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MANAGEMENT OF RESOURCES FOR SUSTAINABLE DEVELOPMENT: ENTROPY "SHOWS" THE WAY

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ABSTRACT

The purpose of "Sustainable Development" raises the following basic question: Which "indicator" should be used to identify the human activities that are contrary to this purpose?

In this paper it will be shown that "Entropy Generation" constitutes this Indicator. To this purpose, we will use three examples where Entropy Generation takes place and demonstrate that this generation of entropy is always contrary to Sustainable Development.

A forecast of future human activities will be then presented which will demonstrate that large Entropy Generation will continue. Sustainable Development can be thus achieved only by entering an "Era of Reduced Entropy Generation", which requires however drastic changes from Institutional policies to our own values and way of life.

KEYWORDS: Sustainable Development, Entropy Generation

INTRODUCTION

ENTROPY

- *Entropy is the arrow of time (Eddington).*
- *The Entropy of the universe tends towards a maximum (Clausius): No temperature differences will be present resulting in what is referred to as the "heat death" of the Universe.*
- *The supreme metaphysical law of the entire universe (Eddington), which governs everything we do (Rifkin).*

The purpose of "Sustainable Development", which in very simple terms refers to economic development that is not achieved at the expense of the resources available to the "future generations", raises the following basic question: Which "indicator" should be used to identify our activities that are contrary to this purpose? Today, for example, it is known –maybe to everyone– that between two processes: one with high equipment cost and low energy consumption and one with lower equipment cost but higher energy consumption, the latter is opposite to the aims of Sustainable Development. But this was not known in the past for the simple reason that the very concept of Sustainable Development did not concern humanity then.

It is, however, possible that even today there are activities contrary to Sustainable Development that we are not aware of. There are, for example, several people - unfortunately including some in policy making positions - that refuse to accept any relationship between the temperature increase of the Earth and the emissions of gases to the atmosphere; or, if they do accept it, refuse to deal seriously with the problem (the Hague meeting for example). How are we to deal with them? We obviously need an “indicator” that can tell us if an activity is contrary to the purposes of Sustainable Development.

In this paper we will show that Entropy Generation constitutes this “indicator”. To this purpose we will use first three examples where entropy generation takes place: (1) the reflux ratio of a distillation column; (2) the greenhouse effect; and (3) the difference in the standards of living between the Western and the Third World countries.

We will then turn to an other issue: the critical for Sustainable Development availability of raw materials which will lead to the so-called “fourth” law of Thermodynamics, proposed by Georgescu-Roegen.

We will proceed to consider the question “will the Entropy Generation continue” and close with our conclusions.

ENTROPY AND ENTROPY GENERATION

Definition

The thermodynamic definition of entropy is:

$$ds = \frac{dq_R}{T}$$

where *ds* is the entropy change resulting from the reversible addition or removal of a small amount of heat *dq* to a body.

According to the “godfather” Clausius: “We might call ‘S’ the ‘transformational content’ of the body, just as we termed the magnitude ‘U’ the ‘thermal and ergonal content’. But as I hold it better to borrow terms for important magnitudes from the ancient languages so that they may be adopted unchanged in the modern languages, I propose to call the magnitude ‘S’ the ‘Entropy’ of the body from the Greek work *τροπή*, transformation”.

It is apparent that neither the thermodynamic definition nor the one of Clausius give us much of an insight as to what Entropy is. We should not be surprised. Entropy is a concept –like love, hate, progress, etc.– and not “something tangible”, something we can measure such as length, volume or mass. No wonder it took Clausius fifteen difficult years - from 1850 when he presented the verbal statement of the 2nd Law of Thermodynamics to 1865, to arrive at the concept of entropy.

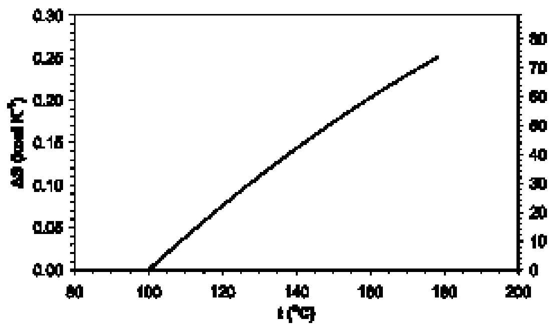

Figure 1. Entropy generation (ΔS) and loss of useful energy (E) in the vaporization of 1 kg of water at 100 °C using saturated steam at a temperature t. Notice that as the driving force for the transfer of heat from the steam to the boiling water, i.e. the difference between the steam temperature t and that of the boiling water (100 °C), increases so does the entropy generation and the loss of useful energy.

Let us thus attempt to develop a “sense” about entropy by trying to describe it, as we would do with other concepts such as “love” or “progress”. The comments about Entropy Generation presented below, which as we will see are related to the concept of Sustainable Development, should help in this endeavor as well as in understanding how entropy generation takes place.

Some comments about Entropy Generation

- It is a measure of the lost useful energy in a process (useful energy is the energy that can be used in a process, like heating water, running a car, etc. For example the large quantity of energy contained in the atmosphere is not useful).
- The larger the “driving force” in a given process, the larger the entropy generation is and, consequently, the larger the loss of useful energy. This is shown in Figure 1, where we notice that as the driving force between the

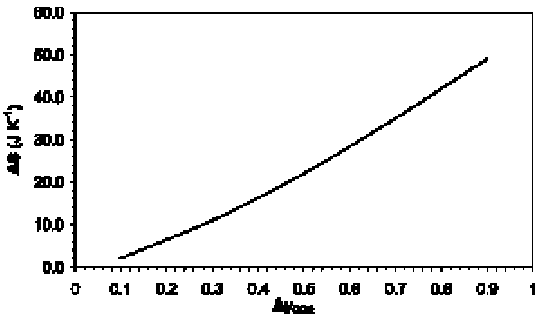

Figure 2. Entropy generation from the mixing of 1 mole of a CO_2+N_2 mixture with 10^6 moles of also a CO_2+N_2 mixture as a function of the driving force Δy_{CO2}. The composition of CO_2 (y_{CO2}) in the 1 mole varies from 10^{-3} to 1, that in the 10^6 moles starts at 10^{-3} and remains practically the same, and Δy_{CO2} is the difference: y_{CO2} (1 mole) - y_{CO2} (10^6 moles). Notice that as the driving force for the mixing of the two $CO_2 + N_2$ mixtures, Δy_{CO2}, increases so does the entropy generation. Both mixtures are at 1 atm and the calculations are made with the expression $\Delta S = -R[y_1 \ln y_1 + y_2 \ln y_2]$, which gives the entropy of mixing per mole of mixture and K by mixing pure 1 with pure 2; y_1 and y_2 are the mole fractions in the final mixture and R is the ideal gas constant.

donor of energy (steam) and the receiver (water) increases, so does the entropy generation and, therefore, the loss of useful energy.

- It occurs when two different fluids are mixed, as it is shown in Figure 2, and it also increases again with increasing driving force, the difference in concentration between the two fluids that are mixed.
- Every process leads to an entropy generation ΔS, which corresponds to the loss of a quantity of useful energy equal to $T_o\Delta S$, where T_o is the temperature of the environment, typically taken as 298 K.

We proceed now with the presentation of three examples that will demonstrate that Entropy Generation represents the "indicator" that identifies those human activities that are not in agreement with the aims of Sustainable Development.

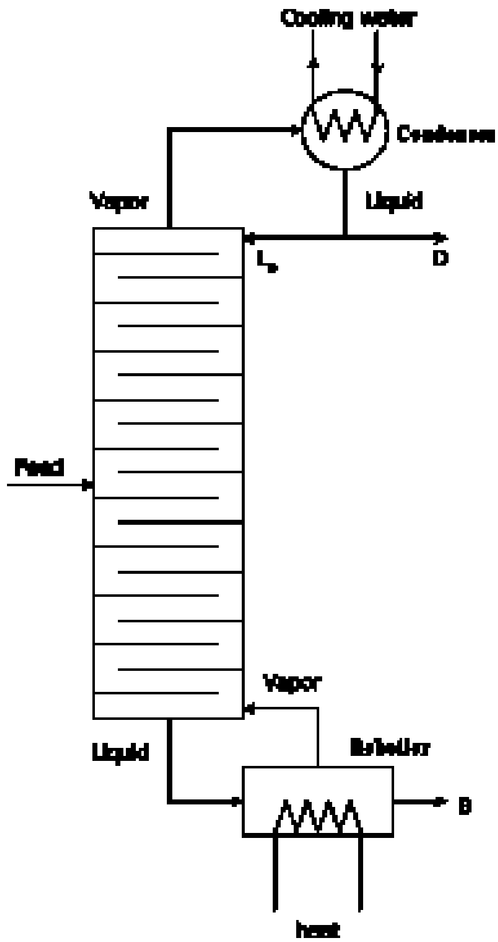

Figure 3. Schematic diagram for a simple distillation system. It consists of the Column, which contains the trays or packing material, the Condenser and the Reboiler. The feed enters the column and is separated into two products of desired purity, the Distillate D and the Bottoms B. This is accomplished as follows: the vapor generated in the reboiler rises and, as it comes in contact with the liquid descending from the condenser becomes richer in the light components, while the liquid becomes richer in the heavier components.

EXAMPLE 1. THE REFLUX RATIO IN A DISTILLATION COLUMN

The common industrial process for the separation of liquid mixtures is distillation. A typical simple distillation system is shown schematically in Figure 3, where its operation is also described briefly. The performance of the system is characterized by two

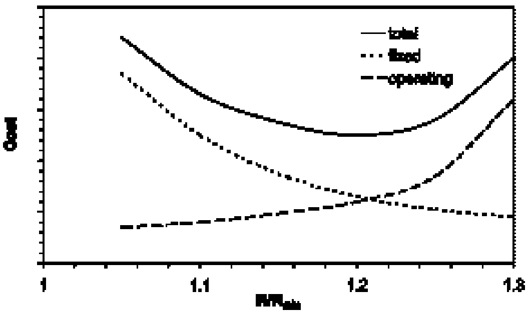

Figure 4. Total cost of a distillation column as a function of (R/R_{min}). As the value of R –and thus R/R_{min}– increases, fewer trays are needed and consequently the fixed cost decreases; at the same time, the operating cost increases as more heat must be added in the reboiler and be removed in the condenser.

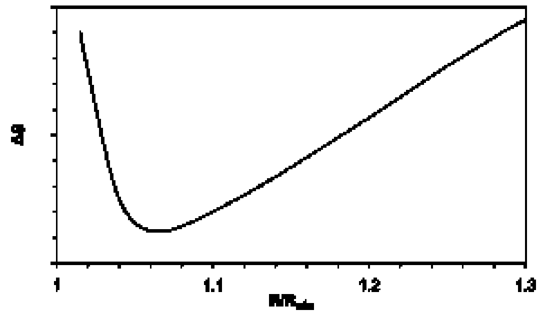

Figure 5. Generation of Entropy (ΔS) as a function of the ratio (R/R_{min}). A schematic diagram reflecting: material of construction and construction, heat added in the reboiler and heat removed in the condenser.

basic quantities: (1) the number of trays (or amount of packing) and (2) the reflux ratio $R=L_o/D$, the ratio of the stream L_o that returns to the column after the condenser, over the distillate stream D, one of the products of distillation.

As L_o increases for a given amount of distillate product, the required number of trays for the separation decreases and so does the equipment cost. At the same time, however, the amount of heat added in the reboiler increases and so does the amount of heat removed in the condenser, i.e. the amount of cooling water. There is, finally, a minimum value of R, R_{min}, below which the separation is not feasible even with an infinite number of trays.

In designing a distillation system we must determine the optimum value of the reflux ratio –typically expressed as R/R_{min}– by minimizing the total cost: fixed plus operating (mainly energy) as shown in Figure 4.

Before the 1973 oil embargo, a typical value of (R/R_{min}) was about 1.3-1.5, which was equivalent to the use of a large amount of energy. This, of course, had as a result a large entropy generation, as shown schematically in Figure 5. It is apparent that the "indicator" of Entropy Generation was already showing that **something was wrong** with respect to the aims of Sustainable Development, but most of us (if not all) did not know it. The increased cost of energy that resulted from the Oil Embargo reduced this ratio to about 1.1 the 90's. However, the Entropy Generation indicator shows that despite the energy savings, which follow the right direction with respect to the objectives of Sustainable Development, **something again is wrong**. The first messages from Industry are already in accordance with this indication. The lost energy causes another problem, the use of cooling water for removing this energy from the process, which is not in abundance and it is becoming progressively a major factor for Sustainable Development. I am certain that in the next decade the ratio (R/R_{min}) will assume values below 1.1 (Figure 6).

EXAMPLE 2: THE GREENHOUSE EFFECT

As shown in Figure 7, the mixing of the CO_2, produced by the combustion of fossil fuels, with the atmosphere has led to an enormous entropy generation and the same applies to the other gases (CH_4, freons, etc) that are released to the atmosphere. Thus, again, the Entropy Generation indicator **warned us** that something went wrong with respect to the objectives of Sustainable Development. Yet it was not until the effect of this CO_2 on the warming of the atmosphere, i.e. the Greenhouse Effect, was recognized that concern about this problem developed; and for those not recognizing this effect of CO_2 on Sustainable Development –unfortunately often in policy making positions– the resulting entropy generation should convince them.

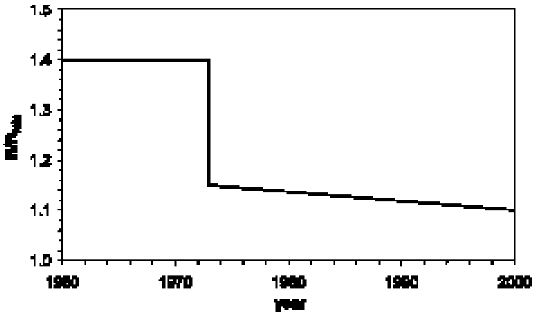

Figure 6. Change of the optimum (R/R_{min}) value with time.

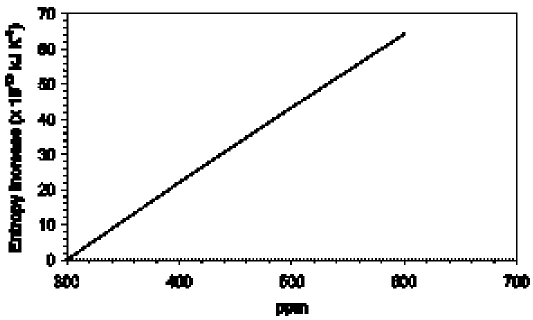

Figure 7. Entropy increase of the atmosphere as a function of the CO_2 concentration above the 300 ppm reference point calculated by the expression: $\Delta S = NR\left[y \ln y + (1-y)\ln(1-y)\right]$, where N is the total moles of atmosphere ($\sim 3.5\times10^{19}$), y is the mole fraction of CO_2 and R is the gas constant.

EXAMPLE 3: THE DIFFERENCE IN DEVELOPMENT BETWEEN THE WESTERN AND THIRD WORLD COUNTRIES

The extremely great difference in the standards of living between the Western and the Third World countries (Latin America, Africa, Asia) constitutes an equally great “driving force”: the strong desire of the Third World people to reach the standards of living of the advanced western societies. This large driving force leads in turn, as we have seen, to a large entropy generation and consequently it has –and it will have– dramatic negative implications on Sustainable Development: social and energy related.

Social. The continuous wars in third world countries, caused mainly by their poverty, leads to the death of millions of people –several million in 1999 according to the International Institute for Strategic Studies (IISS), the decimation of whole tribes and the destruction of valuable resources. Sustainable Development becomes an impossible dream for this people with about a billion of them so malnourished that they can not work and many of them becoming environmental refugees, wondering across landscapes and borders. (Chemical Engineering, April 1997, p.681). Furthermore, the steady streams of refugees to western countries has created substantial social problems and fueled the development of racist attitudes. (According to a recent survey the majority of Italians consider refugees the number one threat to their safety).

Energy related. In the 1990’s the West with about the 1/8 of the world population consumed about 1/2 of the total energy used. If we now consider that a 1 % increase in Gross National Product (GNP) required about the same increase in energy consumption (Edmonds and Reilly, 1985), we conclude that –in order for the third world countries to reach the standards of living of the western ones– the total energy consumption must be quadrupled. Where will all this energy come from? What will it be the impact on its cost and, consequently, on the ability of these countries to purchase it? What will be the consequences of the emitted for this energy production CO_2 on the Greenhouse Effect?

It is apparent that the Entropy Generation resulting from the impoverished state of the Third World has a paramount effect on the Sustainable Development of the world, which will become more so in the future (unless of course we envision Sustainable Development for the Western World only!!!).

RAW MATERIALS: NEED FOR A “FOURTH” LAW?

Sustainable Development does not only depend on the availability of energy or the Greenhouse Effect and other environmental problems. It also depends - and substantially so - on the existence of Raw Materials: top soil, minerals, polymers, etc., not to mention fresh water. The fact that “available” matter –to use Lord Kelvin’s expressive term for energy– becomes “unavailable” is, or should be, apparent to all of us. We all know that these raw materials "are dissipated" as it happens with useful energy. As an example we mention that 15 % of the top soil has been lost or that recycling –under the best conditions– doesn't exceed 50 %.

These observations indicate the need for a "law" which - because of its conceptual similarity to the Second Law - is referred to as the "Fourth Law" (of thermodynamics): "A closed system, instead of being led to 'heat death', where all the energy is non-usable, tends to 'chaos', where the whole material is non-usable", (Georgescu-Roegen, 1971; 1979; Rifkin, 1980). In other words, this law proclaims for matter what the Second Law proclaims for energy. It is worth mentioning that Georgescu-Roegen was among the first economists and environmentalists who claimed that economy faces limits to growth, for which he invoked the Second Law of Thermodynamics. Although generally ignored by mainstream economics, today his work is gaining influence and his insights are being grafted into the new field of Evolutionary economics.

THE FUTURE OF SUSTAINABLE DEVELOPMENT: WILL THE GENERATION OF ENTROPY CONTINUE?

What can we expect in the future? Will the large entropy generation continue rendering Sustainable Development an impossible dream? Or, will we adopt –or be forced to adopt– a "Low Entropy Generation" mode of thinking from Institutional policies to our own values and way of life?

Negative prospects

1. In spite of the RIO conference decision for the reduction of greenhouse-gas emissions the opposite will more likely occur. Thus, emissions of such gases in the U.S. increased 11.5 % from 1990 and 0.5 % from 1997 (Chemical Engineering, April 2000, p.25). It is worth noticing, however, that the increase has been slowed down substantially. Increased emissions of such gases is also observed in most European Union countries. Furthermore, the results of the recent Hague Conference are anything but encouraging.
2. The Report "Technology Vision 2020, The U.S. Chemical Industry", issued by the American Chemical Society in 1996, places very little emphasis –actually it just pays lip service– on Sustainable Development. Furthermore, there is no indication that the European Chemical Industry takes a more serious approach to this problem.
3. Even though the average temperature at the Earth's surface has increased by 1 degree Celcius from 1860 to 1988 (Chemical Engineering, Jan. 1999, p. 37) many people –unfortunately in policy making positions– do not accept that this is due to CO_2 emissions or consider their reduction too costly.

Positive Prospects

1. People in the more developed countries are becoming –but rather slowly– sensitive to the problem.
2. The Rio Conference set very promising goals (but will they be realized, especially after the Hague Conference?)
3. The "Factor 10" scenario advocated by the European Environmental Agency "...in industrialized countries, the current resource productivity must be increased by an average of a factor of 10 during the next 30-50 years. This is technically feasible, if we mobilize our know-how to generate new products, services, as well as new methods of manufacturing." Who believes in it, though?
4. The most, maybe, encouraging fact is the acknowledgement of the problem by the big multinational companies. Robert Shapiro, CEO of Monsanto (Chemical Engineering, April 1997, p. 681-12) says: "Without radical change, the kind of world implied by (unsustainable practices) is unthinkable. It's a world of mass migrations and environmental degradation on an unimaginable scale... We're entering a time of perhaps unprecedented discontinuity. Businesses grounded in the old model will become obsolete and die."
5. The all mighty "market forces" are entering the picture: "We think that by 2050 renewables could count for 50% of the energy market. Right now the market is small, but we believe it will grow." (J. van der Veer, Group Managing Director, Shell Intl., Oct. 1997).
6. Major R&D projects are undertaken in Europe, U.S.A., Canada, Australia and Japan to capture CO_2 from the flue gases and store it either in aquifiers or in the form of stable and inert salts mainly $MgCO_3$ (Chemical Engineering, March 2000, p. 41).

CONCLUSIONS

1. The “Entropy Generation” constitutes the “indicator” which predicts the negative consequences/effects of human activities on Sustainable Development.
2. The enormous Entropy Generation in the Industrial Era –accelerated in the last decades– due to the:
   - waste of energy;
   - increase of CO_2 and other gases emissions;
   - destruction of raw materials;
   - development of an enormous economic gap between the Western and the Third World countries

   has inflicted a severe blow to Sustainable Development.
3. Reversing this course, that is Development leading to much smaller Entropy Generation that will allow Sustainable Development, must be the great challenge of humanity.
4. Will we enter this era of “Reduced Entropy Generation” with the present way of Institutional thinking which is epitomized by the dilemma: “Clear Air: Dollars versus Lives”, as L. Raber (Chemical Engineering, Feb. 1997, p.28) presents it and where it is demonstrated that the odds favor the dollar?
5. Will we also enter this era with our current thinking, or will drastic changes be needed in the way of our life and our values? Here are two of the (provocative?) suggestions by Rifkin (1980):
   - on Material Wealth and Consumption: “more is less” becomes the way of life, not just a slogan.
   - on Urban life: labor-intensive agriculture will replace slowly the current energy intensive one leading to the disappearance of the megalopolis, with “large” cities returning to the preindustrial level of 50,000 to 100,000 inhabitants.
6. The dream of the aforementioned CEO Shapiro could, of course, become a reality, when the chemical products will come from agricultural cultivations: “Ultimately, we’d love to figure out how to replace chemical processing plants with fields of growing plants –literally green plants capable of producing chemicals”.

   The first logical step to enter this era of “Reduced Entropy Generation” is to develop the awareness –all of us– of what must become the “slogan” of Sustainable Development:

“We have not inherited the earth
from our ancestors,
we have borrowed it
from our children”

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