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Exergy Analysis of a PWR Nuclear Steam Supply System – Part I, General theoretical model

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Abstract

The paper provides an alternative, novel methodology to perform the exergetic analysis of a Pressurized Nuclear Reactor (PWR) based on the strictest definition of fission temperature to get to a careful evaluation of Exergy Destruction and exergetic Efficiency of the component.

Up today, the exegetic analyses of Nuclear Power Plants (NPP) have been based on the assumption that Fission Exergy and Fission Energy are almost the same having assumed Carnot Factor almost equal to 1 as T_{fiss} >>T_0. This assumption is based on some simplified hypotheses concerning fission temperature as applied in the definition of the Fission Exergy itself, whose value, to the best knowledge of the authors, was never modeled.

On the contrary, in the first part of the paper, the authors present the results of an ongoing research, just aimed at evaluating the Exergy efficiency of the heat exchange in a PWR reactor, whose first results were already presented in [1], based on the most detailed modeling of T_{fiss}. The modeling, referring to a steady-state operational mode of the Reactor, takes into account all heat transfer phenomena between nuclear fuel UO_2, its Zircaloy clad, cooling water, vessel material and the external environment.

In the second part of the paper, the Exergy analysis is extended to all main Reactor Cooling System components (Vertical recirculating type Steam Generator, primary coolant pump and piping) with the aim to compare the Exergy Destructions and exergetic Efficiencies of the RPV with those of the other components of the Nuclear Steam Supply System, NSSS.

In the Part II of the same paper, a test case is exemplified with the aim to compare the results obtained applying the methodology in question with those obtained applying the most established methodology adopted by other authors.

Keywords: Exergy analysis; Energy conversion; Thermodynamic simulations; Pressurized Water Reactor; Fission energy.

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1. Introduction

During the 19th century physicists and engineers, among the first ones Sadi Carnot (1824), studied the phenomena related to the various forms of heat transfer up to the formulation of the two Principles of Thermodynamics. The First Law concerns the conservation of Energy in an isolated system, and was first enunciated in the works of Mayer (1842) and Joule (1845). Subsequently, in the second half of the century, thanks to Clausius' (1850,1865) and Lord Kelvin's (1851) fundamental work, the Second Law of Thermodynamics was stated, establishing the impossibility to totally convert a certain amount of thermal energy into work. These two great achievements were the point of reference for the industrial processes under development during those years (i.e., thermal machineries to produce electricity).

At the end of the 19th century, a new contribution to the full development of Thermodynamics came from Gouy and Stodola with the enunciation of the theorem on “lost work in a real transformation” (such as irreversible lost work in engines). In the 20th century, after the formalization of the axiomatic Thermodynamics by Caratheodory (1909), physicists, such as Max Born (1921), continued their research in the field of real energy transformations highlighting the importance of computing the irreversibilities that occur in each all energy transformations. Among these researchers Keenan (1932), Bosniakovic (1938), Rant (1956) which first proposed the term "Exergy", up to the latest studies of Gaggioli (1980), Kotas (1980), Tsatsaronis (1985), Valero (1986), Moran (1994) and Sciubba (1994).

Up to day, the use of exergetic analysis has established itself as the only way to measure the efficiency of a thermal system doing work. In particular, the use of Exergy analysis, based on the simultaneous combination of conditions imposed by the First and Second Law of Thermodynamics, is a fundamental methodology for a new design paradigm for complex plants with the ultimate goal of achieving the optimal use of the primary energy resources. Nuclear Power Plants (NPPs) can be considered the most complex examples of a thermal power plant.

In a Nuclear Power plant heat exchanges between the nuclear fuel and the cooling fluid in the reactor core appear to be the main cause of Exergy destruction; this statement emerges in a certain number of studies and technical evaluations, developed in the last fifty years, on prototype or working NPPs. In these works the 2nd Law analyses were performed with the aim to compare the nuclear reactor irreversibilities, or more often the whole “nuclear isle” (named Nuclear Steam Supply System, NSSS) irreversibilities, with those of the conventional secondary systems (named Balance of Plant, BOP). For instance, in the middle Eighties a First and Second Law analysis was performed on the Canadian Pickering NPP (equipped with CANDU reactors) [2], and ten years later an energy and Exergy analysis was performed for the La Salle BWR NPP [3]. At the end of Nineties, another Exergy analysis was performed for the Indian Point 1 PWR NPP, in which the performances of the NPP as such were compared with the performance of the NPP equipped with an external steam superheater fossil fuel fueled [4]. Over the last 10 years, some other Exergy and thermo-economic analyses were performed also applied to Generation IV reactors [5, 6, 7, 8, 9]. In all the aforementioned works for the nuclear reactor component, always simulated as a “black box”, “the maximum work is approximately equal to the Fission thermal power, in other words all Fission thermal power may be considered to be available as work” [5]. This assumption is based on some simplified hypotheses concerning fission temperature as applied in the definition of the Fission Exergy itself in particular, referring to equation 9a, Fission Exergy and Fission thermal power are almost the same being the Carnot Factor almost equal to 1 as $T_{fiss} >> T_0$.

On the contrary, in this paper the authors present the results of an ongoing research primarily aimed at evaluating the exergetic efficiency of the heat exchange in a PWR reactor (first results presented in [1]) on the base of the strictest definition of fission temperature applied in equation 9b to get to a careful evaluation of Exergy Destructions and exergetic Efficiencies of the component.

In the second part of the paper the Exergy analysis is extended to all main RCS components (Vertical recirculating type Steam Generators, primary coolant pumps and piping) with the aim of comparing their Exergy Destructions and exergetic Efficiencies with those of the Nuclear Reactor as a component.

Nomenclature

c_p	isobaric specific heat, J kg^{-1} K^{-1}	E_f	fission Energy, J
ex	specific Exergy, kJ kg^{-1}	ex_i	specific flow Exergy, kJ kg^{-1}
$\dot{E}x$	total Exergy, MW	$\dot{E}x_\delta$	total Exergy destruction, MW
F_P^A	axial peak factor	h	specific enthalpy, kJ kg^{-1}
h_{wall}	convection coefficient, W m^{-2} K^{-1}	H_a	fuel rod active length, cm
H_e	fuel rod extrapolated length, cm	K	thermal conductivity, W m^{-1} K^{-1}
$\dot{L}$	Work flow, kW	$\dot{m}$	mass flow rate, kg s^{-1}
$\dot{m}_{BOP}$	Balance of Plant (SG secondary side) mass flow rate, kg s^{-1}	$\dot{m}_{RCS}$	Reactor Coolant System mass flow rate, kg s^{-1}
$\dot{m}_{SC}$	sub-channel coolant mass flow rate, kg s^{-1}	M	molecular weight, g mole^{-1}
N_A	Avogadro's number	$N_{fr,i}$	Number of fuel rods with "i" enrichment level
p	pressure, bar [Pa]	P_{el}	Reactor Coolant Pump electric power, MW
q'	linear power density, Wcm^{-1}	$\bar{q}'$	average linear power density, Wcm^{-1}
$\bar{q}'''$	average volumetric power density, Wcm^{-3}	$\dot{Q}$	heat transfer rate, kW$_{th}$
r	generic radius, cm	R_{ext}	External radius, cm
RF	Robertson Factor	R_g	gap (Helium) radius, cm
R_p	fuel pellet (uranium dioxide) radius, cm	s	specific entropy, kJ kg^{-1}K^{-1}
S_g	fuel rod gap thickness, m	$\dot{S}$	total entropy, kW K^{-1}
S_c	clad thickness, mm	$\dot{S}_{gen}$	total entropy generation, kW K^{-1}
T	temperature, K	Tb	bulk(coolant) temperature, K
Tc	central fuel rod temperature, K	$T_{ext,SG}$	external SG surface temperature, K
T_{He}	gap (Helium) temperature, K	T_{ig}	internal cladding temperature, K
T_{fiss}	fission temperature, K	T_S	surface pellet temperature, K
T_{vessel}	average vessel temperature, K	T_w	wall (cladding) temperature, K
V	volume, cm^3	w	velocity, m s^{-1}
X_i	generic fuel enrichment level (percentage)	z	height, cm
	Subscript		
0	reference state of environment	b	bulk/coolant (water)
c	central axis of fuel rod	F	Fuel
fiss	Fission	gen	Generated
ge	cladding external side (zircaloy)	gi	cladding internal side (zircaloy)
in	Inlet	H/CLV	Hot/Cold dummy valve
Loss	transferred to the environment	MAX	Maximum
out	Outlet	P	Product
RCP	Reactor Coolant Pump	RPV	Reactor Pressure Vessel
S	pellet surface	SG	Steam Generator
UO_2	Uranium oxide	w	wall (cladding surface)
	Greek Symbols		
δ	adjunctive lenght, cm	η_{Ex}	exergetic efficiency (2nd law efficiency)
$\bar{\Phi}_n$	average neutronic flux, neutrons cm^{-2} s^{-1}	ρ_{UO2}	fuel (uranium dioxide) density, g cm^{-3}
σ_f	microscopic fission cross section (UO_2), barn (cm^2)	σ_{tot}	total microscopic cross section (H_2O), barn (cm^2)
Σ_{tr}	macroscopic transport cross section (H2O), cm^{-1}		

2. Modeling and methods

2.1 General theoretical model of Exergy Analysis

The exergetic analysis of a complex system, operating in a steady-state condition in an open system, is based on the following equations:

Mass balance:

$$\Sigma_{in}\dot{m} = \Sigma_{out}\dot{m} \tag{1}$$

Energy balance:

$$\Sigma_{in}\dot{m}\left(h + gz + {w^2}/{2}\right) + \dot{Q} = \dot{L} + \Sigma_{out}\dot{m}\left(h + gz + {w^2}/{2}\right) \tag{2}$$

Entropy accounting:

$$\Sigma_{in}\left({\dot{Q}}/{T}\right) + \Sigma_{in}\dot{m}s + \dot{S}_{gen} = \Sigma_{out}\left({\dot{Q}}/{T}\right) + \Sigma_{out}\dot{m}s \tag{3}$$

Exergy accounting:

$$\Sigma_{in}\dot{m}ex + \Sigma\dot{E}x_q - \dot{E}x_\delta = \dot{L} + \Sigma_{out}\dot{m}ex \tag{4}$$

Referring to a generic Physical Productive Structure of a complex system [10], as described in Fig.1, Exergy Accounting and Exergetic Efficiency can be expressed as shown in equations (5) and (6).

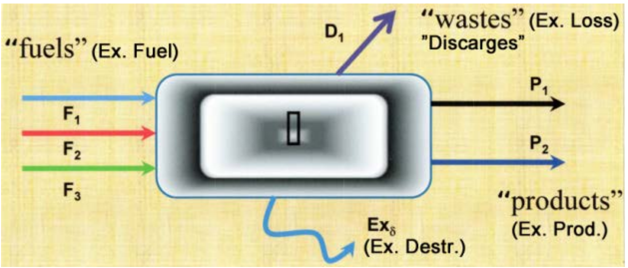

Figure 1. General Physical Productive Structure, P.P.S. [11]

$$\dot{E}x_{Fuel} = \dot{E}x_{Product} + \dot{E}x_{Loss} + \dot{E}x_\delta \tag{5}$$

$$\eta_{Ex} = \frac{\sum \dot{E}x_{Pj}}{\sum \dot{E}x_{Fj}} = 1 - \frac{\sum \dot{E}x_{Lj} + \dot{E}x_\delta}{\sum \dot{E}x_{Fj}} \tag{6}$$

2.2 Pressurized Water Reactor Exergy Analysis

Referring to steady-state operational mode, a Pressurized Water Reactor physical productive structure, P.P.S., and its main exergetic flow rates are shown in Figure 2.

In accordance with the definition depicted in Figure 2, and considering the equations (5) and (6), to assess the reactor Exergy Destruction and exergetic Efficiency the following equations must be considered:

$$\dot{E}x_{\delta,RPV} = \dot{E}x_{Qfiss} + \dot{E}x_1 - \dot{E}x_2 - \dot{E}x_{Loss,RPV} \tag{7}$$

$$\eta_{Ex,RPV} = 1 - \frac{\dot{E}x_{Loss,RPV} + \dot{E}x_{\delta,RPV}}{\dot{E}x_{Qfiss}} = 1 - \frac{Q_{Loss,RPV}(1 - {T_0}/{T_{Vessel}}) + \dot{E}x_{\delta,RPV}}{\dot{E}x_9} \tag{8}$$

and

$$\dot{E}x_{Qfiss} = \dot{Q}_{fiss}\left(1 - {T_0}/{T_{fiss}}\right) \tag{9a}$$

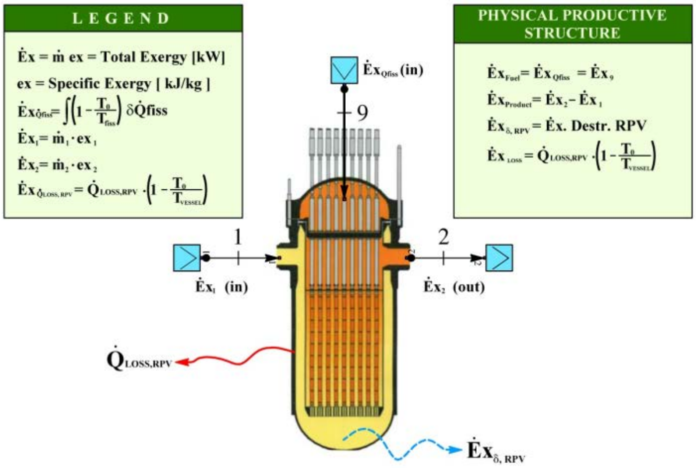

Figure 2. Pressurized Light Water Reactor P.P.S.

Because the fission temperature do not have a fixed value along the active length of the fuel rods, to calculate the thermal fission power Exergy, the equation 9a must be applied in the integral form [12]:

$$\dot{E}x_{Qfiss} = \int \left(1 - \frac{To}{T_{fiss}}\right) \delta \dot{Q}_{fiss} \tag{9b}$$

- $\dot{Q}_{fiss}$ being the thermal power amount generated by fission, assessed with the following equation [13]:

$$\dot{Q}_{fiss} = \overline{q}'''(X) V_{UO2} = E_f \, \sigma_f \, \overline{\Phi}_n \, \rho_{UO2} \, \frac{N_A}{M_{UO2}(X)} X \, V_{UO2} \quad [MW] \tag{10}$$

- T_{fiss} being the fission temperature at which heat is supposed to be generated from the center of each fuel rod to its pellet surface. Whatever fuel assembly enrichment is, it is possible to assess a temperature profile along fuel rod axes that presents an axially symmetric shape similarly, to linear power density q' as shown in Figure 3.

For each fuel rod, depending on the specific enrichment level, to obtain the T_{fiss} profile it is possible to adopt an inverse procedure, analogous to that utilized in [1]. Water coolant profile along the fuel rod must be assessed first, then, knowing the water heat exchange coefficient, Zircaloy thermal conductivity, helium heat exchange coefficient, heat radiation in the clad gap and, lastly, fuel thermal conductivity, it is possible to go back to fuel rod center temperature profile.

To obtain water coolant profile along a single fuel rod, $T_b(z)$, the following equations can be solved integrating it over total active core height, H_e [13]:

$$\dot{m}_{sc} c_p dT = q'(z) dz \tag{11}$$

$$q'(z) = q'_{MAX} \cos(\pi z / H_e) \tag{12}$$

being $q'_{max}(X) = F_P^A \, \overline{q}'(X)$.

Knowing cooling water profile, it is possible to go back to the fuel rod central temperature profile, Tc(z), applying Fourier equation (in cylindrical geometry), taking also into account the appropriate heat exchange coefficients between the cooling water and the fuel through the following steps:

- heat convection between cooling water and external Zircaloy clad surface to obtain clad external temperature profile, $T_w(z)=T_{ge}(z)$;
- Zircaloy thermal conductivity to obtain clad internal temperature profile, $T_{ig}(z)$;
- heat exchange in the helium gap, between internal clad face and external pellet surface, and heat radiation between the two surfaces to obtain pellet surface temperature profile, $T_s(z)$;
- fuel thermal conductivity to obtain center temperature profile $T_c(z)$.

Typical shapes of the above-mentioned temperature profiles are shown in Figure 4.

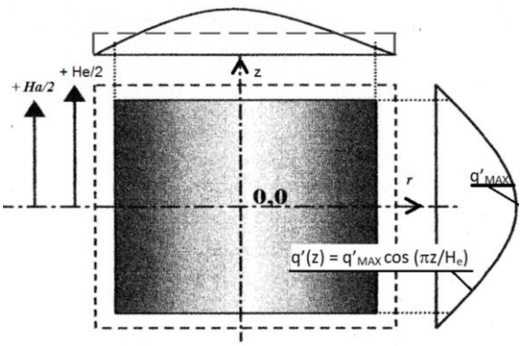

Figure 3. Linear heat flux profile of a PWR core

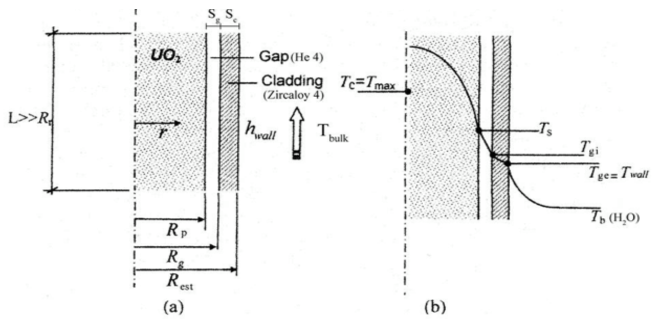

Figure 4. General sub-channel (a) and fuel rod temperature profiles (b)

The main relationships and equations to model the above mentioned temperature profiles are shown in [1], but the following updates must be taken into account for a more effective modeling:

- to assess heat exchange between cooling water and pellet central temperature the Fourier equation has to be adopted in which:
  - Zircaloy conductivity is to be expressed as a function of temperature (in [1] it was considered independent from temperature);
  - to assess heat transfer in the internal gap of the clad, a temperature trend has been simulated taking into account, apart from helium thermal conductivity (helium is stagnant), a heat supplement due to thermal radiation between internal clad surface, T_{ig}, and external pellet surface, T_s;
  - the equation to assess fuel centerline temperature, eq. (23) in [1], must be corrected multiplying the second term by the Robertson Factor, RF, to take into account the mean value of heat distribution in the fuel pellet depending on the enrichment level, X_i, and on pellet radius Rp;
  - cooling water specific heat, cp, is not a constant but has to be expressed as a function of temperature;
- In the core, a cooling water bypass factor has to be considered (mass flow through the core is less than primary coolant flow);
- Vessel temperature has to be calculated in detail taking into account the actual temperature values inside and outside the vessel, applying thermal conduction and thermal convection laws for the specific materials and fluids.

Having assessed central temperature and superficial pellet temperature profiles for each enrichment level present in the fuel assemblies, the corresponding average temperature profile, regarded as equivalent to fission temperature profile, can be calculated. For each enrichment level, using the respective fission temperature profiles and q'_{MAX} values, heat fission Exergy can be assessed through the following equation [12,13] :

$$\dot{E}x_{Qfiss,i} = N_{fr,i} \int_{-Ha/2}^{+Ha/2} \left[\left(1 - {T_0}/{T_{fiss,i}(z)}\right) q'_{MAX,i} \cos\left({\pi z}/{H_e}\right) \right] dz \tag{13}$$

The reactor Exergy Fuel can be calculated as:

$$\dot{E}x_{Fuel} = \dot{E}x_{Qfiss} = \sum_{i=1}^{n} \dot{E}x_{Qfiss,i} \tag{14}$$

To assess Exergetic Efficiency as defined in equation (6), Exergy associated with Product and Loss must be evaluated. Exergy Product, which means Exergy associated with the coolant water mass flow, can be expressed as follow:

$$\dot{E}x_P = \dot{E}x_2 - \dot{E}x_1 = \dot{m}_{RCS} \left(ex_2 - ex_1\right) \tag{15}$$

Exergy associated with transferred heat from vessel to environment (thermal losses), can be expressed using the following equations [12]:

$$\dot{Q}_{Loss,RPV} = \dot{Q}_{fiss} - \dot{m}_{RCS}\,(h_2 - h_1) \tag{16}$$

$$\dot{E}x_{Loss,RPV} = \dot{Q}_{Loss,RPV}\left(1 - {}^{T_0}/_{T_{vessel}}\right) \tag{17}$$

T_{vessel} being the average temperature of reactor vessel surfaces temperatures.

2.3 PWR Reactor Coolant System Exergy Analysis

For a Pressurized Water Reactor, apart from the reactor, the Reactor Coolant System, RCS, consists of a steam generator, SG, a reactor coolant pump and connecting piping. A nuclear power plant can be built with up to four primary RCS loops (depending upon the power output of the plant) and a pressurizer connected just on one of them (here neglected under steady state operational mode hypothesis). The Reactor Coolant System is equipped with a Chemical and Volume Control System, here neglected as a circuit. With regards to piping, total pressure drops along hot and cold legs of a loop can be simulated by entering equivalent concentrated pressure drops through two dummy valves as shown in Figure 5 (CLV and HLV valves).

For all RCS components, Physical Productive Structures are shown in Table 1; more details for Steam Generator and main reactor coolant pump are shown in Figure 6.

Table 1. RCS components P.P.S.

Components	FUEL EXERGY	PRODUCT EXERGY	LOSSES EXERGY
RPV	$\dot{E}x_9 = \dot{E}x_{Qfiss}$	$\dot{E}x_2 - \dot{E}x_1$	$\dot{Q}_{Loss,RPV}\left(1 - {}^{T_0}/_{T_{vessel}}\right)$
LV	$\dot{E}x_2$	$\dot{E}x_3$	-----
SG	$\dot{E}x_3 - \dot{E}x_4$	$\dot{E}x_7 - \dot{E}x_6$	$\dot{Q}_{Loss,SG}\left(1 - {}^{T_0}/_{T_{ext,SG}}\right)$
RCP	$\dot{E}x_8 = P_{el,RCP}$	$\dot{E}x_5 - \dot{E}x_4$	-----
CLV	$\dot{E}x_5$	$\dot{E}x_1$	-----

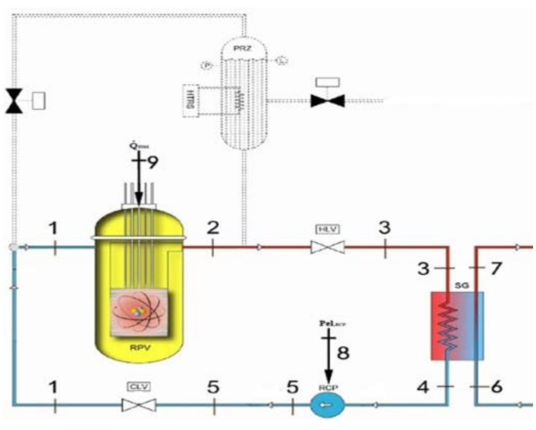

Figure 5. Simplified scheme of PWR Reactor Coolant System (RCS)

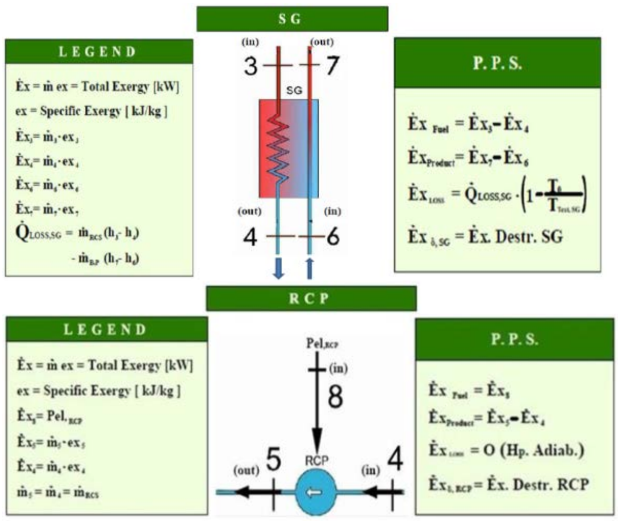

Figure 6. Steam Generator and Reactor Coolant Pump P.P.S.s

After having performed all Energy balances and Entropy accountings, for each node specific Exergy can be assessed as follow [12]:

$$ex_i = (h_i - h_o) - T_0(s_i - s_0) \quad (18)$$

where "0" subscript identifies environmental reference conditions.

4. Conclusions

The paper provides an alternating, novel model to assess the exergetic analysis of a Pressurized Light Water Reactor. The novelty of such an analysis is due to the detailed modeling of heat exchanges within the Nuclear Reactor to document its main exergetic flow rates. The modeling, referring to a steady-state operational mode, takes into account all heat transfer phenomena between nuclear fuel itself, fuel and its clad, clad and cooling water and thermal losses of cooling water through the vessel towards the external environment.

The methodology differ from others similar models in which almost reductive working hypotheses are assumed, in particular the hypothesis in reference [5, 7, et al.] assumes that Fission Exergy and Fission thermal power are almost the same.

To perform a numerical assessment using the methodology in question a test case is exemplified in the Part II of the paper, in which the results are compared with the those obtained applying the most employed methodology adopted by other authors [5, 7, et al.].

This work is, for the authors, the most significant step to performing the modeling of a whole PWR Nuclear Power Plant where all NPP components will be simulated also to assess the exergetic efficiency of the NPP as a whole.

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