Original Article: Exergy and the Fusion and Fission Nuclear Reactions in Nuclear Powerplants

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ABSTRACT

The present research specializes in the second law analysis to characterize the balances of properties and efficiencies of processes occurring in nuclear reactions. The conceptual schema is underpinned by the paradigm of microscopic few-particle systems and the inter-particle kinetic energy and binding potential energy determined by interactions among atomic nuclei and subatomic particles in non-equilibrium states along with irreversible phenomena. The proposed thermodynamic entropy calculation is based on energy and exergy, both being measurable properties used to directly derive entropy variations determined by elemental fission and fusion nuclear reactions in operating industrial plants.

Introduction

The interest in developing second law analysis founded on exergy method applied to fission and fusion nuclear reactions can be found in: i) the observation of physical phenomena and nuclear processes through a thermodynamic standpoint; ii) the need of adopting a more extended approach to nuclear reactors design in the perspective of the optimization and confrontation of different types of technologies and plant configurations [1-3]. The exergy method focuses on irreversible phenomena associated with non-equilibrium states and processes occurring in all macroscopic and microscopic physical systems. The degree of irreversibility of non-equilibrium processes is correlated to the amount of exergy destruction, representing the degree of dissipation of all energy and interaction forms. For these reasons, it is worth applying this method to nuclear reactions to extend the overall plant mass and energy

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balances and evaluate exergy efficiencies. To do so, an analysis of concepts underpinning the definitions of thermodynamic entropy and exergy properties is summarized to demonstrate their implications in nuclear physics [4-6].

Usually, second law analyses consider the conventional plant or the nuclear reactor or jointly combined to achieve an overall balance. Regarding light water boiling technology and Boiling Water Reactors (BWR) power units, a study was carried out by Dunbar et al. on an operating plant [1]. As regards light water pressurized technology, more recent studies are reported in the literature for Pressurized Water Reactors (PWR) [7-9] and Multipurpose Advanced Reactor inherently Safe (MARS) [3]. Despite the accuracy of those studies, no specific mention is provided on the elemental nuclear reaction and the implication on the behavior and performance of plant core. Here, the purpose is to bridge this gap with the analysis focusing on the elementary fission or fusion nuclear reaction representing the crucial process stage occurring in the core of fission power plants or the plasma chamber of ITER (under construction) DEMO (under design) fusion reactors [10-12].

Regarding the nuclear physical aspect, the literature reports studies focusing on nuclear radiation and decay processes' exergy analysis [4, 5]. In particular, classical and quantum statistical methods have been adopted to evaluate exergy based on barions motion and momentum to achieve exergy fluxes calculated utilizing physical parameters characterizing the motion of the particles [4, 5]. Statistical models underpin these evaluations to describe nuclear fuel bulk reactions occurring in operational industrial plants. The present research focuses on the thermodynamic processes occurring within the core of reactors. Here, the intent is to analyze the elemental fission and fusion reactions and propose an alternative method based on binding potential energy among protons and neutrons, calculated based on a mass defect in different physical states [6]. The objective is to evaluate the thermodynamic state and process variables governing nuclear reactions and provide the basis to complete a complete evaluation of plant configurations and a confrontation among different technologies. This perspective allows assessing the balance and efficiency that should be accounted for in an overall Second Law analysis based on the exergy method adopted to provide an operative tool for calculations in applications and reactors design. To do so, Second Law analyses need to be carried out adopting measurable properties. For this very reason, the exergy method and the formulation of thermodynamic entropy defined by Hatsopoulos, Gyftopoulos, and Beretta will be adopted as described in the following sections [13-15].

Theoretical Framework

First Law Analysis (Energy Analysis)

The estimation of the power generation and other thermodynamical parameters are done using the first law of thermodynamics. The first law is dedicated to the energy equilibrium concept and uses its principles in the modeling control volumes [5, 6]. This

concept tells us that the energy can be converted into different forms and is always conserved in conversions [7]. Using this principle helps to model each component in the term of energy separately. The equations used to define the efficiencies are described in this section [16-18].

All the equations used in the energy analysis are derived from the SS open system general energy equilibrium. The kinetic and potential energy terms are being neglected because of the small amounts and simplifying the calculations. The schematics of a control volume for a particle in general energy equilibrium are illustrated in Figure 1.
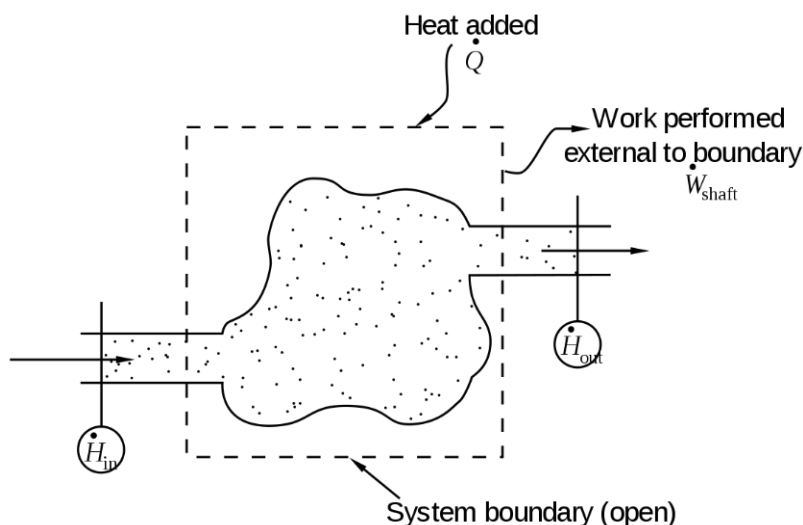

Figure 1. The schematics for the general energy equilibrium for a control volume.

$$0 = \dot{Q} - \dot{W} + \sum \dot{m}_{in}\left(h_{in} + \frac{V_{in}^2}{2} + gz_{in}\right) - \sum \dot{m}_{out}\left(h_{out} + \frac{V_{out}^2}{2} + gz_{out}\right) \quad (1)$$

Equation 1 describes the general equilibrium, and in this equation, Q stands for heat flow, W for work performed by the system, m for mass flow, V for velocity, h for specific enthalpy, and z for elevation. In the first law, heat and work are assumed as networks, and heat enters or exits the system boundary [19-21].

Second Law Analysis (Exergy Analysis)

Exergy is a term for thermodynamics and refers to the maximum useful force received from a system to achieve thermodynamic exchange. Simple but unscientific definition: Exergy is the part of the total force consumed, for example, keeping the car steady. The wasted part of the energy is called inertia. In thermodynamics, the exergy of the system is the most useful work possible in a process that balances the system with the heat source [22-25]. When the environment is around the spring, exergy is the system's potential for change when the system reaches equilibrium with

the environment. Exergy is the energy available for use. After the system and the environment are in equilibrium, the exergy becomes zero. The study of exergy was also the first goal of thermodynamics. The term exergy was coined in 1956 by Zoran Rent using the Greek words ex and ergon. Energy is never lost in a process but changes from one form to another [25].

Conversely, exergy is an irreversible factor in a process due to increased entropy. Exergy always disappears when the temperature changes. This destruction is proportional to the increase in entropy of the system with its surroundings. Destroyed exergy is called anergy. For an isothermal process, exergy and energy are interchangeable. Exergy analysis is performed in the field of the industrial environment for more efficient use of energy. Engineers use exergy analysis to optimize applications with physical constraints, such as choosing the best use of roof space for solar energy technology. Ecologists and design engineers often consider a reference model for a spring that may differ from the actual system environment [16-18].

Energy is a ratio of the system's composition and its environment because it depends on the state of both the system and the environment. The exergy of the system is at zero equilibrium with the environment. Exergy is neither the thermodynamic property of matter nor the thermodynamic potential of the system. Exergy and energy both have units of joules. Therefore, the internal energy is always measured from a fixed reference state and is a state function.

Some authorities define system exergy as a variable with environmental changes, in which case it is not a function of the state. Some other authors offer a slightly different definition in which they define the environment around the absolute, immutable reference state, which replaces a property of the system state alone.

Exergy applications when the first law of thermodynamics is expressed as the principle of energy conservation, we deal with different forms of energy. From an engineering point of view, a quantity of energy has quality. In general, quality means the degree of usefulness. Reactions of work and heat cause changes in systems. Previous observations show that the reaction of work is much more important than heat reaction to change the system's state. Since work reactions have a high degree of usefulness, it is said that they have a higher quality than heat reactions. Even the second law of thermodynamics sets a higher standard for work than heat. Work is completely converted to heat, but the conversion of heat to work by a device operating in a thermodynamic cycle is very limited. Therefore, work is more useful than heat, and it is sometimes very difficult to obtain. Exergy is one of the ways of energy analysis, which includes all the energies of the fluid flow. This energy can be caused by the motion of the reaction or anything else.

$G = H-TS$ is the basis of exergy analysis. The above equation should be used instead of the energy balance, for example, for a current in a reactor. In recent decades, process integration issues have been raised. Previously, it was thought that only by using

the single processes of a system can the best-operating conditions of the system be achieved, but the study of the interaction of processes and their impact on each other leads to the efficiency of the whole system. This method has two parts: the analytical tool Exergy and the applied tool pinch. Exergy is based on the second law of thermodynamics, and pinch is based on the first law of thermodynamics. The exergy method is a solution for thermodynamic analysis of processes, defined as a universal measure of work's potential or the quality of various forms of energy concerning an environment. An exergy balance application expresses how much of the usable (useful) work potential entered into the process is consumed by the process. This amount of loss is the same as irreversibility [19].

Exergy is the maximum useful or high-quality energy in a system. With the help of exergy, irreversibilities are more easily seen in single components. This insight can lead to better designs by focusing on the largest processes of exergy destruction. The sensitivity to fluid flow is determined for wherever h_0, T_0, s_0. are specific enthalpy, temperature, and entropy, respectively, in the case of a particular ambient of reference to perform an exergy analysis (see Figure 2) [9].
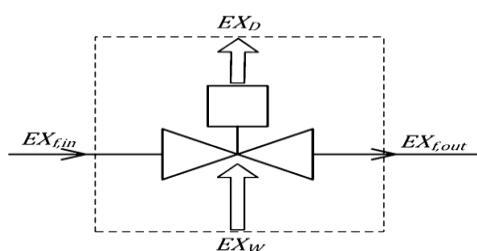

Figure 2. The second law of thermodynamics for a control volume.

$$\dot{E} = \dot{m}(h - h_0) - T_0(s - s_0) \qquad (2)$$

The reactor's exergy is characterized by a simple model[45], which determines the total sensitivity based on the heat generated and the reactor temperature:

$$\dot{E}_r = \dot{Q}_{in}(1 - \frac{T_0}{T_r}) \qquad (3)$$

With exergy values from any state point, the destruction of exergy loss can be found for each component. Exergy destruction (E_d) reduces the amount of energy that could theoretically be useful, but not because of the limitations of the components of the cycle, such as turbine efficiency and the efficiency of the heat exchanger [4]. These values can be compared in each of the components and in different cycles to determine when the destruction in the cycle occurs.

Exergy Method Applied to Nuclear Reactions

Nuclear reactions can be regarded as elemental non-equilibrium irreversible processes occurring in few-particle systems constituted by nuclei, neutrons, and other sub-nuclear particles interacting because of collisions occurring at defined thermodynamic conditions. The definition of entropy property of a system A, beside the classical formulation of Clausius $= \frac{\delta Q}{T}$, has

been expressed by Hatsopoulos, Gyftopoulos, and Beretta in the following form [7-11]:

$$S_1 - S_0 = \frac{1}{C_R}[(E_1 - E_0) - (\Omega_1^R - \Omega_0^R)] \quad (4)$$

where C_R is a constant characterizing an external reference system R behaving as a reservoir, E is the internal energy determined by the temperature associated to the kinetic energy of interacting particles and reaction products, and Ω^R is the available energy of the system interacting with the reservoir. The literature reports the proof that $C_R = T_R$ [7]. Moreover, it has been proved that entropy is an inherent property of any system, large or small, in any state, equilibrium or non-equilibrium [8, 9], and, for this reason, the reservoir behaves as an auxiliary system only [4]. The definition of thermal entropy can be expressed in the form:

$$S_1^T - S_0^T = \frac{1}{T_R}[(E_1 - E_0) - (EX_1^R - EX_0^R)]^T \quad (5)$$

where the available energy Ω^R is replaced by the thermal exergy EX^R. This expression has been proved [7] employing the concept of the non-existence of Perpetual Motion Machine of the Second Kind (PMM2). Indeed, the non-existence of PMM2 implies the impossibility of a complete thermal-mechanical conversion of thermal energy into work, thus meaning that the energy conversion efficiency $\eta^T < 1$. This logical inference can be replicated for nuclear-mechanical conversion of mass into work

where mass interaction is associated with the potential energy, or binding energy, among particles constituting a system. Hence, the definition of nuclear entropy can be assumed to be:

$$S_1^N - S_0^N = \frac{1}{\mu_R^N}[(E_1^N - E_0^N) - (EX_1^R - EX_0^R)]^N \quad (6)$$

where $C_R = \mu_R^N$ and μ_R^N is the reference nuclear potential of the reservoir and E^N is the binding potential energy associated with strong interactions among nucleons? The method adopted is founded on the binding energies calculated in mass defects before and after a nuclear reaction according to the approach already used and reported in the literature by Badescu and Isvoranu [4, 5] and by Hermann [6]. Figure 3 describes the curves of binding potential energy for nuclei involved in fission and fusion reactions, respectively.

In this particular case, the non-existence of PMM implies the impossibility of a complete nuclear-mechanical conversion of nuclear potential into work, thus meaning that the energy conversion efficiency $\eta^T < 1$.

Finally, the mechanical entropy S^M Accounts for the density of (i) interparticle kinetic energy correlated to the frequency of collisions, and (ii) the potential energy correlated to the intensity of actions, both depending on the volume. Hence, the following expression:

$$S_1^M - S_0^M = \frac{\bar{R}}{R_R V_R}[(E_1 - E_0) - (EX_1^R - EX_0^R)]^M \tag{7}$$

in which $\frac{1}{C_R} = \frac{\bar{R}}{R_R V_R}$ Constitutes an additional term of the generalized thermodynamic entropy suitable to characterize the mechanical internal energy PV associated with pressure and volume. As entropy is an additive property, the generalized definition is obtained by the sum of its thermal, nuclear, and mechanical components: $S^G = S^T + S^N + S^M$ [12-13].

With the definitions of entropy related to exergy and AR, the composite of mutually interacting system A and reservoir R, the generalized exergy balance of an individual fission or fusion nuclear reaction can be expressed through different exergy contributions [20].

They are thermal exergy producing available work interaction $EX^T = (W_{10}^{AR \to})_{HEAT}^{MAX}$, nuclear exergy producing work interaction $EX^N = (W_{10}^{AR \to})_{MASS}^{MAX}$, mechanical exergy producing heat interaction $EX^M = (Q_{10}^{AR \to})_{WORK}^{MAX}$, mechanical exergy producing mass interaction $EX^M = (M_{10}^{AR \to})_{WORK}^{MAX}$; therefore, the expression of generalized exergy is the following [14]:

$$EX_{NUCLEAR \atop REACTION}^{G} = EX^T + EX^N + EX^M = (W_{10}^{AR \to})_{HEAT}^{MAX} + (W_{10}^{AR \to})_{MASS}^{MAX} + (Q_{10}^{AR \to})_{WORK}^{MAX} + (M_{10}^{AR \to})_{WORK}^{MAX} \tag{8}$$
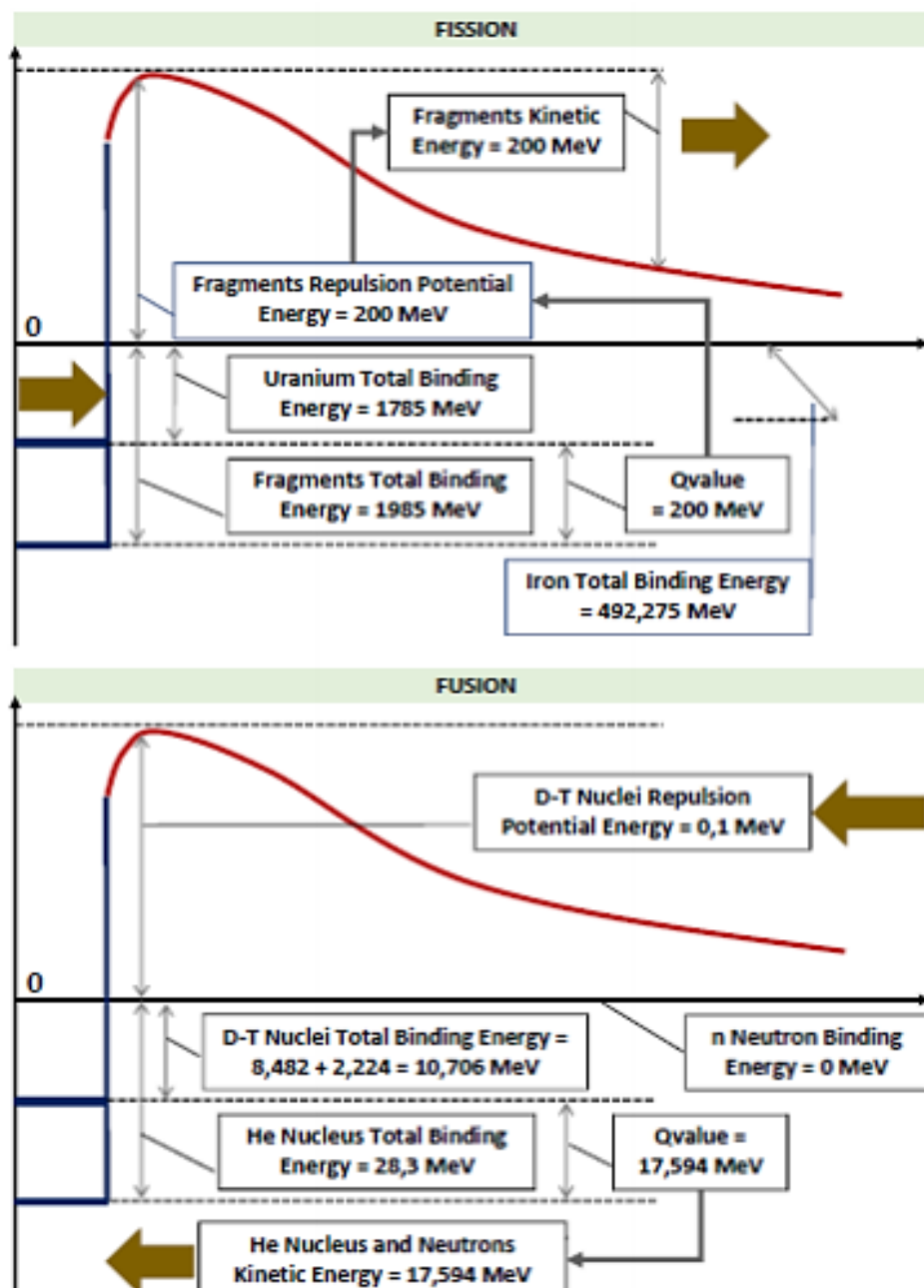
Figure 3. Binding potentials in fission and fusion nuclear reactions. The horizontal x-axis represents the distance between interacting particles, and the vertical y-axis represents the inter-particle energy

This definition of generalized exergy of nuclear reactions is underpinned, on the one side, by the concept of equivalence between heat interaction and work interaction and the equivalence between mass interaction and work interaction; on the other side, the inter-convertibility of heat-to-work and work-to-heat, as well as

the inter-convertibility of mass-to-work and work-to-mass, is a counter-proof of the equivalence above mentioned [15-18]. It is worth using the expressions above discussed for nuclear processes since energy and exergy are measurable properties. Moreover, the thermodynamic state of the reference system behaving as a reservoir can be arbitrarily selected being an auxiliary system only in the definition of thermodynamic entropy [8-10] and its components [14]. Hence, entropy calculation can be directly derived once thermodynamic states before and after nuclear reactions are defined. This method, usually adopted for many-particle systems and properties describing macroscopic systems in plant optimization [19], will be here specially applied to elemental fission and fusion processes, as demonstrated in the following sections [21].

Fission Nuclear Reaction Exergy Analysis

A typical Uranium $^{235}_{92}U$ fission reaction is represented by [20-21]:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236*}_{92}U \rightarrow ^{A1}_{Z1}X + ^{A2}_{Z2}Y + 2.43^{1}_{0}n + Qvalue \qquad (9)$$
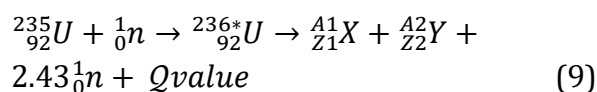
Before the fission occurs, strong attraction interactions among nucleons behave as a constraint and hold the nucleus as a wholly unique system. The nucleus fission produces fragments $^{A1}_{Z1}X$, $^{A1}_{Z1}X$ composed by nuclei of lower atomic number, the uranium atomic number, neutrons, and gamma radiation. The increase of particle

mass dispersion and interaction distribution among fragments causes the transition from a concentrated mass, characterized by a unique position and velocity, to a subdivided configuration. This transition implies that positions are dispersed and velocities distributed with random spectra compared with the initial nucleus due to phenomena' intrinsically probabilistic statistical and quantum nature at the microscopic nuclear and sub-nuclear levels. Once the inter-nucleons attraction bond barrier has been overcome during the fission, fragments move to accelerate away from each other due to electromagnetic repulsion interactions. The repulsion potential energy existing immediately after the fission is transformed into fragments of kinetic energy released to the surrounding fuel bulk, and the fission temperature is decreased to the fuel rod's temperature. The fission temperature is conventionally calculated considering the relation $k^T_B = 210 \ MeV$ where $k_B = 8.617 \times 10^{-11} MeV/K$ is the Boltzmann constant and $MeV = 1.602 \times 10^{-13} J$.

This temperature difference is not used in a conventional industrial reactor to produce work interaction; it is irreversibly dissipated. The reaction is not reversible because the heat interaction amount released is insufficient to reverse the nucleus to its original configuration, thus requiring an inverse fusion reaction with heat input [9-11]. The fission determines the stochastic distribution of velocity vectors about every fission fragment in such a way as to prevent the occurrence of any reversible process back to the initial

unique mass state with the energy associated with the nucleus center of mass. Thus, nucleus fission into fragments increases the degree of velocity distribution and position dispersion among all particles, increasing the entropy property characterizing the thermodynamic state change after the fission process. The entity of entropy increase caused by the two different contributions identified above is the objective of the following analysis [11-13].

The definition of generalized thermodynamic entropy S^G variation, outlined in the previous section and here adopted, requires the calculation of the generalized exergy EX^G the variation that can be expressed in the following terms taking into account the contribution balance of all components:

$$\Delta EX^G_{\substack{NUCLEAR \\ FISSION}} = (\Delta EX^M + \Delta EX^T + \Delta EX^N)_{\substack{NUCLEAR \\ FISSION}}$$

$$= -\left[(EX^M + EX^T + EX^N)^{\substack{BEFORE \\ FISSION}}\right] =$$

$$-\left[-(EX^M + EX^T + EX^N)^{\substack{AFTER \\ FISSION}}\right] \qquad (10)$$

Before the fission, the mechanical exergy EX^M consists of the capability of colliding neutron and target nucleus kinetic energy to be converted into thermal energy along a reversible process, however for moderated neutrons, this component is negligible. The thermal exergy EX^T related to the fuel bulk temperature characterizing the target nucleus concerning the environment is negligible. The nuclear

exergy EX^N associated to the nucleus binding potential energy, is equal to the sum of inter-nucleons strong attraction potential energy and inter-nucleon electromagnetic repulsion potential energy $E^{NUCLEUS}_{BINDING} = E^{ATTRACTION}_{POTENTIAL} + E^{REPULSION}_{POTENTIAL}$. This resulting potential energy can be theoretically transferred as maximum net useful work interaction along a mass-to-work direct conversion cycle with efficiency η^N Hence, only nuclear exergy is available before fission. The total binding potential energy of one nucleus of uranium $^{235}_{92}U$ can be assumed equal to about $1785.5\ MeV$ [20] and constitutes the theoretical available potential energy $E^{NUCLEUS}_{BINDING}$ that the nucleus can release in the form of repulsion potential energy among all nucleons [14-16].

After the fission, fragments with lower atomic numbers and atomic mass are generated. The initial nucleus binding potential energy of the starting whole nucleus is transformed into two contributions: i) fragments binding potential energy, and ii) repulsion potential energy transformed into fragments kinetic energy expressed as $Qvalue$ representing the useful energy released along with the fission reaction. Hence, thermal energy only is available that can be converted into mechanical energy and transferred as work interaction to the external system along a heat-to-work conversion direct cycle with efficiency η^T. This implies that, in turn, thermal exergy only is available after fission [16-18].

The overall exergy balance, based on the definition of exergy property components before and after fission, is the following:

$$\Delta EX^G_{\substack{NUCLEAR \\ FISSION}} = - \left[\left(0 + 0 + \right. \right.$$

$$M^{\substack{NUCLEUS \\ BINDING \\ ENERGY}} \eta^N \right)^{\substack{BEFORE \\ FISSION}} \right] = - \left[- \left(0 + \right. \right.$$

$$Q^{\substack{FRAGMENTS \\ KINETIC \\ ENERGY}} \eta^T + 0 \right)^{\substack{AFTER \\ FISSION}} \right] \qquad (11)$$

In the case of nucleus fission, η^T and η^N are the efficiencies of ideal direct conversion cycles operating between the reservoir and the thermodynamic system conditions corresponding to kinetic energy and the potential energy of fission fragments. Interactions in the above equation can be expressed in terms of energy transfer associated with interacting particles before and after fission:

$$\Delta EX^G_{\substack{NUCLEAR \\ FISSION}} = - \left[\left(0 + 0 - \right. \right.$$

$$E^{\substack{NUCLEUS \\ BINDING}} \eta^N \right)^{\substack{BEFORE \\ FISSION}} \right] = - \left[- \left(0 - \right. \right.$$

$$E^{\substack{FRAGMENTS \\ KINETIC}} \eta^T + 0 \right)^{\substack{AFTER \\ FISSION}} \right] \qquad (12)$$

The $Qvalue$ of nuclear fission is about $210 \, MeV$, and it is calculated by measuring the mass defect of nuclei before and after fission [20]. The $Qvalue$ is partitioned in the following contributions (in V): kinetic energy of fission fragments = 170; prompt neutron = 10; prompt $\gamma = 10$. Moreover,

as concerns the decay of fission fragments: kinetic energy of delayed neutrons = negligible; energy associated to $\beta^- = 5$; energy associated to delayed $\gamma = 5$; energy associated with neutrinos $\bar{\nu} = 10$ taking into account that neutrinos (generated by β^- decay) are not recovered, and their energy is irreversibly lost. In addition to the mass defect, equal to the amount of thermal energy release and the associated thermal entropy contribution, nuclear fissions also determine a subdivision of the initial nucleus mass into fragments, implying thermal entropy production due to inherently stochastic processes distribution of fragments velocities. Considering that the mechanical exergy is null before and after fission, then the calculation of generalized thermodynamic entropy for nuclear fission results from the following expression:

$$\Delta S^G_{FISSION} = (S_1 - S_0)^T + (S_1 - S_0)^N = \frac{1}{T_R} [(E_1 - E_0) - (EX^R_1 - EX^R_0)]^T + \frac{1}{\mu^N_R} [(E_1 - E_0) - (EX^R_1 - EX^R_0)]^N \qquad (13)$$

As the reservoir is an auxiliary external reference system, its thermodynamic state can be arbitrarily selected to simplify the calculation. It can be assumed that reservoir conditions are those existing before the fission occurs. Then, the temperature and nuclear potential of the reservoir are: $T_R = 298 \, K$ corresponding to the initial environmental temperature of target nucleus and neutron before fission;

$$\mu^N_R = \mu^N_1 = - \frac{E^{\substack{NUCLEUS \\ BINDING \\ FRAGMENTS}}}{n_1} = 1785/4.43 \cong 403 MeV \qquad (14)$$

is the potential nuclear corresponding to the ratio of binding potential energy over the number n_1 of fragments after fission, with a minus sign. Once the fission has occurred, then for the selected thermodynamic state of the reservoir, the calculation of entropy change can be separated for the thermal and nuclear processes [19-21]. As concerns the thermal entropy variation related to the reference temperature:

$$(S_1 - S_0)^T = \frac{1}{T_R}[(E_1 - E_0) - (EX_1^R - EX_0^R)]^T = \frac{1}{298}\left[210 - \left(200 \cdot \left(1 - \frac{T_R}{T_1}\right) - 0\right)\right]^T \tag{15}$$

It should be noticed that the whole amount of $Qvalue$, released as thermal energy along with the nucleus fission, can be assumed as subdivided among two fission fragments and 2,43 neutrons as a mean value, that is 4,43 particles generated from 2 initial interacting particles, namely neutron, and target nucleus. Therefore, under the equipartition theorem of energy among all fission fragments, each particle has associated an amount of kinetic energy equal to $\frac{210}{4.43} \cong 47.4\ MeV$ constituting the thermal potential to be accounted for:

$$(S_1 - S_0)^T = \frac{1}{298}\left[210 - \left(200 \cdot \left(1 - \frac{0.025 \cdot 10^{-6}}{47.4}\right) - 0\right)\right]^T \cong 0.0336 MeV/K \tag{16}$$

where the heat-to-work conversion efficiency has been assumed as $\eta^T \cong 1$ is the final fission temperature far higher than the initial reference temperature; hence, the energy released during fission can be considered equal to the thermal

exergy content. The increase of thermal entropy is due to the kinetic energy associated with lost neutrinos [22-24].

As concerns the nuclear entropy variation related to the reference nuclear potential:

$$(S_1 - S_0)^N = \frac{1}{\mu_R^N}\left[\left(E_1^{\substack{FRAGMENTS \\ BINDING}} - E_0^{\substack{NUCLEUS \\ BINDING}}\right)\right]^N + \frac{1}{\mu_R^N}\left[\left(E_1^{\substack{FRAGMENTS \\ BINDING}}\left(1 - \frac{\mu_R^N}{\mu_1^N}\right)\right)\right]^N + \frac{1}{\mu_R^N}\left[\left(E_0^{\substack{NUCLEUS \\ BINDING}}\left(1 - \frac{\mu_R^N}{\mu_0^N}\right)\right)\right]^N \tag{17}$$

where binding energies before fission and after fission are those calculated employing the mass defect as reported in the literature [18]; nuclear potentials account for the number of particles, hence $\mu_0^N = 1985 MeV$ and $\mu_1^N = \mu_R^N = 403 MeV$ as assumed, thus:

$$(S_1 - S_0)^N = \frac{1}{403}\left[(1785 - 1985) - \left(0 - 1985 \cdot \left(1 - \frac{403}{1985}\right)\right)\right]^N \cong 3.4 MeV/K \tag{18}$$

The positive increase in thermal and nuclear components of entropy variation above calculated confirms that a fission reaction determines an increase of fragments velocities associated with the velocity distribution and position dispersion caused by the increase of the number of particles generated from a unique nucleus.

Finally, the variation of the generalized thermodynamic entropy resulting from the sum of its components is:

$$\Delta S^G_{FISSION} = (S_1 - S_0)^T + (S_1 - S_0)^N \cong$$
$$0.0336 MeV / K + 3.4 MeV / K \cong$$
$$3.4336 MeV / K \tag{19}$$

The amount of $Qvalue$ is available as thermal energy and transferred to the cooling medium assumed at $573K$ (typical average temperature of the coolant in a Light Water Reactor) employing heat interaction. In terms of thermal exergy, this implies that the maximum net useful work is derived considering the amount of heat interaction converted into work interaction by a reversible process between the fragments temperature and the medium cooling temperature. However, the temperature corresponding to $E^{FRAGMENTS}_{KINETIC}$ is much higher; therefore, the thermal exergy between fission and medium cooling temperatures is irreversibly lost. The $Qvalue$ is the amount of inter-fragments repulsion potential energy $E^{REPULSION}_{POTENTIAL}$ transformed into inter-fragments kinetic energy $E^{FRAGMENTS}_{KINETIC}$ resulting from the nucleus fission, which the cooling medium can finally withdraw from the temperature of fuel rods. However, an additional amount is recovered from structures and the coolant itself. Hence, the difference between the initial binding energy of the nucleus and the $Qvalue$ of the fission process represents the amount of available energy irreversibly dissipated, corresponding to the exergy destruction, along the process starting from a unique system and ending to a set of fragments [25-27]. The generalized exergy balance is:

$$\Delta EX^G_{NUCLEAR\,FISSION} =$$
$$-\left[\left(-E^{NUCLEUS}_{BINDING}\eta^N\right)^{BEFORE}_{FISSION}\right] =$$
$$-\left[-\left(E^{FRAGMENTS}_{KINETIC}\eta^T +\right.\right.$$
$$\left.\left. E^{FRAGMENTS}_{BINDING}\eta^N\right)^{AFTER}_{FISSION}\right] \tag{20}$$

As the difference of thermodynamic potentials between nuclear fuel and external environment (reservoir) is high, then $\eta^N \cong 1$ can be assumed, therefore:

$$\Delta EX^G_{NUCLEAR\,FISSION} = -\left[(-1785) - \left(200 \cdot \left(1 - \frac{298}{573}\right) - 1985\right)\right] = -[-1785 - 200 \cdot 0.48 + 1985] = -104 MeV \tag{21}$$

The above amount of generalized exergy decrease $\Delta EX^G_{NUCLEAR\,FISSION} = -104 MeV$ expresses the available mechanical exergy EX^M irreversible destruction along the fission process of a single neutron and target nucleus. The reason for irreversibility implying exergy destruction is that a fraction of the initial binding energy of the whole nucleus is irreversibly dissipated because of: i) the subdivision of the nucleus into three or more fragments determining a change from high-density energy to low-density energy, and ii) the lower temperature, assumed at $573\,K$, of $Qvalue$ heat-to-work conversion concerning the fission temperature that makes the available energy, immediately after the fission, as a quasi-exergy. Finally, considering the definition of exergy efficiency $\eta^{EX} = 1 - EX_{DESTR} / EX_{INPUT}$,

the equation relating to an elemental fission reaction of $^{235}_{92}U$ is:

$$\eta^{EX}_{FISSION} = 1 -$$
$$\Delta EX^{\substack{NUCLEAR \\ FISSION \\ DESTR}} \Big/ \Delta EX^{\substack{NUCLEUS \\ BINDING \\ AVAILABLE}} = 1 -$$
$$(200 - 104)/200 = 0.52 \qquad (22)$$

The enhancement of fission nuclear plants' overall efficiency can be achieved through optimized plant configurations such as cogeneration to produce process heating and the generation of electric power [28].

Fusion Nuclear Reaction Exergy Analysis

A typical fusion nuclear reaction occurs through the following process [2-31]:

$$^2_1H + ^3_1H \rightarrow ^4_2He(3.5MeV) + ^1_0n(14.1MeV) \qquad (23)$$
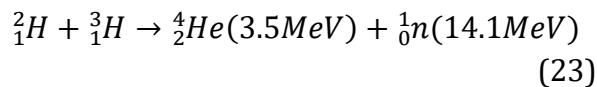
where ^2_1H ^3_1H are isotopes of hydrogen, Deuterium (D), and Tritium (T), respectively. Thermodynamic conditions to allow this reaction to be generated inside the plasma chamber where electromagnetic fields are suitable for confining charged particles. Unlike fission, the fusion process is generated by colliding nuclei with initial kinetic energy far much higher than the inter-nuclei kinetic energy corresponding to the environment temperature; those nuclei move along the same direction and opposite way to ensure that the collision occurs. This additional nuclei's kinetic energy is needed to overcome the electromagnetic repulsion potential before short-radius strong

nucleon interactions prevail. After the fusion, the system results to be more stable with a higher binding potential energy implying a release of energy consisting of the $Qvalue = 17.594 MeV$ representing the net useful energy transferred to the external system. The $Qvalue$ corresponds to the thermal energy used by the heat transfer system conveying this thermal interaction to be converted into work interaction, released to be utilized by the useful external system. Fusion results from colliding ^2_1H and ^3_1H nuclei and the subsequent transmutation into ^4_2He with the higher atomic number and by-production of one neutron [31-33]. An increase of reaction products' kinetic energy, due to the fusion process and corresponding to the $alue$, occurs. The amount of $Qvalue$ is calculated with the mass defect of nuclei before and after fusion [33-35]. Unlike fission, nuclear fusion creates an aggregation of the initial nuclei masses into one unique nucleus, implying thermal entropy decrease due to the annihilation of the stochastic distribution of initial nuclei velocities [34-36].

The exergy balance of a nuclear fusion can be stated as follows:

$$\Delta EX^G_{\substack{NUCLEAR \\ FISSION}} = \Delta EX^M + \Delta EX^T + \Delta EX^N =$$
$$- \left[(EX^M + EX^T + EX^N)^{\substack{BEFORE \\ FUSION}} \right] -$$
$$\left[-(EX^M + EX^T + EX^N)^{\substack{AFTER \\ FUSION}} \right] \qquad (24)$$

Before the collision occurs, Deuterium and Tritium nuclei increase velocity along the same direction and opposite ways needed to provide the thermodynamic conditions

for nuclei fusion. To do so, an amount of work interaction input is used to increase the kinetic energy $E_{KINETIC}^{NUCLEI}$ of nuclei up to a range of $116 \cdot 10^6 K$ to $1160 \cdot 10^6 K$ corresponding to a range of $10\ keV$ to $100\ keV$. This work interaction is associated with the mechanical $EX^M = Q_{ENERGY}^{\substack{NUCLEI \\ KINETIC}}$ calculated in terms of maximum net useful heat output resulting in thermal energy transfer associated with colliding nuclei temperature. Instead, the work interaction associated with the mechanical exergy $EX^M = M^{\substack{NUCLEI \\ POTENTIAL \\ ENERGY}}$ calculated in terms of maximum net useful mass is negligible because both strong and electromagnetic interactions are negligible at a distance between particles before the collision. The thermal exergy $EX^T = W^{\substack{NUCLEI \\ KINETIC \\ ENERGY}}$ relating to the temperature of nuclei equal to the environment temperature before entering the confined plasma can be considered null. The nuclear exergy $EX^N = W^{\substack{NUCLEI \\ POTENTIAL \\ ENERGY}}$ of Deuterium and Tritium is null as the binding potential energy $E_{BINDING}^{NUCLEI}$ of individual interacting nuclei is equal to the sum of $_1^2H = 2.224 MeV$ and $_1^3H = 8.482 MeV$ thus, it couldn't be converted into maximum net useful work being in a more stable configuration concerning isolated protons and neutrons as reported in Figure 1.

After the collision has occurred, products velocity is distributed over random directions so that it is characterized by product kinetic energy $E^{\substack{PRODUCTS \\ KINETIC}}$

determining the thermal energy being transferred as heat interaction output $Q^{\substack{PRODUCTS \\ KINETIC \\ ENERGY}}$ to the external system through the first wall, the breading blanket and diverters constitute the main components of the primary heat transfer system from the plasma chamber of a fusion reactor. The binding potential energy $E^{\substack{PRODUCTS \\ BINDING}}$ of $_2^4He$ formed after the collision is equal to $28.3\ MeV$ representing the mass interaction output $M^{\substack{PRODUCTS \\ POTENTIAL \\ ENERGY}}$ The mechanical exergy EX^M after the fusion process is null since the whole energy content is released in the form of thermal energy, based on these contributions, the exergy balance is the following:

$$
\Delta EX_{\substack{NUCLEAR \\ FUSION}}^{G} = -\left[\left(Q^{\substack{NUCLEI \\ KINETIC \\ ENERGY}} + W^{\substack{NUCLEI \\ KINETIC \\ ENERGY}} + W^{\substack{NUCLEI \\ POTENTIAL \\ ENERGY}}\right)^{\substack{BEFORE \\ FUSION}}\right] - \left[-\left(0 + Q^{\substack{PRODUCTS \\ KINETIC \\ ENERGY}}\eta^T + M^{\substack{PRODUCTS \\ KINETIC \\ ENERGY}}\eta^N\right)^{\substack{BEFORE \\ FUSION}}\right]
$$

$$(25)$$

that can be expressed as:

$$
\Delta EX_{\substack{NUCLEAR \\ FUSION}}^{G} = -\left[\left(E_{KINETIC}^{NUCLEI}\eta^T + 0 + E_{POTENTIAL}^{NUCLEI}\eta^N\right)^{\substack{BEFORE \\ FUSION}}\right] - \left[-\left(0 + E^{\substack{PRODUCTS \\ KINETIC}}\eta^T + E_{POTENTIAL}^{PRODUCTS}\eta^N\right)^{\substack{AFTER \\ FUSION}}\right] \quad (26)
$$

It is noteworthy that, before fusion, the attraction potential energy between Deuterium and Tritium due to strong interactions $E_{POTENTIAL}^{NUCLEI}$ is negligible. Instead, after fusion, the importance of attraction strong interactions potential energy becomes prevailing and provides an additional contribution to the product's kinetic energy that is to be accounted for in the $Qvalue$. In terms of exergy balance, the attraction potential energy could not be transferred as useful work, thus implying that it does not contribute to the exergy balance, so the difference between before and after only contributes [37-39].

The calculation of generalized thermodynamic entropy for nuclear fusion thus results in the following expression:

$$\Delta S_{FUSION}^{G} = (S_1 - S_0)^T + (S_1 - S_0)^N = \frac{1}{T_R}[(E_1 - E_0) - (EX_1^R - EX_0^R)]^T + \frac{1}{\mu_R^N}[(E_1 - E_0) - (EX_1^R - EX_0^R)]^N \qquad (27)$$

As concerns the thermal entropy variation related to the temperature, assuming, also, in this case, that T_R corresponds to the initial environmental temperature of target nucleus and neutron before fusion, then:

$$(S_1 - S_0)^T = \frac{1}{T_R}[(E_1 - E_0) - (EX_1^R - EX_0^R)]^T \qquad (28)$$

In the special case of the fusion reaction, T_R can be assumed equal to the temperature of ^2_1H and ^3_1H before nuclei collision, that is:

$T_R = 10\ keV = 0.01 MeV = 116 \cdot 10^6 K$, so that:

$$(S_1 - S_0)^T = \frac{1}{116 \cdot 10^6}\left[17.594 - \left(17.594 \cdot \right.\right.$$

$$\left.\left.\left(1 - \frac{T_R}{T_1}\right) + 0.01 \cdot \left(1 - \frac{T_R}{T_0}\right)\right)\right] \qquad (29)$$

that, using the numerical values becomes:

$$= \frac{1}{116 \cdot 10^6}\left[17.594 - \left(17.594 \cdot \left(1 - \right.\right.\right.$$

$$\left.\left.\left.\frac{0.01}{17.594}\right) + 0.01 \cdot \left(1 - \frac{0.01}{0.01}\right)\right)\right] \cong$$

$$\frac{1}{116 \cdot 10^6}(-17.594 - 17.594 \cdot 0.9994) \cong 9.1 \cdot$$

$$10^{-5} \cdot 10^{-6} MeV/K \qquad (30)$$

This result demonstrates that the variation of thermal entropy along a nuclear fusion is negligible under the high temperature of products before and after the collision and nuclei aggregation has occurred. The even negligible increase of thermal entropy reveals that the available energy, or the $alue$, is released under the subdivided thermal form of energy associated with the thermal entropy positive variation. It is noteworthy that this variation is substantially lower concerning the case of nuclear fission. Indeed, the rationale behind this difference is twofold: i) fission implies the increase of particles as fragments of the initial target nucleus while fusion does not since it creates two products, Helium, and neutron, from two reactants, Deuterium and Tritium; ii) the Helium nucleus has an atomic number, and therefore a mass number, higher than Deuterium or Tritium hence implying a higher mass concentration in one nucleus thus determining a decrease of thermal entropy associated to an increase of kinetic energy density.

As far as the nuclear entropy variation related to the nuclear potential is concerned, the following expression applies:

$$(S_1 - S_0)^N = \frac{1}{\mu_R^N}[(E_1 - E_0) - (EX_1^R - EX_0^R)]^T \tag{31}$$

where μ_R^N can be assumed equal to the nuclear potential of ^2_1H and ^3_1H before nuclei collision, that is $\mu_R^N = 2.224 MeV + 8.482 MeV = 10.706 MeV$, then the previous expression is as follows:

$$(S_1 - S_0)^N = \frac{1}{\mu_R^N}\{(E_1 - E_0)\} +$$
$$\frac{1}{\mu_R^N}\left\{-\left[(\mu_1^N n_1^N) \cdot \left(1 - \frac{\mu_1^N}{\mu_1^N}\right) - (\mu_0^N n_0^N) \cdot \left(1 - \frac{\mu_1^N}{\mu_0^N}\right)\right]\right\} \tag{32}$$

that, using the numerical values, becomes:

$$= \frac{1}{10.706}\left[(10.706 - 28.3) - \left(10.706 \cdot \left(1 - \frac{10.706}{10.706}\right) - 28.3 \cdot \left(1 - \frac{10.706}{28.3}\right)\right)\right] =$$
$$\frac{1}{10.706}[(-17.594) - (-17.594)] = 0 MeV/K \tag{33}$$

In this case, the variation of nuclear entropy is null since there is no variation of the number of particles between the initial and final states of the reaction: thus, from a physical standpoint, there is no change in the degree of subdivision of the binding energy content before and after releasing the $Qvalue$. Moreover, it has been assumed that, for two interacting particles, the nuclear potential μ_R^N equals the system's potential energy; hence, the whole potential energy is transferred as work interaction to the useful external system.

Instead, from three interacting particles on, the nuclear potential would progressively decrease as the progressive increase of the number of particles is accounted for. Hence, the variation of nuclear entropy becomes positive because of the not complete transfer of nuclear potential into work interaction regarding Second Law.

The number of particles before and after the reaction is conserved. Although mass aggregation is not, the variation of entropy depends on both distribution of mass and velocity caused by the collision and the consequent fusion process.

The variation of exergy property, calculated before and after ^2_1H and ^3_1H nuclei collision can be assumed as the maximum net useful interaction expressing the definition of generalized exergy. Therefore:

$$-\Delta EX_{NUCLEAR}^G{}_{FUSION} = (0.1\eta^T + 0 + 2.224\eta^N + 8.482\eta^N)_{FUSION}^{BEFORE} - (0 - 17.594\eta^T + 28.3\eta^N)_{FUSION}^{AFTER} - \Delta EX_{NUCLEAR}^G{}_{FUSION} =$$
$$6.274\ MeV \tag{34}$$

where it is assumed that η^N from plasma chamber, fusion temperature to blanket temperature assumed $823\ K$ and $\eta^T = \left(1 - \frac{298}{823}\right) = 0.638$ from blanket to environment temperature at $298\ K$, then a decrease of exergy occurs in fusion process equal to $\Delta EX_{NUCLEAR}^G{}_{FUSION} \cong -6.274\ MeV$.

The physical meaning of this result is that almost the entire amount of energy

released along a nuclear fusion process constitutes the available energy, in terms of generalized exergy, deriving from the decrease of mass after the increase of inter-nucleon potential energy the isolated nucleons before fusion. The decrease of exergy is accompanied by a decrease of entropy due to a different configuration of the whole system in which an increase of level in the hierarchical structure is due to the mass fusion $^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + n$. Indeed, free hydrogen isotopes result in a bind system of higher mass. To do so, a fraction of initial nuclei kinetic energy $E^{NUCLEI}_{KINETIC}$ is adsorbed during the fusion reaction. Then, the fusion process is irreversible due to the destruction of a part of the initial exergy content that does not completely compensate for the entropy reduction due to the fusion of D and T nuclei [38-40].

Finally, the exergy efficiency is:

$$\eta^{EX}_{FUSION} = 1 -$$
$$\Delta EX^{NUCLEAR}_{DESTR}{}^{FUSION} / \Delta EX^{NUCLEI}_{AVAILABLE}{}^{BINDING} = 1 -$$
$$(17.594 - 11.22)/17.594 = 0.638 \qquad (35)$$

This is a theoretical result that is to be reduced considering the real processes occurring in the plasma chamber of a fusion reactor [41].

Conclusion

Two main conclusions can be outlined from the present research. Firstly, the model of few-particle thermodynamic systems is adopted to determine all phenomena and properties involved in nuclear fission and fusion processes. This investigation has been carried out in the Second Law analysis based on the exergy method adopted to calculate entropy property variations. The second result concerns the decrease or increase of nuclei atomic number and mass number after elemental fission and fusion nuclear reactions and, therefore, the subdivision or aggregation of atomic nuclei. The role of entropy property, in these special cases, is to quantify the impact on energy and exergy balances, along with nuclear fission or fusion processes, responsible for the different behavior of a few-particle system. A conclusive consideration from the results mentioned above is that nuclear physics and the physics of elementary particles undergo non-equilibrium processes. In this regard, irreversibilities determined by non-equilibrium states and processes are governed by extrema principles, rooted in entropy property variations, such as the maximum entropy production principle, representing an innovative contribution to analysis methods and research those fields.

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