ENERGY AND EXERGY ANALYSES OF A NUCLEAR STEAM POWER PLANT

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ABSTRACT

Thermodynamic analyses of a nuclear steam power plant are presented. The analyses, which are based on both the first and second laws of thermodynamics, were performed using a process-simulation computer code which had previously been enhanced by the authors for energy and exergy analyses. The results yield some interesting new insights into the performance of nuclear steam power plants, and could prove useful to the designers of nuclear-related, and other, technologies. The additional insights into process performance gained when exergy analysis is considered in addition to energy analysis are discussed.

1. INTRODUCTION

In this study, energy and exergy analyses are used to assess the performance of a nuclear steam power plant. It is hoped that this examination, primarily because it includes exergy analysis, will yield new insights into the performance of nuclear steam power plants.

A complete analysis of the thermodynamic performance of a process generally requires the use of both energy and exergy analyses. Exergy analysis, because it accounts for losses due to internal consumptions and external wastes, is regarded by many to give more meaningful and illuminating results than energy analysis (1-6).

For nuclear technologies, exergy analysis can be particularly effective in identifying ways to improve the performance of existing operations, and designing and optimizing future plants. When cogeneration systems for power and heat are considered, exergy analysis should be used because, unlike energy analysis, exergy analysis weights heat and work according to their usefulnesses (by assessing the "work potential equivalent" of the heat).

2. BACKGROUND

The particular plant considered in the present analysis is the Pickering Nuclear Generating Station. The station uses the CANDU (Canadian Deuterium Uranium) reactor concept. The process flowsheet for the plant is shown in Fig. 1. The letters identifying the streams in Fig. 1 are explained in Table 1. The main process data, drawn from Refs. 7 and 8, are summarized in Table 2. For convenience and to bring out important points in later discussions, the plant is separated into four sections.

2.1 The Steam Generation Section

In the Steam Generation section (Devices A, B, C and D in Fig. 1), heat is produced in a reactor and transferred via the Primary Heat Transport (PHT) loop to the boilers, where it is used to generate steam from preheated water.

In each unit of the Pickering Generating Station, natural uranium, in the presence of a moderator, is fissioned to produce heat. 7724 kg/s of pressurized heavy water (D_2O) flows in the PHT loop, which transfers heat from the reactor to the boilers. The D_2O is heated from 249°C and 9.54 MPa to 293°C and 8.82 MPa in the nuclear reactor. 815 kg/s of steam (H_2O) at 4.2 MPa and 251°C is produced in the boiler, and is transported through the Secondary Heat Transport loop. Spent fuel is removed from the reactor, and heat generated in the moderator is rejected.

2.2 The Power Production Section

Basically, in the Power Production section (Devices E, F, G, H and I in Fig. 1), the steam produced in the Steam Generation Section is passed through a series of turbine generators. The voltage of the electricity is adjusted in a transformer. Extraction steam from the turbines is used in the Preheating Section.

Each unit of the Pickering Generating Station has a 1800-rpm, tandem-compound, impulse-reaction turbine generator containing one double-flow high-pressure cylinder, and three double-flow low-pressure cylinders. The steam exhausted from the the high-pressure cylinder passes through a moisture separator, and a closed reheater (which uses steam from the boiler as the heat source).

2.3 The Condensation Section

In the Condensation section (Device J in Fig. 1), cooling water condenses the steam exhausted from the turbines. The flow rate of the cooling water is adjusted so that a temperature rise of 11°C in the cooling water is achieved across the condenser.

2.4 The Preheating Section

In the Preheating section (Devices K, L, M, N, O and P in Fig. 1), the temperature and pressure of the condensed steam are increased in a series of pumps and heat exchangers.

3. THEORY

Three fundamental principles are involved in energy and exergy analyses:

- Conservation of mass.
- Conservation of energy (the first law of thermodynamics).
- Non-conservation of entropy (the second law of thermodynamics). The entropy of an isolated system remains constant (when reversible processes occur in it), or increases (when irreversible processes occur in it).

For a control volume (Fig. 2) undergoing a steady-state process, with material, heat and work interactions occuring at discrete points on its surface, the expressions for the three principles respectively are

$$0 = \Sigma \dot{m}_j \tag{1}$$

$$0 = \Sigma (e + Pv)_j \dot{m}_j + \Sigma \dot{Q}_j + \Sigma \dot{W}_j \tag{2}$$

$$-\dot{\sigma} = \Sigma s_j \dot{m}_j + \Sigma \dot{Q}_j / T_j \tag{3}$$

where the summations are over all streams interacting with the control volume, and where

$\dot{m}$: mass flow rate
e : energy per unit mass crossing the control surface (including internal kinetic and potential energy)
P : pressure
v : specific volume
s : entropy per unit mass
T : temperature
$\dot{Q}$: heat flow rate
$\dot{W}$: work rate
$\dot{\sigma}$: rate at which entropy is created in the control volume.

Flows into the control volume are defined as positive, and out of the control volume as negative.

Exergy is defined as the maximum amount of work which can be produced by a stream of matter, heat or work as it comes to

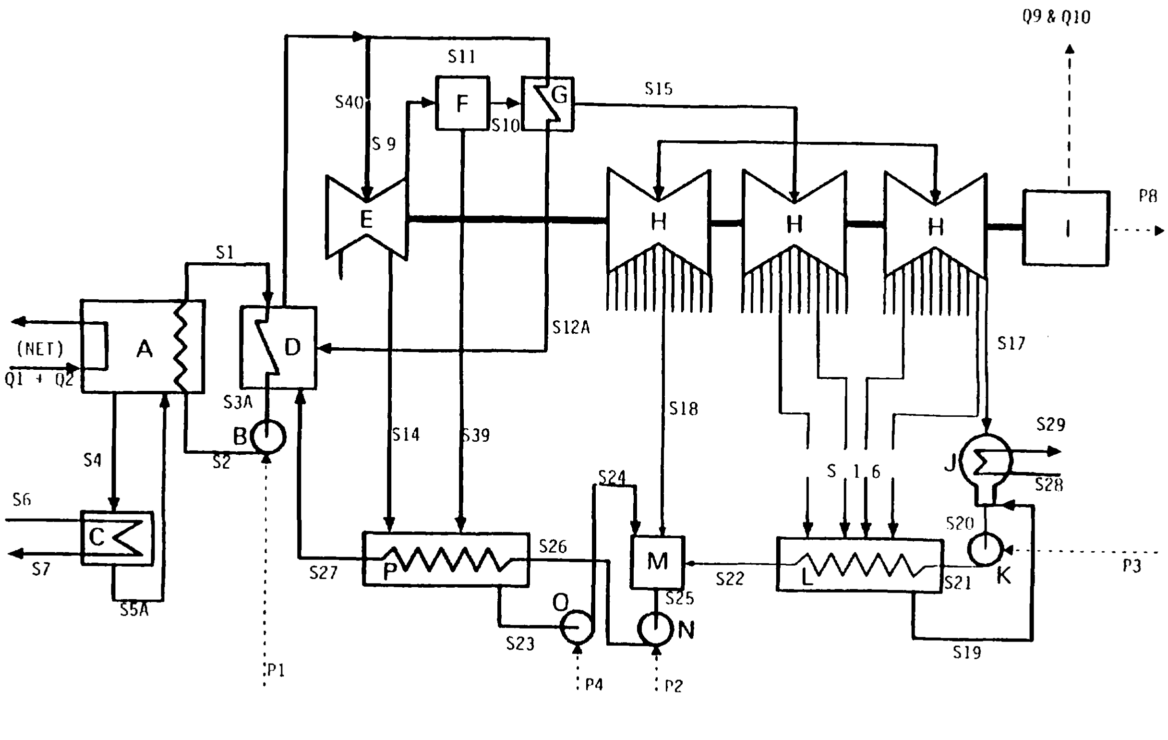

Fig. 1. The Pickering Nuclear Generating Station. A: nuclear reactor, B: heavy water pump, C: moderator cooler, D: steam generator, E: high-pressure turbine, F: moisture separator, G: closed reheater, H: low-pressure turbines, I: generator and transformer, J: condenser, K: hot well pump, L: closed heat exchangers, M: open deaerating heat exchanger, N: boiler feed pump, O: pump, P: closed heat exchangers. Flows of cooling water into and out of Devices C and J, and the flow of uranium into and out of Device A, are indicated.

TABLE 1 STREAM DATA

Stream*	Flowrate** (kg/s)	Temperature (°C)	Pressure (N/m^2)	Vapour Fraction	Energy (MW)	Exergy (MW)
S5A	1000.00	43.00	$1.01x10^5$	0.0	117.02	5.34
S6	1956.83	15.00	$1.01x10^5$	0.0	0	0
S3A	7724.00	249.00	$8.32x10^6$	0.0	7861.16	2188.64
S12A	61.00	254.00	$4.25x10^5$	0.0	63.57	17.78
S8A	814.00	254.00	$4.25x10^6$	1.0	2226.90	826.32
S28	24,073	15.00	$1.01x10^5$	0.0	0	0
S35	120.85	15.00	$1.01x10^5$	0.0	0	0
S37	119.65	15.00	$1.01x10^5$	0.0	0	0
S1	7724.00	291.93	$8.82x10^6$	0.0	9548.21	2984.23
S4	1000.00	64.52	$1.01x10^5$	0.0	207.02	15.99
S7	1956.83	26.00	$1.01x10^5$	0.0	90.00	1.67
S2	7724.00	249.38	$9.60x10^6$	0.0	7875.44	2201.64
S40	753.00	254.00	$4.25x10^6$	1.0	2060.02	797.70
S11	61.00	254.00	$4.25x10^6$	1.0	166.88	64.62
S14	55.00	176.66	$9.28x10^6$	0.90	138.7	44.6
S9	698.00	151.83	$5.00x10^5$	0.88	1705.5	500.4
S10	603.00	160.00	$5.00x10^5$	1.0	1629.83	476.54
S39	95.00	160.00	$6.18x10^5$	0.03	75.7	23.7
S15	603.00	237.97	$4.50x10^5$	1.0	1733.17	508.35
S18	22.00	186.05	$2.55x10^5$	1.0	61.06	16.03
S16	83.00	60.81	$2.07x10^4$	0.95	204.0	28.1
S17	498.00	23.32	$2.86x10^3$	0.90	1125.1	44.4
S20	581.00	23.32	$2.86x10^3$	0.0	20.15	0.17
S29	24,073.	26.00	$1.01x10^5$	0.0	1107.20	20.61
S21	581.00	23.40	$1.48x10^6$	0.0	211.55	1.13
S19	83.00	60.81	$2.07x10^4$	0.0	15.89	1.13
S22	581.00	100.20	$1.40x10^5$	0.0	207.88	26.50
S25	753.00	123.69	$1.40x10^5$	0.0	344.21	53.16
S26	753.00	124.20	$5.40x10^5$	0.0	347.93	56.53
S27	753.00	163.94	$5.35x10^5$	0.0	476.02	96.07
S23	150.00	134.00	$3.04x10^5$	0.0	75.04	12.29
S24	150.00	134.17	$1.48x10^5$	0.0	75.27	12.50
S36	120.85	26.00	$1.01x10^5$	0.0	5.56	0.10
S38	119.65	26.00	$1.01x10^5$	0.0	5.50	0.10
Q1					1673.	1673.
Q2					90.	90.
Q9					0.56	0.0
Q10					0.55	0.0
P1					14.28	14.28
P2					3.73	3.73
P3					1.00	1.00
P4					0.23	0.23
P12					555.84	555.84
P7					550.28	550.28
P8					554.78	544.78

* Stream identifiers beginning with S are material, Q are heat and P are power.

** All streams are H_2O, except S1, S2, S3A, S4 and S5A which are D_2O.

equilibrium with an environment. The environment is defined by specifying the temperature T_o, pressure P_o and chemical composition. The concept of the environment, and recommendations on selecting an appropriate reference environment for a specific problem, are discussed elsewhere (1-6).

Equations 2 and 3 can be used to derive the following steady-state "exergy balance:"

$$\Sigma \dot{Ex}_m + \Sigma \dot{Ex}_h + \Sigma \dot{Ex}_w = \dot{Ex}_c \tag{4}$$

where the summations are over all streams.

The exergy consumption rate in the control volume is given by

$$\dot{Ex}_c = T_o \dot{\sigma} \tag{5}$$

The exergy flow rates of work, heat and material streams respectively are:

$$\dot{Ex}_w = \dot{W} \tag{6}$$

$$\dot{Ex}_h = \dot{Q} \tag{7}$$

$$\dot{Ex}_m = (\dot{H}-\dot{H}_o) - T_o(\dot{S}-\dot{S}_o) + \Sigma \dot{N}_i(\mu_{io}-\mu_i^o) \tag{8}$$

TABLE 2 MAIN PROCESS DATA FOR ONE STEAM UNIT

Steam Generation Section	
Nuclear Reactor and PHT Loop	
Heavy Water mass flow rate	724 kg/s
D_2O temperature at reactor inlet	249°C
D_2O temperature at reactor outlet	293°C
System pressure at reactor outlet header	8.8 MPa
Boilers	
Feed Water temperature	171°C
Total evaporation rate	815 kg/s
Steam temperature	251°C
Steam pressure	4.2 MPa
Power Production Section	
Turbine	
Condenser pressure	5 kPa
Generator	
Gross power output	542 MW
Net power output	515 MW
Condensation Section	
Cooling water flow rate	23.7 m^3/s
Cooling water temperature rise	11°C

where

τ : dimensionless exergetic temperature $= (1 - T_0/T)$
$\dot{H}$ $= \dot{m}(e+Pv)$
$\dot{S}$ $= \dot{m}\, s$
$\dot{H}_0$ $= \dot{H}$ (evaluated at T_0 and P_0)
$\dot{S}_0$ $= \dot{S}$ (evaluated at T_0 and P_0)
$\dot{N}_i$: molar flow rate of component i
μ_{io} : chemical potential of component i at T_0 and P_0
μ_i^{o} : chemical potential of component i in the environment

and other symbols are as defined previously.

4. ANALYSIS APPROACH

The plant was modelled and simulated using Aspen Plus, a state-of-the-art process-simulation computer code. Then, energy and exergy analyses were performed using a version of Aspen Plus which had previously been enhanced by the authors for complete and unified energy-exergy analysis. The development of the enhanced version of Aspen Plus is described in Refs. 9-11. The enhanced code has been applied to coal-fired steam power plants (12), nuclear steam power plants (11-13), and production processes for hydrogen (9-11,14-18), methanol (9,11,19) and ammonia (9).

4.1 Assumptions

Several assumptions were used to simplify modelling:

- The turbines were assumed to have isentropic efficiencies of 80% and mechanical efficiencies of 95%.
- Heat losses from all components were neglected, except for the generators and transformers, which were each assumed to be 99% efficient.
- Heat losses from the generator and transformer are taken to occur at the temperature of the environment; consequently, zero exergy is associated with the heat.
- D_2O was modelled as H_2O.
- The net heat delivered from the entering fuel and exiting spent fuel was considered as the main energy input to the plant.
- The potential temperature of the heat produced in the nuclear fuel was assumed to be high enough that the quantities of energy and exergy of the heat could be considered equal.
- The supply and removal of fuel was assumed to be a steady-state process.

4.2 The Selected Environment Model

The environment model used is as follows: T_0 = 15°C and P_0 = 1 atm. An environment temperature of 15°C was used because that is the approximate mean temperature of the lake cooling water. An environment pressure of 1 atm was used because it is representitive of the mean atmospheric pressure in which the plant operates. The exergy analysis results are independent of the choice of the chemical composition of the environment.

5. RESULTS

5.1 Simulation Results

The simulation results (e.g., flows, temperatures, pressures, etc.) are summarized in Table 1 for the main process streams identified in Fig. 1. Detailed results are given in Ref. 12.

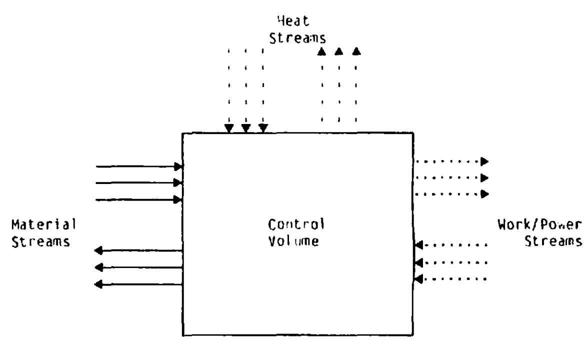

Fig. 2. A control volume.

5.2 Results of Energy and Exergy Analyses

Energy and exergy values for the streams identified in Fig. 1 are given in Table 1. Exergy-consumption values for the devices are listed, according to flowsheet sections, in Table 3. These data are presented diagramatically in energy and exergy flowsheets (Fig. 3). The net energy and exergy flows and exergy consumptions are shown. The magnitude of the energy (or exergy) of a stream is indicated by the width of the flowsheet line representing the stream.

The data are summarized in an informative manner in the overall energy and exergy balances shown in Fig. 4. Inputs and outputs (as well as internal consumptions for exergy) are represented. Note that cooling water inputs, because they contain zero energy and exergy, are not shown on the left sides of the pie charts; and that the reactor is taken to be only the fission reactor itself, not the total PHT loop.

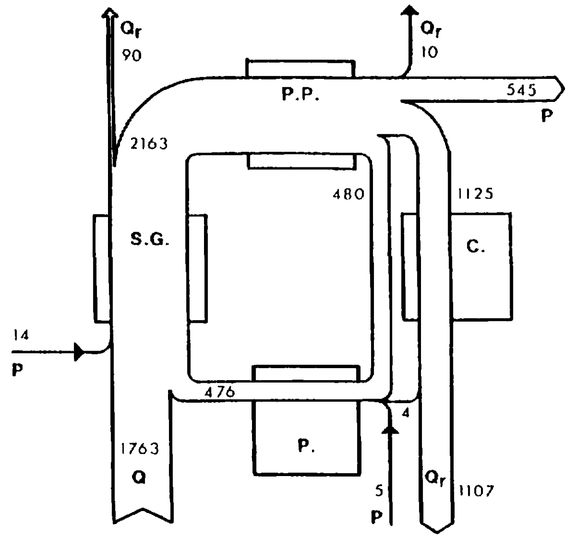

Fig. 3a. Simplified flow diagram indicating net energy flows in MW. Sections of plant shown are Steam Generation (S.G.), Power Production (P.P.), Condensation (C.), and Preheating (P.). Streams shown are power (P), heat input (Q) and heat rejected (Q_r).

TABLE 3 BREAKDOWN BY DEVICE OF EXERGY CONSUMPTIONS (IN MW)

Steam Generation Section		
Reactor	969.7	
D_2O-H_2O Heat Exchanger	47.4	
D_2O Pump	1.1	
Moderator Cooler	9.0	
		1027.2
Power Production Section		
H.P. Turbine	36.9	
L.P. Turbines	79.7	
Generator	5.5	
Transformer	5.5	
Steam Separator	0.2	
Closed Steam Reheater	15.0	
		142.8
Condensation Section		
Condenser	24.7	
		24.7
Preheat Section		
Low-Pressure Heat Exchangers	1.6	
Deaerating Heat Exchanger	1.8	
High-Pressure Heat Exchangers	16.4	
Hot Well Pumps	0.04	
Heater Condensate Pumps	0.03	
Boiler Feed Pumps	0.43	
		20.8
Total		1215.5

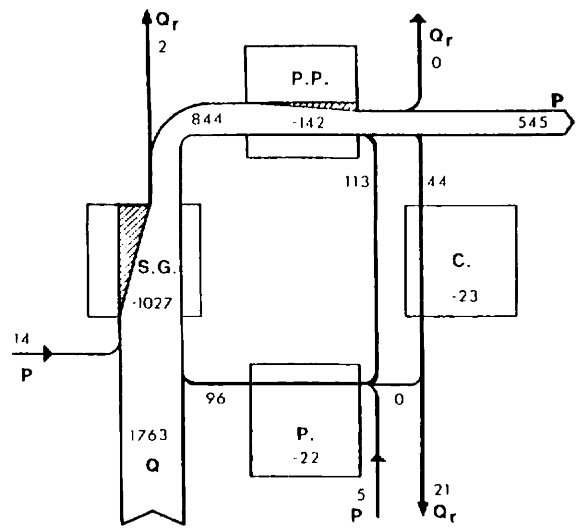

Fig. 3b. Simplified flow diagram indicating net exergy flows and consumptions in MW. Exergy consumptions in devices are given by negative numbers, and are illustrated as shaded regions. Other details as in Fig. 3a.

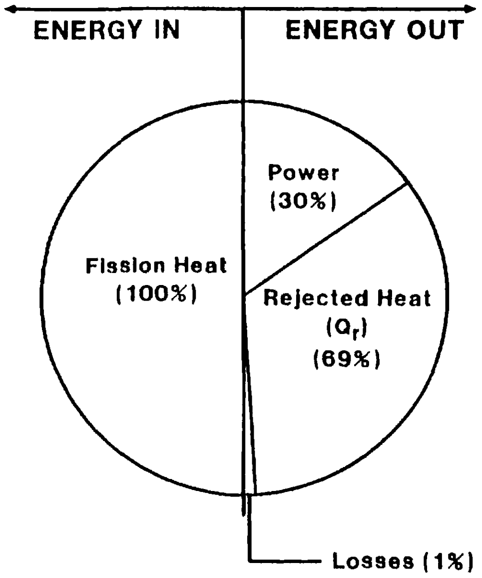

Fig. 4a. Overall plant energy balance. The left half represents energy inputs and the right half energy outputs.

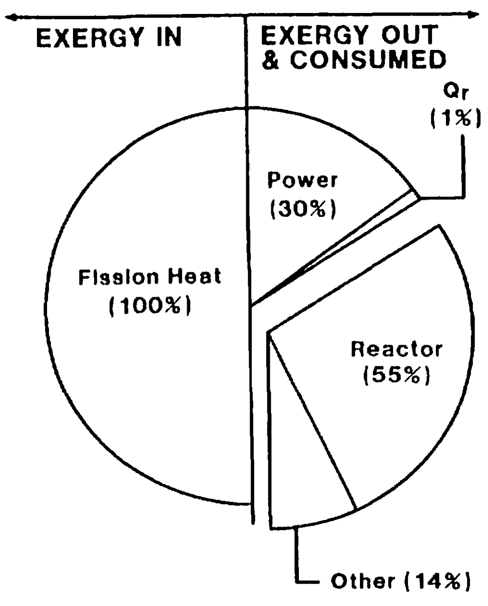

Fig. 4b. Overall plant exergy balance. The left half represents exergy inputs and the right half exergy outputs and consumptions (exploded section).

6. DISCUSSION

6.1 Overall Process Efficiencies

Energy efficiency, η, and exergy efficiency, ε, values were evaluated for the overall plant:

$$\eta = \frac{\dot{E}_{product} - \dot{E}_{pumps}}{\dot{E}_{heat}} = \frac{545 - 19}{1763}$$

$$= 30\%$$

and

$$\varepsilon = \frac{\dot{Ex}_{product} - \dot{Ex}_{pumps}}{\dot{Ex}_{heat}} = \frac{545 - 19}{1763}$$

$$= 30\%$$

where $\dot{E}$ and $\dot{Ex}$ denote respectively flows of energy and exergy. The energy and exergy efficiencies are identical here because it was assumed in the analysis that the specific energy and specific exergy of uranium are equal. The energy efficiency of 30% calculated here compares well with the value of 29.5% reported elsewhere for the same plant (7).

Although the overall energy and exergy efficiencies were found to be identical, there were many subprocesses within the station for which the energy and exergy efficiencies differed markedly. Therefore, the location of the principal losses were indicated to be in different subprocesses, depending on whether an energy or exergy analysis had been used. Generally, it was shown (see Fig. 4) that the main losses occur due to internal consumptions (as exergy analysis indicates), not due to external emissions (as energy analysis indicates).

6.2 Examination of the Steam Generation Section

Substantial exergy consumptions occur in the Steam Generation section. Exergy consumptions in the nuclear reactor and the other devices in the PHT loop are responsible for

$$[1027 \;/\; (1763 - (545 - 19))] \; [100\%]$$

$$= 83\%$$

of those in the plant.

The energy and exergy efficiencies were found to be:

$$\eta = \frac{1780 - 487}{1368} = 95\%$$

and

$$\varepsilon = \frac{838 - 132}{1427} = 49\%$$

for the Steam Generation section. The Steam Generation section appears significantly more efficient on an energy basis, than it does on an exergy basis. Physically, this discrepancy implies that although 95% of the input energy is transferred to the preheated water, the energy is degraded as it is transferred. Energy analysis neglects such losses, whereas exergy analysis accounts for them.

Of the 1027 MW of exergy consumed in the PHT loop, 47 MW was consumed in the boiler, 9 MW in the moderator cooler, 1 MW in the heavy-water pump, and 970 MW in the reactor. The exergy consumptions in the reactor can be broken down further by considering the separate subprocesses occuring within it (Fig. 5):

- Heating of the moderator.
- Heating of the fuel pellets (to their maximum temperature of approximately 2000 C).
- Transferring the heat within the fuel pellets to the surface of the pellets (where the temperature is approximately 400 C).
- Transferring the heat from the surface of the fuel pellets to the cladding surface (at 304 C).
- Transferring the heat from the cladding surface to the preheated boiler feedwater to produce steam.

For convenience, it was assumed that all the heat responsible for heating the moderator was produced in the moderator. Detailed analyses by Ontario Hydro of heat losses indicate that of the 90 MW lost to the moderator, only 82 MW is produced in it. Of the remaining 8 MW which ends up in the moderator, 2.6 MW is lost from the fuel channel to the moderator, and 6.1 MW is produced in other reactor components and then transferred to the moderator. The breakdown of the devices in which the 6.1 MW is produced is as follows: 1.1 MW in the shield, 0.1 MW in the dump tank, 2.4 MW in the calandria and 2.5 MW in the calandria tubes.

The step in which heat is generated by fissioning nuclear fuel (also shown for completeness in Fig. 5) is taken to be outside the boundary of the nuclear reactor considered in this study. (It was earlier assumed that the net heat delivered by the nuclear fuel is the main energy input to the nuclear station.) The energy and exergy efficiencies calculated could be significantly different if this step were considered. In this case, the energy and exergy associated with the fresh and spent nuclear fuel would be required. The question of what is the exergy of uranium is not yet resolved (6,20). Most researchers contend that the exergy of uranium is the same as its energy. Some contend that it depends on the technology being considered.

Since D_2O was modelled as H_2O, a species with no chemical exergy because it exists as a condensed phase in the environment, the chemical exergy of D_2O was neglected. A complete exergy analysis, however, should account for the chemical exergy of D_2O-containing streams. The chemical exergy of D_2O is discussed in the appendix. Neglecting the chemical exergy of D_2O does not significantly affect the exergy analysis

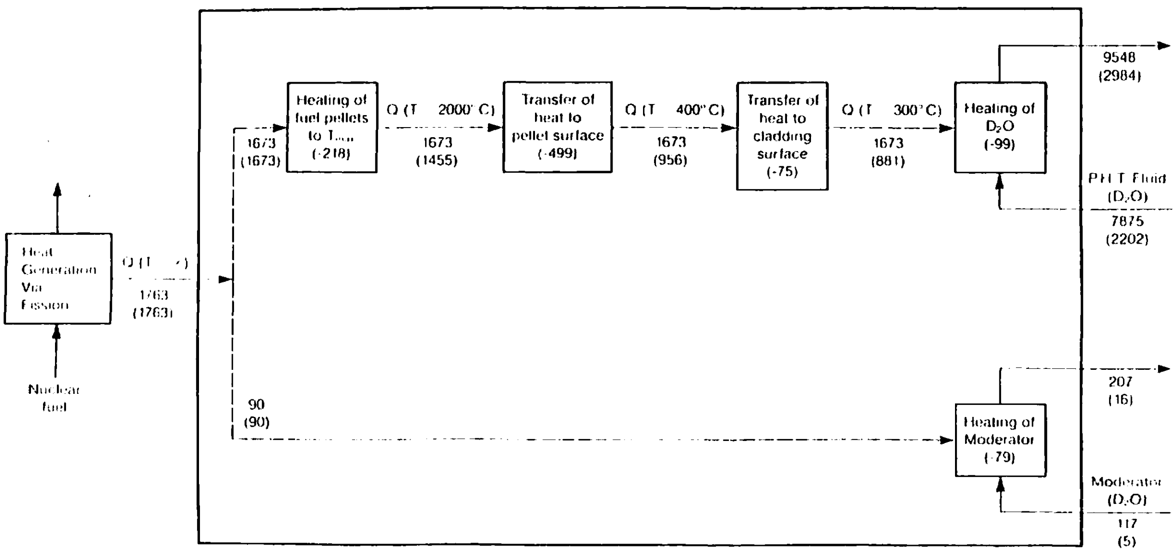

Fig. 5. Breakdown of the inefficiencies by process in a nuclear reactor. Material flows are represented by solid lines, and heat flows by dashed lines. The heavy solid line encloses the part of the nuclear reactor considered in the present analysis. The approximate temperatures of heat streams are indicated. Exergy flow rates (in parentheses) and energy flow rates are indicated for streams, and exergy consumptions (negative values in parentheses) for processes. All values are in MW.

results because the D_2O is contained in the closed PHT loop of the Steam Generation Section. Since D_2O is used only as a medium to transfer thermal energy, it is only the physical exergy of D_2O that is of interest. If, on the other hand, a heavy-water distillation plant was being considered, the chemical exergy would be significant, because in that case D_2O would be the principal product.

6.3 Examination of the Condensation Section

Energy analysis indicates that almost all the losses are associated with the heat rejected by the condensers (see Fig. 4). Exergy analyses indicate that the condensers are not responsible for large losses. This discrepancy arises because heat is rejected by the condensers at temperatures very near that of the environment.

In general, the condensers are devices in which:

- a large quantity of energy enters (1125 MW), of which close to 100% is rejected, and
- a small quantity of exergy enters (44 MW), of which approximately 50% is rejected and 50% is internally consumed.

The characteristics of condensers can be seen more clearly by evaluating the "net station condenser heat (energy) rejection rate,"

$$R_{energy} = \frac{\text{heat rejected by condenser}}{\text{net power produced by station}} \tag{9}$$

and comparing it to an analogous quantity, the "net station condenser exergy rejection rate,"

$$R_{exergy} = \frac{\text{exergy rejected by condenser}}{\text{net exergy produced by stn.}} \tag{10}$$

For the nuclear steam power plant:

$$R_{energy} = 1107 \text{ MW} / (545 - 19) \text{ MW} = 2.10$$

and

$$R_{exergy} = 21 \text{ MW} / (545 - 19) \text{ MW} = 0.0399$$

The R values indicate that the exergy rejected by the condensers is less than 4% of the net exergy produced, while the energy rejected is approximately 200% of the net energy produced.

6.4 Examination of Other Sections

In the Power Production and Preheating Sections, energy losses were found to be very small (less than 10 MW total), and exergy losses were found to be moderately small (approximately 150 MW in the Power Production Section and 25 MW in the Preheating Section). The exergy losses are almost completely associated with internal consumptions.

7. CONCLUSIONS

Both energy and exergy analyses, because they provide different information about process performance, are useful tools for examining the performance of electrical generation processes. Tasks, such as design, optimization and synthesis of processes, as well as other endeavours involving decision making, can likely be better performed if the results of an exergy analysis, in addition to those of an energy analysis, are considered. For instance, other processes for utilizing nuclear energy (Ref. 21 discusses some possibilities) may be better analyzed if both energy and exergy analyses are performed.

In particular, it was shown for nuclear steam power plants that the greatest potential for improving efficiency is in the nuclear reactors, and that the heat rejected by the condensers, which is substantial in quantity but low in quality (i.e., at a temperature near to that of the environment), is for the most part not very desirable. Exergy analysis brought out some points that energy analysis did not. Also, for results that were brought out by both analysis techniques, the results were illustrated in a more intuitive way using exergy analysis than energy analysis. In the development of future nuclear technologies and cogeneration systems, exergy analysis should be applied.

ACKNOWLEDGEMENTS

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NOMENCLATURE

$\dot{E}$ energy rate
e specific energy
$\dot{E}x$ exergy rate
ex specific exergy
$\dot{H}$ enthalpy rate
$\dot{m}$ mass flow rate
$\dot{N}$ mole flow rate
P pressure
R universal gas constant
R_{energy} net station condenser energy (heat) rejection rate
R_{exergy} net station condenser exergy rejection rate
$\dot{Q}$ heat rate
$\dot{S}$ entropy rate
s specific entropy
T temperature
v specific volume
$\dot{W}$ work rate
x concentration of D_2O

ε exergy (second-law) efficiency
μ chemical potential
η energy (first-law) efficiency
$\dot{\sigma}$ entropy production rate

Subscripts

c consumption
h heat
i ith constituent
j jth stream
m material
o property of the environment (for T, P and x), or properties evaluated at T_o and P_o
w work

Superscripts

ch chemical
o environment parameters

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APPENDIX
ON THE CHEMICAL EXERGY OF HEAVY WATER

D_2O has chemical exergy due to its purity with respect to D_2O found in the environment. The chemical exergy of pure D_2O is the minimum amount of work required to produce a unit of D_2O from the environment.

Using equations for ideal solutions (22), the specific chemical exergy of D_2O can be evaluated at T_0 as follows:

$$ex^{ch} = R\ T_o\ [x_o \ln (x_o/x^o) + (1-x_o) \ln ((1-x_o)/(1-x^o))] \quad (11)$$

where R is the universal gas constant (8.314 J/mol K), T_0 is the temperature of the environment, x_0 the mole fraction of D_2O in a stream of D_2O at T_0, and x^o the mole fraction of D_2O in the environment.

By noting that reactor-grade D_2O is 99.75% pure and that the concentration of D_2O in environmental water is 1 mole D_2O to 7000 moles H_2O (23), the specific chemical exergy of reactor grade D_2O at 298 K can be evaluated:

$$\begin{aligned} ex^{ch} &= (8.314 \text{ J/mol K})\ (298 \text{ K}) \\ &\quad [.9975 \ln (.9975/.000143) \\ &\quad + (1-.9975) \ln ((1-.9975) \\ &\quad /(1-.000143))] \\ &= 21{,}835 \text{ J/mol} \end{aligned}$$