its time constant for the repair time. This helped suggest metrics that might be used to assess a living system's life span or ability to generate negative entropy which decreases over the lifespan of a living system. Therefore, if one could monitor the repair rate and fractional repair efficiency during the system's life, it would likely be a good measure of a living system's negative entropy production capability. We briefly suggested a possible example of how one might measure a living system's negative entropy capability in humans by assessing amino acid levels which are anticipated to change as aging occurs (Canfield, 2019; Houtkooper et al., 2011; Uchitomi et al., 2019).

In general, we find that negative entropy is an important thermodynamics quantity as it is not only internal to the mechanism in growth and repair in living systems, but plays a major role as Schrödinger pointed out in our everyday life. As such, we hope that this paper provides new insights into living system negative entropy thermodynamics.

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