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Energy and Exergy Based Performance Analysis of Westinghouse AP1000 Nuclear Power Plant

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Abstract: Energy and exergy analyses of the performance of the Westinghouse Advanced Passive 1000-MWe Nuclear Plant (AP1000) was conducted with the primary objectives to identify and quantify the operational locations having the largest energy and exergy losses under normal operating conditions. The energy and exergy losses in the reactor units were determined from formulations of the energy and exergy rate balances based on the Gouy-Stodola theorem. The performance of the overall AP1000 plant was estimated by component wise modeling and detailed break-up of energy and exergy losses in the various plant sections. Operating at maximum core power of 3400 MW, the AP1000 reactor core experienced moderately small thermal loss of 125.1 MW and very substantial exergy consumption of 1814.8 MW achieving energy and exergy efficiencies of 96.3% and 46.6% respectively. For the entire AP1000 plant, energy losses occurred mainly in the condenser where 1849.8 MW was lost to the environment. Exergy analysis, however, revealed lost energy in the condenser was thermodynamically insignificant due to the low quality and that irreversible losses of 1868.4 MW in the reactor and steam generator assembly were the major source of irreversibilities in the plant. The study confirmed that the major heat transfer inefficiencies occurring in nuclear reactor plants resided in the reactor cores and efforts to increase the efficiency of the plant should concentrate on the design of the core components.

Keywords: Energy Analysis, Exergy Analysis, Gouy-Stodola Theorem, Irreversibility, Maximum Work, Energy Conversion Systems, Reactor Core, Nuclear Power Plant

1. Introduction

The emphasis on energy resource conservation and environmentally sustainable power production processes have generated increased interest among researchers and in industry to find high efficiency and low emission solutions to energy related problems.

Conventionally, energy efficiency analyses emphasize reducing energy emissions or wastes to improve efficiency. The only inefficiencies detected by the analysis of a system are the energy transfers out of the system that are not further used in the installation [1, 2].

Consequently, energy analysis provides no information on the degradation of energy or resources during a process and does not account for the usefulness (or quality) of the various energy and material streams flowing through a system and exiting as products and wastes [3, 4].

All real processes involve energy losses due to their irreversible nature. In real processes, energy is not destroyed but rather transformed into other forms less suitable for feeding and driving real processes. Hence beside energy, the concept of exergy was introduced to characterize the quality of the energy under consideration. The exergy method of analysis, based on the second law of thermodynamics and the concept of irreversible production of entropy, overcomes the limitations of energy analysis [5, 6].

Exergy is the maximum work potential of energy in relation to the environment and is a measure of the ability to do work by the variety of energy streams (mass, heat, and work) that are transferred through a system [7]. The key attribute of exergy is the provision of common grounds for the comparison of the various energy streams based on the second law of thermodynamics.

The elementary irreversible phenomena that generate entropy are mechanical or hydraulic friction, heat transfer with a finite temperature gradient, diffusion with a finite gradient of concentration, and the mixing of substances with different parameters and chemical composition [3].

The exergy method is useful for providing a detailed breakdown of the losses for plants and components, in terms of waste emissions and irreversible losses, and quantifies the types, causes and locations of the losses, such that inefficiencies in processes are better pinpointed. In exergy analysis, more meaningful efficiencies are evaluated since exergy efficiencies are always a measure of the approach to the physically ideal output [3].

In systems analysis, the irreversibilities associated with combustion, heat transfer, mixing and pressure losses are considered separately and used to estimate the contribution of each component or process to the total exergy destruction in a system [8].

There are various irreversible losses that exist within energy production systems which transform part of the total energy to forms unavailable for power production [9]. Thus complete energy analysis of thermal power and other energy intensive systems requires a combination of the first and second laws of thermodynamics to account for the quality and quantity of the energy flows [10].

The research problem investigated was to develop a mathematical model of the thermodynamic efficiency of the Westinghouse Advanced Passive 1000-MWe Nuclear Plant (AP100) through formulating of energy and exergy balances for the Westinghouse AP1000 power reactor system under steady state conditions in order to:

(1) Determine of the magnitude of energy losses and dissipations (or exergy consumptions) in the energy conversion processes within the components of the reactor assembly.
(2) Identify of the locations and types of irreversibilities within the systems, and
(3) specification of the sites or components that contribute significant losses to the system.
(4) Determine of the energy and exergy efficiency of the reactor components and the overall operating efficiencies under nominal conditions.
(5) Contribute to a comprehensive understanding of the thermodynamic characteristics of reactor systems.

2. Method

2.1. Schematic Setup

The general equations used in conventional energy and exergy analysis are shown in Table 1. The schematic setup for the plant was obtained through sectioning the reactor core and process cycles separately and modelling the exergy and energy transfer processes of the individual components within the sectioned parts to perform the analysis

According to Dincer and Rosen, the energy and exergy transfer processes that occur within the steam generation of a water cooled nuclear reactor consists of heating of the fuel pellets to their maximum temperature, transfer of the heat within the fuel pellets to the surface of the pellets, transfer of heat from the surface of the fuel pellets to the cladding outer surface, and the transfer of heat from the cladding surface to the primary coolant [1]. The equations employed to calculate the exergy efficiencies of the reactor core are shown in Table 2.

Table 1. *General equations used in conventional energy and exergy analysis [3].*

	Equation	No.
Energy Balance	$\frac{dEx_{cv}}{dt} = \sum_j \left(1 - \frac{T_o}{T_j}\right)\dot{Q}_j - \left(\dot{W}_{cv} - p_o \frac{dV_{cv}}{dt}\right) + \sum_i \dot{m}_i x_{fi} - \sum_e \dot{m}_e x_{fe} - \dot{I}_d$	1
Entropy Analysis	$\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{S}_{gen}$	2
Irreversibility	$I = \dot{W}_{u,max} - \dot{W}_{actual}$	3
Irreversibility (Gouy-Stodola)	$I_d = T_o S_{gen}$	4
Energy efficiency	$\eta = \frac{\dot{W}_{cycle}}{\dot{Q}_{in}} = \frac{\dot{W}_{actual}}{\dot{Q}_{in}}$	5
Exergy efficiency	$\psi = \frac{\dot{W}_{actual}}{\dot{W}_{u,max}}$	6
Energy efficiency of the reactor core	$\eta_R = 1 - \frac{\dot{Q}_{loss}}{\dot{Q}_{fission}}$	7

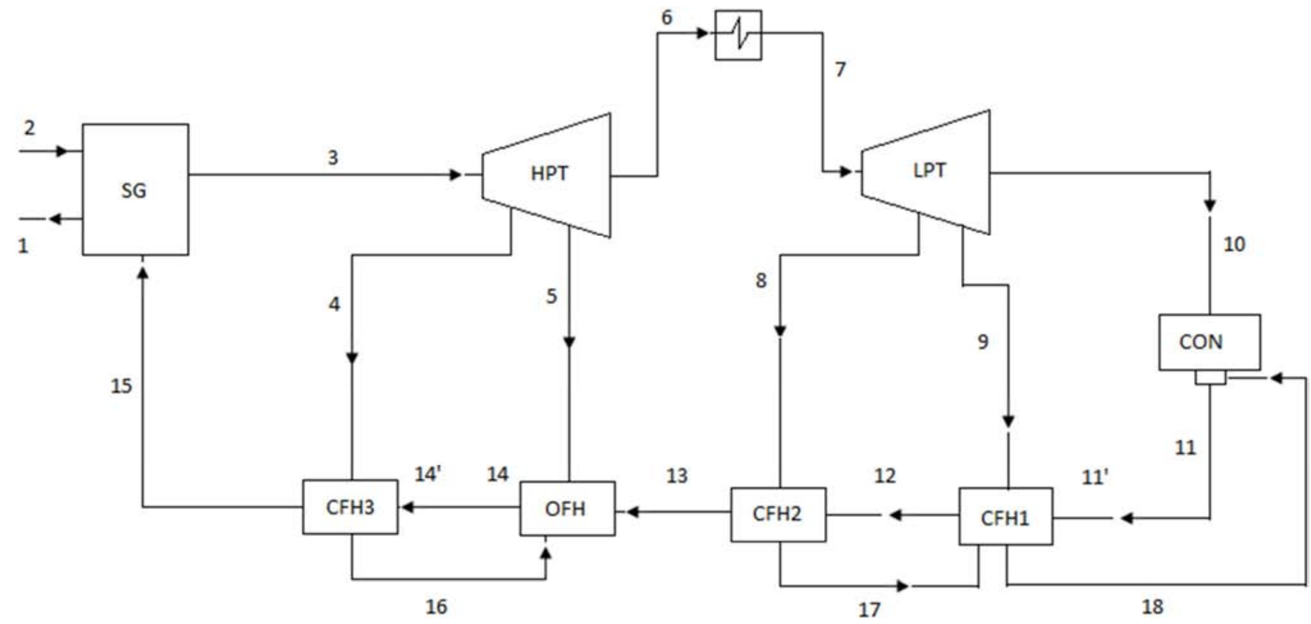
The experimental setup for the plant was obtained through sectioning the reactor core and process cycles separately and modelling the exergy and energy transfer processes of the individual components within the sectioned parts to perform the analysis.

According to Dincer and Rosen, the energy and exergy transfer processes that occur within the steam generation of a water cooled nuclear reactor consists of heating of the fuel pellets to their maximum temperature, transfer of the heat within the fuel pellets to the surface of the pellets, transfer of heat from the surface of the fuel pellets to the cladding outer surface, and the transfer of heat from the cladding surface to the primary coolant [1]. The equations employed to calculate the exergy efficiencies of the reactor core are shown in Table 2.

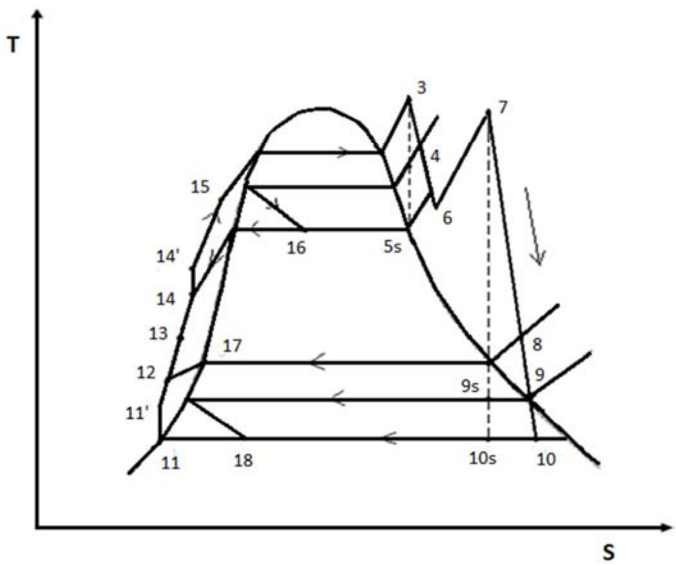
The process cycle for the AP1000 power cycle was idealized with the simplified model of Figure 1, which was derived from the complete heat balance of Figure 2 [11] based on the regenerative vapour cycle design which drives steam through a series of low and high pressure turbine generators, and preheating feed-water in connected low and high pressure heat exchangers and open de-aerating heat chambers.

Table 2. *Equations employed to calculate the exergy efficiencies of the reactor core [12].*

	Parameter	Equations	No.
The maximum work	Fission	$(\dot{W}_{u,\max})_{fission} \approx \dot{Q}_{fission}$	8
	Fuel rod centerline	$(\dot{W}_{u,\max})_{fuel} = \dot{Q}_{fission}\left(1 - \frac{T_o}{T_{max}}\right)$	9
	Outer surface of pellet	$(\dot{W}_{u,\max})_{pellet} = \dot{Q}_{fission}\left(1 - \frac{T_o}{T_p}\right)$	10
	Outer surface of clad	$(\dot{W}_{u,\max})_{clad} = \dot{Q}_{fission}\left(1 - \frac{T_o}{T_c}\right)$	11
	Coolant	$(\dot{W}_{u,\max})_{coolant} = \dot{m}\,[(h_e - h_i) - T_o(s_e - s_i)]$	12
Irreversibility	Fuel rod	$\dot{I}_{fuel} = (\dot{W}_{u,\max})_{fission} - (\dot{W}_{u,max})_{fuel} = (\dot{W}_{u,max})_{fission}\left(\frac{T_o}{T_{max}}\right)$	13
	Pellet	$\dot{I}_{pellet} = (\dot{W}_{u,\max})_{fuel} - (\dot{W}_{u,\max})_{pellet}$	14
	Clad	$\dot{I}_{clad} = (\dot{W}_{u,\max})_{pellet} - (\dot{W}_{u,\max})_{clad}$	15
	Coolant	$\dot{I}_{coolant} = (\dot{W}_{u,\max})_{clad} - (\dot{W}_{u,\max})_{coolant}$	16
	Reactor (total)	$\dot{I}_{reactor} = \dot{I}_{fission} + \dot{I}_{fuel} + \dot{I}_{pellet} + \dot{I}_{clad} + \dot{I}_{coolant}$	17
Exergy efficiency		$\psi_R = 1 - \frac{\dot{I}_{reactor}}{(\dot{W}_{u,\max})_{fission}}$	18



(a)



(b)

Figure 1. *(a) Simplified model of the AP1000 process cycle (b) T-S diagram of the regenerative vapour cycle. The property data for the flow streams are listed in Table 4.*

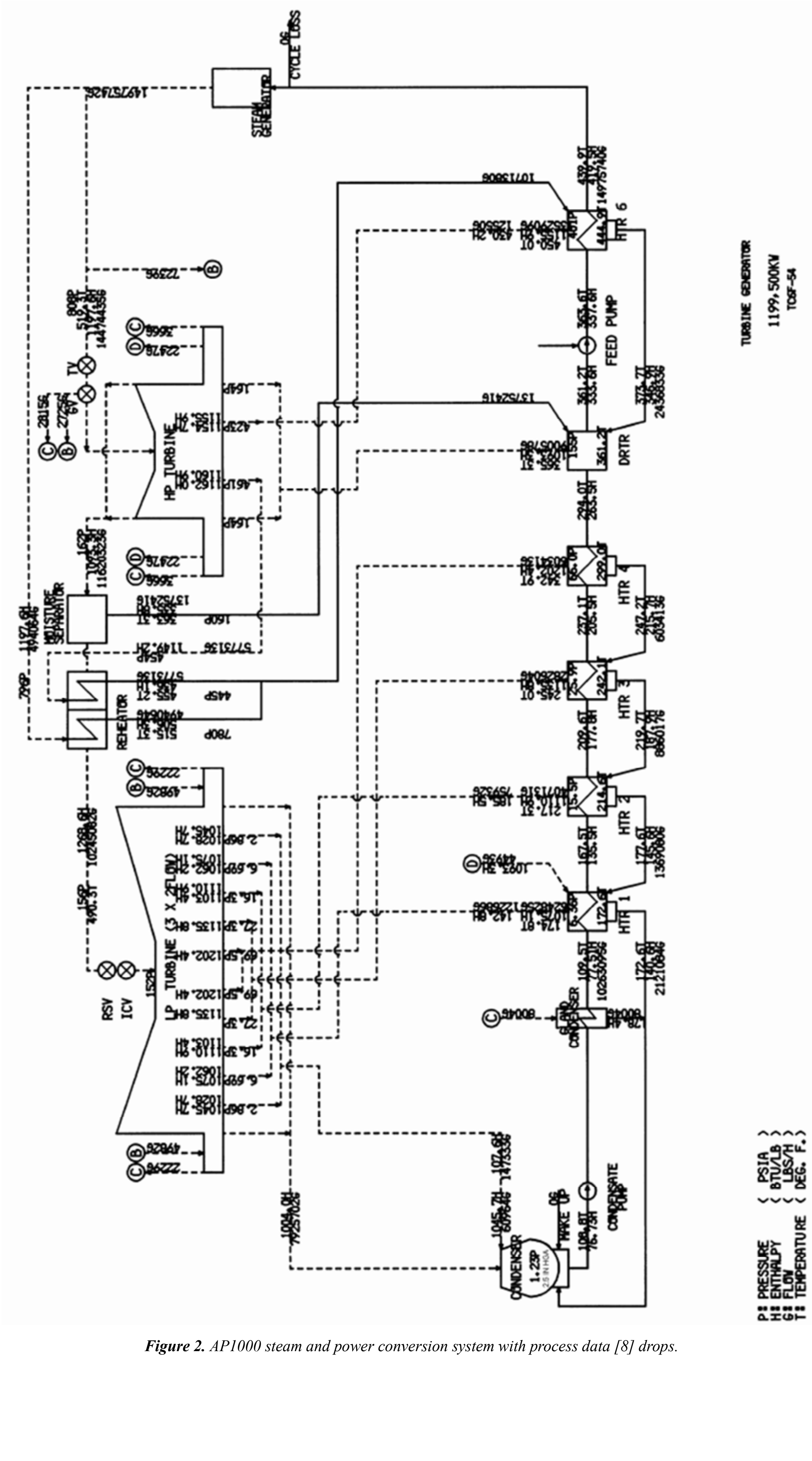


Figure 2. *AP1000 steam and power conversion system with process data [8] drops.*

2.2. Thermodynamic Analysis

The thermodynamic modelling of the subsystems of the process cycle of the AP1000 plant was initiated by considering in turns the major components working under steady state.

Operating under full power conditions, the steady state fuel temperature distribution within the AP1000 reactor core was assumed to be maximum at the fuel centerline at T_{max} (1339.9°C) and fall to temperature T_c (315.75°C) at the fuel cladding surface [13].

General equations used to calculate the energy and exergy rates for the identified streams in the simulated AP1000 process cycle of Figure 1, and the general performance parameters used in the exergy analysis are presented in Table 3.

The process cycle was analysed based on the following assumptions and simplifications:

(1) Kinetic and potential energy changes were negligible for all processes.
(2) Pump work as a contribution to net work output was insignificant
(3) Frictional irreversibilities in the turbines were ignored (i.e. turbines had mechanical efficiencies of 100%.)
(4) The reference environment model used had the following property values: temperature T_o =32°C and pressure P_o=1atm.
(5) Turbine output ($\dot{W}_T$) = 1199.5MW

Thus the only irreversibilities considered for all the plant components were internal irreversibilities due to heat transfer.

2.3. Computation of Energy and Exergy Loss Rates

General equations used to calculate the energy and exergy loss rates for streams and general performance parameters used in the conventional exergy analysis are given in Table 3.

The operational data used in the analysis of the processes within the AP1000 power cycle is presented in Table 5 [8]. The enthalpy and entropy values were obtained by finding the mass weighted average enthalpy and entropy values of streams specified for components in the AP1000 Design Control Document [11].

The energy and exergy rate balances for the AP1000 power cycle, presented in Table 3, was solved for the energy and exergy loss rates specified for the various plant components through the substitution of the parameters of mass flow rates, enthalpy and entropy values into the respective equations.

The total energy and exergy loss values were obtained from an aggregation of the energy and exergy loss values computed for the various plant components.

Table 3. *Equations employed to calculate the energy and exergy loss rates of the plant components.*

	Parameter	Equations	No.
Energy	Entire turbine	$\dot{W}_T = \dot{m}_3(h_3 - h_4) + (\dot{m}_3 - \dot{m}_4)(h_4 - h_5) + (\dot{m}_3 - \dot{m}_4 - \dot{m}_5)(h_5 - h_6) + \dot{m}_7(h_7 - h_8) + (\dot{m}_7 - \dot{m}_8)(h_8 - h_9) + (\dot{m}_7 - \dot{m}_8 - \dot{m}_9)(h_9 - h_{10}) - Energy\ loss$	19
	Steam generator	$\text{Energy loss(SG)} = \dot{m}_1(h_2 - h_1) - \dot{m}_3(h_{15} - h_3)$	20
	Closed Feedwater Heater No. 1	$\text{Energy loss(CFH1)} = \dot{m}_9 h_9 + \dot{m}_{17} h_{17} - \dot{m}_{11'}(h_{12} - h_{11'}) - \dot{m}_{18} h_{18}$	21
	Closed Feedwater Heater No. 1	$\text{Energy loss(CFH2)} = \dot{m}_8(h_8 - h_{17}) - \dot{m}_{12}(h_{13} - h_{12})$	22
	Open feedwater heater	$\text{Energy loss(OFH)} = \dot{m}_5 h_5 + \dot{m}_{16} h_{16} + \dot{m}_{13} h_{13} - \dot{m}_{14} h_{14}$	23
	Closed Feedwater Heater No. 1	$\text{Energy loss(CFH3)} = \dot{m}_4(h_4 - h_{16}) - \dot{m}_{14}(h_{15} - h_{14'})$	24
	Condenser	$\text{Energy loss(Con)} = \dot{m}_{10}(h_{10} - h_{11}) - \dot{m}_{cw}(h_{co} - h_{ci})$	25
Exergy Balance	High pressure turbine	$T_o\dot{S}_{gen} = T_o[\dot{m}_3(s_4 - s_3) + (\dot{m}_3 - \dot{m}_4)(s_5 - s_4) + (\dot{m}_3 - \dot{m}_4 - \dot{m}_5)(s_6 - s_5)]$	26
	Low pressure turbine	$T_o\dot{S}_{gen} = T_o[\dot{m}_7(s_8 - s_7) + (\dot{m}_7 - \dot{m}_8)(s_9 - s_8) + (\dot{m}_7 - \dot{m}_8 - \dot{m}_9)(s_{10} - s_9)$	27
	steam generator (Irreversibility	$T_o\dot{S}_{gen} = T_o[\dot{m}_1(s_1 - s_2) - \dot{m}_3(s_{15} - s_3)]$	28
	Closed Feedwater Heater No.1	$T_o\dot{S}_{gen} = T_o[\dot{m}_{18}s_{18} + \dot{m}_{11'}(s_{12} - s_{11'}) - \dot{m}_9 s_9 - \dot{m}_{17}s_{17}]$	29
	Closed Feedwater Heater No.2	$T_o\dot{S}_{gen} = [\dot{m}_8(h_8 - h_{17}) - \dot{m}_{12}(h_{13} - h_{12})] - T_o[\dot{m}_8(s_8 - s_{17}) - \dot{m}_{12}(s_{13} - s_{12})]$	30
	Open Feedwater Heater	$T_o\dot{S}_{gen} = T_o[\dot{m}_{14}s_{14} - \dot{m}_5 s_5 - \dot{m}_{16}s_{16} - \dot{m}_{13}s_{13}]$	31
	Closed Feedwater Heater No.3	$T_o\dot{S}_{gen} = [\dot{m}_4(h_4 - h_{16}) - \dot{m}_{14}(h_{15} - h_{14})] - T_o[\dot{m}_4(s_4 - s_{16}) - \dot{m}_{14}(s_{15} - s_{14})]$	32
	Condenser	$T_o\dot{S}_{gen} = T_o[\dot{m}_{10}(s_{10} - s_{11}) - \dot{m}_{cw}(s_{co} - s_{ci})]$	33
Energy efficiency	Plant	$\eta_{plant} = \frac{\dot{W}_{net}}{\dot{E}_{fuel}} = \frac{\dot{W}_T}{\dot{Q}_{fission}}$	34
Exergy efficiency	Plant	$\psi_{plant} = \frac{\dot{W}_{net}}{\dot{Ex}_{fuel}} = \frac{\dot{W}_T}{\dot{Q}_{fission}}$	35

Table 4. *Thermodynamic property data for flow streams listed in Figure 1(a).*

State	Mass flow rate kg/s	Enthalpy[1] kJ/kg	Entropy[1] kJ/kg. K	Temp °C	Pressure MPa	Condition	Vapour fraction
0				32.0	0.101		
1	14275.8[1]	1239.5	3.073	280.7	15.513	Subcooled liquid	0.0
2	14275.8[1]	1468.9	3.503	321.1	15.513	Subcooled liquid	0.0
3	1886.7	2765.8	5.924	270.7	5.571	Saturated vapour	1.0
4	170.4	2688.6	7.257	232.2	2.916	Two phase mixture	0.56
5	113.4	2543.0	5.840	229.4	1.103	Two phase mixture	0.40

State	Mass flow rate kg/s	Enthalpy[1] kJ/kg	Entropy[1] kJ/kg. K	Temp °C	Pressure MPa	Condition	Vapour fraction
6	1464.1	2543.0	5.840	184.1	1.117	Two phase mixture	0.90
7	1290.9	2950.8	7.980	254.6	1.075	Saturated vapour	1.0
8	172.5	2695.4	6.901	152.3	0.191	Saturated vapour	1.0
9	94.8	2146.0	7.830	79.3	0.046	Two phase mixture	0.84
10	1025.9	2252.0	8.407	42.7	0.008	Two phase mixture	0.98
11	1293.1	178.4	0.606	42.7	0.008	Saturated liquid	0.0
11'	1293.1	180.7	0.570	43.1	0.043	Subcooled liquid	0.0
12	1293.1	315.2	1.070	95.7	0.247	Subcooled liquid	0.0
13	1293.1	612.9	1.795	145.6	1.068	Subcooled liquid	0.0
14	1886.7	776.0	2.166	182.9	1.068	Subcooled liquid	0.0
14'	1886.7	785.3	2.187	184.2	2.764	Subcooled liquid	0.0
15	1886.7	975.8	2.578	226.6	5.570	Subcooled liquid	0.0
16	306.9	806.9	2.900	189.8	1.068	Subcooled liquid	0.0
17	172.5	338.7	1.080	80.9	1.190	Subcooled liquid	0.0
18	267.2	327.0	1.081	78.1	0.043	Subcooled liquid	0.0
Cwin	37665.8	137.0	0.453	32.0	0.101	Subcooled liquid	0.0
Cwout	37665.8	185.0	0.663	46.8	0.101	Subcooled liquid	0.0

[1] The mass flow rate for the primary coolant was derived from the best estimate core flow provided in AP1000 Design Control Document [14].

3. Results

The results of the energy and exergy analysis of the AP1000 reactor core and process cycle are summarized in Table 5.

The results show that energy loss was largest in the condensation section, From first law analysis, a large quantity of energy (1808 MW) entered the condenser of which close to 100% was rejected to the environment. On the other hand, the power production section of the AP1000 unit (consisting of the turbines), experienced low combined energy loss of 17.6 MW. The preheating sections consisting of two low pressure closed heat exchangers, a high pressure closed heat exchanger and a de-aerating chamber, were are found to have higher aggregate energy loss of 31.2MW.

This was followed by the steam generation sections, consisting of the reactor core and steam generator devices. In this section, the energy loss was found to be moderate at 227.4MW with the reactor core contributing 125.1MW of the total, and the steam generator device experiencing the remaining 102.3MW loss.

The exergy analysis of components revealed that, the condenser consumed the least amount of exergy (28.4MW) during heat transfer to the cooling water. In the power production section of the AP1000 unit, the total exergy losses were found to be moderate at 99.3 MW. Of this total, the low pressure turbine was observed to account for the highest loss of 72.4 MW, with the high pressure turbine contributing a loss of 26.9 MW.

The preheating sections were found to have small exergy consumptions adding up to a total loss of 33.6MW. The exergy consumption associated with the reactor core and steam generator assembly, collectively called the steam generation sections, was found to be substantial contributing 1868.4MW of exergy loss, thereby accounting for 92% of the total exergy consumed.

The main energy process in the steam generation sections was heat transfer, and of the total exergy consumed, 1814.8MW was consumed in the heat transfer processes of the reactor core, and 53.6MW internally consumed in the steam generator device.

The overall energy and exergy efficiency values were calculated using $\dot{W}_T = 1199.5\,MW$ and modeled as the theoretical energy and exergy efficiency values. These were found to be 35.3%. Consequently, the theoretical energy and exergy loss values calculated from were found to be same at $2200.5\,MW$

4. Discussion

The energy analysis of the AP1000 reactor core indicated that operating at nominal core power of 3400 MW, energy was lost at the rate of 125.1 MW to the surroundings, and transferred at the rate of 3274.9 MW to the primary coolant. On percent basis, only 3.7% of the total heat (energy) generated from the fuel was wasted, yielding a reactor energy efficiency of 96.3%.

The exergy consumption in the AP1000 reactor core was separated into irreversible losses in heating the fuel centerline to the maximum temperature of 1339.9°C, transferring of heat to the cladding surface at 315.75°C, and heating of the primary coolant.

Of the 1814.8 MW total exergy consumption observed in the reactor core, 643.2 MW was consumed in heating the fuel centerline to the maximum temperature, 1118.6 MW in transferring heat to the cladding surface, and 53.1 MW was destroyed in heating the primary coolant. The maximum work available from the coolant was observed to be 1585.2 MW, thereby achieving exergy efficiency of 46.6%.

Table 5. Energy and exergy loss rates in sections of AP1000 power cycle.

Section/device	Energy loss rate		Exergy loss rate	
	(MW)	% of total energy loss	(MW)	% of total exergy loss
Steam generation section				
Reactor				
Fuel Centerline	-		643.2	31.7
Cladding surface	-		1118.6	55.1
Coolant	-		53.1	2.6
Total	125.1	6.0	1814.8	89.4
Steam generator	102.3	4.9	53.6	2.6
Section Total	227.4	10.9	1868.4	92.0
Power production section				
High-pressure turbine	-		26.9	1.3
Low-pressure turbine	-		72.4	3.6
Total	17.6	0.8	99.3	4.9
Condensation section				
Condenser((rejected)	1808.0		28.5	
Total	1808.0	86.7	28.5	1.4
Preheat section				
Low-pressure heat exchanger (CFH1)	0.6	0.0	2.0	0.1
Low-pressure heat exchanger (CFH2)	21.5	1.0	1.2	0.1
Deaerating heat exchanger (OFH)	7.9	0.4	10.9	0.5
High-pressure heat exchanger (CFH3)	1.2	0.1	19.5	1.0
Total	31.2	1.5	33.6	1.7
General Total	2084.2	100.0	2029.8	100.0

The high thermal efficiency and moderate exergy efficiency achieved by the AP1000 reactor core was ascribed to the high temperatures of heat generation in the fuel, and heat-transfer under high temperature and pressure to the coolant. By this mechanism, the primary circuit maintained a high average temperature of heat addition to the working fluid in the secondary circuit.

The exergy destruction profile of the AP1000 reactor, which detailed the sectional contributions to total consumption within the core, showed that a substantial proportion (97%) of total exergy consumption in the core was associated with heat transfer processes occurring within the fuel meat. This finding was consistent with the exergy consumption profile observed for the nuclear reactor of the Pickering Nuclear Generating Station in Canada [1].

For the AP1000 power cycle, the theoretical values of the plant overall energy and exergy efficiencies were found to be similar. However, the energy and exergy analysis revealed that individual component contributions to the total energy and exergy losses differed significantly for most plant sections as depicted in Figures 3 & 4.

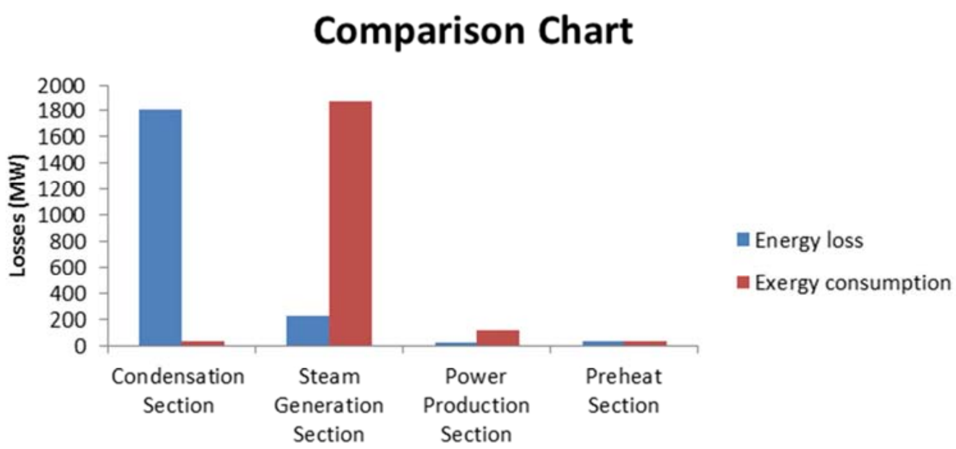


Figure 3. Comparison of sectional energy and exergy losses within the AP1000 plant.

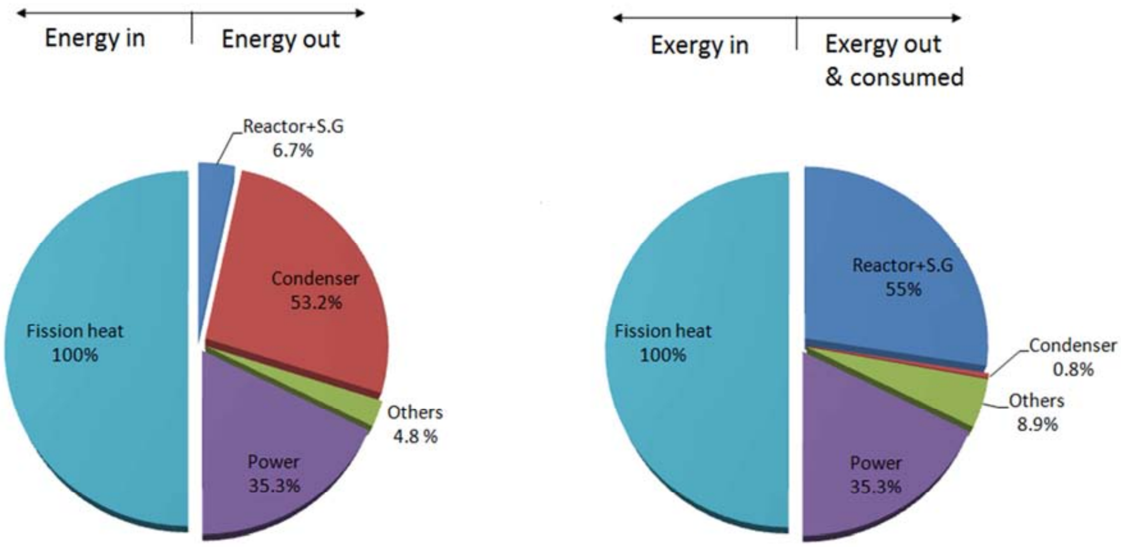


Figure 4. *Energy and exergy balances for the entire AP1000 plant indicating power input, output and sectional losses.*

Energy analysis, thus, leads to the erroneous conclusion that almost all losses in net work output were associated with heat rejected by the condensers. However, as reported by Dincer [1], the sources for majority of useful losses were the steam generation sections which experienced the largest irreversible losses or internal consumptions.

The steam generation sections of the AP1000 unit appeared significantly more efficient on an energy basis than on an exergy basis. The implication was that although a large quantity of the input energy was transferred to the coolant, and subsequently to the working fluid, the quality of energy was degraded as it was transferred.

The overall energy efficiency value calculated for the AP1000 plant was observed to be comparable to the value specified from literature [15]. The marginal deviation was ascribed to the assumptions, simplifications and idealizations adopted for the study.

Generally, the energy loss and exergy consumption values obtained for the AP1000 plant were found to be in broad agreement with other published works on nuclear power plants, and indicated the operational locations with the biggest potential for efficiency improvements as reported by the researchers [1, 16].

5. Conclusion

In the study, energy and exergy analysis of the Westinghouse Advanced Passive 1000-MWe Nuclear Plant (AP1000) was presented. The primary objectives of the study were to analyze the AP1000 reactor core and power cycle separately, and to identify and quantify the sites having the largest energy and exergy losses under normal operating conditions.

Mathematical models of the energy and exergyrate balances for the AP1000 plant were formulated under steady state normal operating conditions and evaluated using process data sourced from literature and AP1000 design documents.

Of the 3400 MW core power generated by the AP1000, heat was lost at the rate of 125.1 MW to the environment, and transferred at a rate of 3274.9 MW to the reactor coolant, yielding a thermal efficiency of 26.7%. Exergy analysis, on the other hand, revealed that of the total exergy (3400 MW) input to the reactor, 1814.8 MW was consumed in the reactor core.

The AP1000 reactor core achieved very high energy efficiency and modest exergy efficiency which was comparable to other power reactor cores. This was attributed to the high temperatures associated with heat generation in the fuel and heat-transfer to the coolant.

For the AP1000 plant, maximum energy loss was observed in the condenser where close to 100% of energy entering this section was rejected. The condenser alone accounted for 86.7% of the total energy loss by the power cycle to the environment. The overall energy efficiency of the plant based on fission power generated wasfound to be 35.3%.

Exergy analysis of the AP1000 station showed that energy loss in the condenser was thermodynamically insignificant due to the low quality of the ejected heat. In terms of exergy consumption (or irreversible losses), substantial loss was found in the steam generation sections where 1868.4MW of exergy, constituting 55% of the fission exergy input, was destroyed.

The overall energy and exergy efficiency for the power cycle was found to be the same at 35.3%. However, energy and exergy analyses gave markedly different accounts of the component contributions to the total losses in the plant. Thus, while energy analysis gave only the energy emissions from processes without providing information about internal losses, exergy analysis highlighted the degradations in energy quality as it was transferred.

Generally, the energy and exergy loss and efficiency values evaluated for the process subsections and overall plant were found to be comparable to modern power plants and were in broad agreement with other published works on nuclear power reactors.

The study demonstrated that nuclear reactor cores have the largest potential for efficiency improvement in nuclear plants and, therefore, efforts to increase station efficiency should concentrate on this section.

Nomenclature

$\dot{E}_{fuel}$	fuel energy rate (W)
$\dot{E}x_{fuel}$	fuel exergy rate (W)
h	specific enthalpy (J/kg)
I_d	exergy destruction (J)
I	Irreversibility (J)
$\dot{I}_d$	exergy destruction (irreversibility) rate (W)
$\dot{I}_{fission}$	irreversibility of fission (W)
$\dot{I}_{fuel}$	Irreversibility in heating fuel centreline (W)
$\dot{I}_{pellet}$	irreversibility rate of heating fuel pellet surface (W)
$\dot{I}_{clad}$	irreversibility rate of clad (W)
$\dot{I}_{coolant}$	irreversibility rate of coolant (W)
$\dot{I}_{reactor}$	irreversibility rate of reactor core (W)
k	Boltzmann constant (J/K)
M	molecular weight (g/g mole)
$\dot{Q}_{net}$	net heat flow rate(W)
$\dot{Q}_{loss}$	rate of heat loss(W or J/s)
T	temperature (K or °C)
T_a	Temperature of fission fragments (K)
$W_{rev,out}$	reversible work (J)
$W_{u,out}$	useful work (J)
$\dot{W}_{net}$	net work output rate (W)
$W_{u,total}$	total useful work (W)
$\dot{W}_{u,max}$	maximum useful work (W)
$\dot{W}_{actual}$	actual work rate (W)
$(\dot{W}_{u,\max})_{fission}$	maximum work obtainable from fission (W)
$(\dot{W}_{u,\max})_{fuel}$	maximum work available from fuel centreline (W)
$(\dot{W}_{u,\max})_{pellet}$	maximum work available from fuel pellet surface (W)
$(\dot{W}_{u,\max})_{clad}$	maximum work available from clad surface (W)
$(\dot{W}_{u,\max})_{coolant}$	maximum work obtainable from coolant (W)
$\dot{W}_{HPT}$	work output by high pressure turbine (W)
$\dot{W}_{LPT}$	work output by low pressure turbine (W)
$\dot{W}_T$	work rate $W_{rev,out}$ reversible work (J)
x	specific exergy (J/kg)
x_f	specific flow exergy (J/kg)
z	elevation (m)
η	energy efficiency (%)
η_s	isentropic efficiency (%)
η_{th}	Carnot efficiency (%)
η_R	energy efficiency of reactor core (%)
η_{plant}	overall energy efficiency of plant (%)
ψ	exergy efficiency (%)
ψ_R	exergy efficiency of reactor core (%)
ψ_{plant}	overall exergy efficiency of plant (%)

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