NATIONAL EXAMINATIONS

May 2011

07-MEC-B3 ENERGY CONVERSION AND POWER GENERATION

Three hours duration

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Notes to Candidates

1. This is a Closed Book examination.

2. Exam consists of two Sections, each has three (3) questions. Section A is Calculative and Section B is Descriptive.

3. Do two (2) questions (including all parts of each question) from Section A (Calculative) and two (2) questions from Section B (Descriptive) Note that Question 2 is on two pages.

4. Four questions constitute a complete paper. (Total 60 marks).

5. All questions are of equal value. (Each 15 marks).

6. If doubt exists as to the interpretation of any question, the candidate is urged to submit, with the answer paper, a clear statement of any assumptions made.

7. Candidates may use one of the approved Casio or Sharp calculators.

8. Reference data for particular questions are given on pages 8 to 11. These pages are to be returned with the Answer Booklet.

9. Reference formulae and constants are given on pages 12 to 15.

10. Steam Tables from "Thermodynamics and Heat Power" are provided.
SECTION A CALCULATIVE SECTION

QUESTION 1 COAL FIRED AND HYDRO POWER PLANT EFFICIENCIES

PART I NANTICOKE EFFICIENCY

Refer to Examination Paper Attachments Page 8 Nanticoke Generating Station.

Using the data for Nanticoke do the following:

(a) Sketch a flow diagram of the system and identify the key points, at which the enthalpies will be determined, by number. Sketch a T-s diagram showing the components or processes and identify the same key points by number. (2)

(b) Calculate the enthalpy of the water entering the boiler and the superheated steam leaving the boiler. (2)

(c) Calculate the enthalpy of the reheated steam entering and leaving the boiler. (2)

(d) Calculate the thermal efficiency of the boiler defined as heat absorbed by the steam over heat input by the fuel. (1)

(e) Calculate the cycle efficiency of the steam system defined as electrical output of the generator over heat absorbed by the steam. (1)

(f) Calculate the overall efficiency of the plant defined as electrical output of the generator over heat input by the fuel. (1)

(g) Explain why the efficiencies in (c) and (d) are different. (1)

(10 marks)

Question continued on next page.
PART II  MACTAQUAC EFFICIENCY

Hydro turbines of the Kaplan type are installed at Mactaquac on the Saint John River. In order to determine the efficiency of the Mactaquac turbines the following hypothetical measurements are considered:

- **Turbine-Generator speed**: 112.5 rev/min
- **Generator electrical output**: 110 MW
- **Water flow rate**: 354 m$^3$/s
- **Inlet pipe diameter**: 6.4 m
- **Outlet pipe diameter**: 7.0 m
- **Inlet water pressure**: 226 kPa gauge
- **Outlet water pressure**: -4.5 m H$_2$O

The elevation of the outlet pressure measuring point is 5.0 m below that of the inlet pressure measuring point.

Determine the efficiency of the turbine.  

(5 marks)  

[15 marks]
QUESTION 2 COMBINED CYCLE PLANT

Refer to the Examination Paper Attachments Page 9 Combined Cycle Plant

In a combined cycle power plant based on a Brayton and a Rankine Cycle, as shown in the attached sketch on Page 9, the gas turbine exhaust heat is used to generate steam. The gas turbine cycle is an open cycle while the steam turbine cycle is a closed cycle with one stage of feedwater heating operating on the direct contact principle with steam bled from the turbine. The gas cycle has an air compressor, a combustion chamber, a gas turbine and a heat recovery steam generator. The steam cycle has, besides the heat recovery steam generator, a steam turbine, a steam condenser, a condensate pump, a direct contact heat exchanger and a feedwater pump. The combined cycle is illustrated on Page 9 with appropriate conditions given at various points.

Assume a cold air standard cycle (constant specific heats with \( k = 1.4 \)). For a gas mass flow of 100 kg/s calculate the following:

(a) Rate of heat input to combustion chamber. \( (1) \)
(b) Mass flow rate of main steam. \( (1) \)
(c) Mass flow rate of bled steam. \( (1) \)
(d) Power (net) generated by gas turbine. \( (2) \)
(e) Power generated by steam turbine. \( (2) \)
(f) Efficiency of air compressor. \( (2) \)
(g) Efficiency of gas turbine. \( (2) \)
(h) Efficiency (internal) of steam turbine. \( (2) \)
(i) Work done by pumps \( (1) \)
(j) Overall efficiency of plant assuming that the power for the condensate and feedwater pumps is taken from the steam turbine output. \( (1) \)

[ 15 marks ]
QUESTION 3  FEEDWATER HEATERS AND CONDENSERS

PART I  BELLE DUNE FEEDWATER HEATER

In a boiler plant the feedwater entering the boiler is progressively preheated in a series of feedwater heaters which draw heating steam from the steam turbine. At Belledune Generating Station in the last stage of feedwater heating the feedwater temperature is increased from 230°C to 280°C while the pressure remains constant at 20 MPa. The heating steam enters at 400°C (superheated), is condensed and leaves as water at 240°C (subcooled) while the pressure remains constant at 5 MPa. If the feedwater flow is 350 kg/s calculate the required steam flow. Use Steam Tables. Note that a sketch to properly identify the key points around the heater is required.

( 5 marks )

PART II  CONDENSER PERFORMANCE

Refer to the Examination Paper Attachments Page 10 Koeborg Condenser and Page 11 Temperature Profiles. Note that 1 bar = 0.1 MPa.

Consider the condenser to be operating under the given conditions. Sketch on the given axes the design temperature profile, with specified temperatures for both cooling water and steam, along the condenser tubes (from inlet to outlet). Show clearly the change in cooling water temperature ΔT and the difference between the average cooling water temperature and the condensing steam temperature θ.

No detailed calculations are required and temperatures should be rounded to nearest 1°C. The estimates should be based on average temperature differences (not log mean temperature differences) and in each case the new values for ΔT and θ should be stated.

If the conditions are changed as indicated below, sketch on the given axes the anticipated temperature profiles with numerical values for both cooling water and steam across the condenser for each of the following conditions:

(a) Cooling water inlet temperature increased to 18°C

(b) Turbine load reduced to one quarter of its original value.

(c) Cooling water flow reduced to one half of its original value which also results in the overall heat transfer coefficient being reduced to 70% of its original value

(d) Overall heat transfer coefficient reduced by 20% due to fouling of tubes.

( 10 marks )
[ 15 marks ]
SECTION B DESCRIPTIVE SECTION

QUESTION 4 COAL CHARACTERISTICS AND ANALYSIS

(a) Compare and state the characteristics (constituents and heating value) of coals of different grade or rank. Indicate how these characteristics change according to the degree of metamorphism.

(4)

(b) With regard to coal state what constitutes an Proximate Analysis and what constitutes an Ultimate Analysis. Clarify the usefulness of each.

(4)

(c) State what is meant by heating value and clarify the difference between higher heating value and lower heating value. State which is commonly used.

(3)

(d) Explain what characteristics in a coal are required for pulverised fuel firing and why the coal needs to be pulverised before firing. Clarify how the fineness of pulverised coal is measured.

(4)

[ 15 marks ]

QUESTION 5 ENERGY STORAGE

(a) Sketch a typical daily demand curve (load versus time) for a typical electric power system with the time of day clearly indicated on the horizontal axis. Explain why the curve has the shape indicated and state what factors affect the shape.

(5)

(b) Explain what implications a significant difference between the maximum and minimum demand can have on the generation of electric power by thermal plants (coal, oil or nuclear), and on the operation and capital investment of these power plants.

(5)

(c) Explain the role of a pumped hydro storage system in alleviating the problems identified in (b) above. Sketch a revised daily demand and production curve for the system combining the power inputs of both thermal and pumped hydro plants

(5)

[15 marks ]
QUESTION 6  WIND TURBINES

(a) Explain the basic principles of wind energy and show, in a suitable sketch, the changes in air pressure and velocity as the wind passes through the turbine blades.

(5)

(b) Explain why the ideal or theoretical efficiency (maximum power obtained from wind/total power in wind) of a wind turbine is no more than 59.3%. Explain also why the actual power produced by a wind turbine is only about three quarters of this value, that is, about 45%.

(5)

(c) Describe the operational limitations and possible environment effects (good and bad) of large scale use of wind energy.

(5)

[ 15 marks ]
### QUESTION 1  NANTICOKE GENERATING STATION

The data below is taken from the technical specifications for Nanticoke Generating Station:

<table>
<thead>
<tr>
<th><strong>Location</strong></th>
<th>On the north shore of Lake Erie in the City of Nanticoke, Ontario, 13 kilometers east of Port Dover.</th>
</tr>
</thead>
</table>
| **Boiler**   | Babcock & Wilcox Canada Ltd.  
| Steam Generator Manufacturer          | Natural Circulation Radiant Boiler  
| Type                                    | 453.6 kg/s (3 600 000 lb/hr)  
| Design Steam Output                     | 16.9 MPa (2 450 lbf/in²)  
| Superheater outlet pressure             | 538°C (1000°F)  
| Superheater outlet temperature          | 4.0 MPa  
| Reheat steam pressure                   | 343°C (650°F)  
| Reheat inlet steam temperature          | 538°C (1000°F)  
| Reheat outlet steam temperature         | 47.9 kg/s (190 ton/hr)  
| Coal consumption at full load           | 30 240 kJ/kg (13 000 Btu/lb)  
| Coal calorific value                    | 5 per unit  
| Number of pulverizers                   | 17.5 MPa  
| Economiser inlet water pressure         | 252.5°C (487°F)  
| Economiser inlet water temperature      | 359.6°C (680°F)  
| Water temperature in steam drum         | |

**Turbine**

| **Manufacturer** | C.A. Parsons and Company Ltd.  
| Speed            | 3 600 rpm  
| **Generator**    | 500 000 kW  
| Rating           | |
**QUESTION 2  COMBINED CYCLE PLANT**

**SYSTEM DIAGRAM**

![Combined Cycle Plant Diagram]

**SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>Point</th>
<th>Pressure (MPa)</th>
<th>Temperature (°C)</th>
<th>Enthalpy (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>344</td>
<td></td>
</tr>
<tr>
<td>2S</td>
<td>1.2</td>
<td>422</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
<td>353</td>
<td></td>
</tr>
<tr>
<td>4S</td>
<td>0.1</td>
<td>418</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>159</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.005</td>
<td>33</td>
<td>136</td>
</tr>
<tr>
<td>7</td>
<td>0.4</td>
<td>33</td>
<td>136</td>
</tr>
<tr>
<td>8</td>
<td>0.4</td>
<td>144</td>
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<td>9</td>
<td>5.0</td>
<td>144</td>
<td>610</td>
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<tr>
<td>10</td>
<td>5.0</td>
<td>400</td>
<td>3195</td>
</tr>
<tr>
<td>11S</td>
<td>0.4</td>
<td>144</td>
<td>2634</td>
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<tr>
<td>11</td>
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<td>2719</td>
</tr>
<tr>
<td>12SS</td>
<td>0.005</td>
<td>33</td>
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<tr>
<td>12S</td>
<td>0.005</td>
<td>33</td>
<td>2025</td>
</tr>
<tr>
<td>12</td>
<td>0.005</td>
<td>33</td>
<td>2201</td>
</tr>
</tbody>
</table>

Note that s represents isentropic conditions.
QUESTION 3  KOEBERG CONDENZER

Steam flow rate
Water make-up flow rate
Cooling water flow rate
Cooling water inlet temperature
Cooling water outlet temperature
Cooling water density
Cooling water friction head loss
Mean steam velocity at tube bank
Cooling water velocity inside tubes
Number of tubes
Number of support plates
Tube material
Cooling surface area
Tube overall length
Tube effective length
Tube diameter (OD)
Tube wall thickness (normal tubes)
Tube wall thickness (impact tubes)
Tube configuration
Tube pitch across array
Tube pitch along array
Tube fixing method
Tube mass
Total volume under vacuum
Steam inlet pressure
Steam inlet temperature
Terminal temperature difference
Condenser hotwell capacity
Number of water boxes (inlet and outlet)
Water box internal lining
Condenser shell thickness
Tube plate thickness
Support plate thickness
Condenser length
Condenser width
Condenser mass without LP Heaters

NAME .................................................................

2996 t/h
9 t/h
141 000 t/h
13°C
24°C
1.025
4.7 m
92 m/s
2 m/s
76968
14 (per bundle)
titanium
57 426 m²
12.84 m
12.50 m
19 mm
0.5 mm
0.6 mm
diagonal array
26 mm
45 mm
expanding
132 t
7500 m³
0.043 bar abs
30°C
6°C
700 m³ (approx.)
12
neoprene
18 mm
25 mm
12 mm
43 m (approx.)
25 m (approx.)
1267 t
QUESTION 3  TEMPERATURE PROFILES

Show initial conditions as dotted lines on each diagram
Show new conditions for each case as solid lines
Give temperatures on axes
Show basic calculations and new values for $\Delta T$ and $\theta$ below each diagram

(a) Increase in cooling water temperature  
(b) Reduction in turbine load

(c) Reduction in cooling water flow  
(d) Reduction in heat transfer coefficient
### NOMENCLATURE FOR REFERENCE EQUATIONS (SI UNITS)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Flow area, Surface area</td>
<td>m²</td>
</tr>
<tr>
<td>c_p</td>
<td>Specific heat at constant pressure</td>
<td>J/kg°C</td>
</tr>
<tr>
<td>c_v</td>
<td>Specific heat at constant volume</td>
<td>J/kg°C</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
<td>m</td>
</tr>
<tr>
<td>E</td>
<td>Energy</td>
<td>J</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
<td>m/s²</td>
</tr>
<tr>
<td>h</td>
<td>Specific enthalpy</td>
<td>J/kg</td>
</tr>
<tr>
<td>k</td>
<td>Ratio of specific heats</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
<td>m</td>
</tr>
<tr>
<td>m</td>
<td>Fractional mass flow rate</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Mass flow rate</td>
<td>kg/s</td>
</tr>
<tr>
<td>p</td>
<td>Pressure</td>
<td>Pa(N/m²)</td>
</tr>
<tr>
<td>q</td>
<td>Heat transferred</td>
<td>J/kg</td>
</tr>
<tr>
<td>Q</td>
<td>Heat</td>
<td>J</td>
</tr>
<tr>
<td>R</td>
<td>Specific gas constant</td>
<td>J/kg K</td>
</tr>
<tr>
<td>s</td>
<td>Entropy</td>
<td>J/kg K</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>u</td>
<td>Specific internal energy</td>
<td>J/kg</td>
</tr>
<tr>
<td>v</td>
<td>Specific volume</td>
<td>m³/kg</td>
</tr>
<tr>
<td>V</td>
<td>Velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>w</td>
<td>Specific work</td>
<td>J/kg</td>
</tr>
<tr>
<td>W</td>
<td>Work</td>
<td>J</td>
</tr>
<tr>
<td>x</td>
<td>Length</td>
<td>m</td>
</tr>
<tr>
<td>z</td>
<td>Elevation</td>
<td>m</td>
</tr>
<tr>
<td>η</td>
<td>Efficiency</td>
<td></td>
</tr>
<tr>
<td>θ</td>
<td>Nozzle angle</td>
<td></td>
</tr>
<tr>
<td>μ</td>
<td>Dynamic viscosity</td>
<td>Ns/m²</td>
</tr>
<tr>
<td>ν</td>
<td>Kinematic viscosity</td>
<td>m²/s</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>T</td>
<td>Thrust</td>
<td>N</td>
</tr>
<tr>
<td>Ω</td>
<td>Heat transfer rate</td>
<td>J/s</td>
</tr>
</tbody>
</table>
GENERAL CONSTANTS

- Acceleration due to gravity: \( g = 9.81 \text{ m/s}^2 \)
- Atmospheric pressure: \( p_{\text{atm}} = 100 \text{ kPa} \)
- Density of water: \( \rho_{\text{water}} = 1000 \text{ kg/m}^3 \)

Specific heat of air: \( c_p = 1.005 \text{ kJ/kg°C} \)
Specific heat of air: \( c_v = 0.718 \text{ kJ/kg°C} \)
Specific heat of water: \( c_p = 4.19 \text{ kJ/kg°C} \)

THERMODYNAMICS REFERENCE EQUATIONS

Basic Thermodynamics

- **First Law:** \( dE = \delta Q - \delta W \)
- **Enthalpy:** \( h = u + pv \)
- **Continuity:** \( pVA = \text{constant} \)
- **Flow Work:** \( w = \Delta(pv) \)
- **Energy Equation:** \( zg + V^2/2 + u + pv + \Delta w + \Delta q = \text{constant} \)
- **Entropy:** \( \Delta s = \Sigma \delta q / T \) (reversible conditions)

Ideal Gas Relationships

- **Gas Law:** \( pv = RT \)
- **Specific Heat at Constant Pressure:** \( c_p = \Delta h / \Delta T \)
- **Specific Heat at Constant Volume:** \( c_v = \Delta u / \Delta T \)
- **Gas Constant:** \( R = c_p - c_v \)
- **Specific Heat Ratio:** \( k = c_p / c_v \)
- **Isentropic Relations:** \( p_1 / p_2 = (v_2 / v_1)^k = (T_1 / T_2)^{k/(k-1)} \)
FLUID MECHANICS REFERENCE EQUATIONS

Fluid Mechanics

Continuity Equation: \( \rho_1 V_1 A_1 = \rho_2 V_2 A_2 = M \)

Bernoulli's Equation: \( \rho_1 \Delta p + z_1 + V_1^2/2g = \rho_2 \Delta p + z_2 + V_2^2/2g \)

Momentum Equation: \( F = \rho_1 A_1 - \rho_2 A_2 - \rho V A (V_2 - V_1) \) (one dimensional)

Steam Turbines

Nozzle Equation: \( h_1 - h_2 = (V_2^2 - V_1^2)/2 \)

Work: \( w = [(V_1^2_{\text{absolute}} - V_2^2_{\text{absolute}}) + (V_2^2_{\text{relative}} - V_1^2_{\text{relative}})]/2 \)

Gas Turbines

State Equation: \( pv = RT \)

Isentropic Equation: \( \frac{T_2}{T_1} = (\frac{p_2}{p_1})^{(k-1)/k} \)

Enthalpy Change: \( h_1 - h_2 = c_p(T_1 - T_2) \) (ideal gas)

Nozzle Equation: \( h_1 - h_2 = (V_2^2 - V_1^2)/2 \)

Jet Propulsion

Thrust: \( \tau = M(V_{\text{jet}} - V_{\text{aircraft}}) \)

Thrust Power: \( \tau V_{\text{aircraft}} = M(V_{\text{jet}} - V_{\text{aircraft}}) V_{\text{aircraft}} \)

Jet Power: \( P = M(V_{\text{jet}}^2 - V_{\text{aircraft}}^2)/2 \)

Propulsion Efficiency: \( \eta_p = 2V_{\text{aircraft}}/(V_{\text{jet}} + V_{\text{aircraft}}) \)

Wind Turbine

Maximum Ideal Power: \( P_{\text{max}} = 8 \rho AV_1^3/27 \)
NUCLEAR REFERENCE EQUATIONS

Number of nuclei per gram of material

\[ N = \frac{N_A}{M} \]

Number of fissile nuclei per cm\(^3\) of material

\[ N_f = \gamma \left( \frac{N_A}{M} \right) \rho \]

Heat release rate in nuclear fuel

\[ q^* = \phi N_f \sigma_f E_f \]

Nomenclature

- \( N \): number of nuclei (number/g)
- \( N_A \): Avogadro's Number
- \( M \): molecular weight
- \( \gamma \): fuel enrichment
- \( \rho \): density (g/cm\(^3\))
- \( q^* \): heat release rate (J/cm\(^3\))
- \( \phi \): neutron flux (neutrons/cm\(^2\)s)
- \( N_f \): number of fissile nuclei (number/cm\(^3\))
- \( \sigma_f \): cross section (barn) (1 barn = \(10^{-24}\) cm\(^2\))
- \( E_f \): energy release per fission of one atom

Avogadro's Number

\[ N_A = 0.602 \times 10^{24} \text{ atoms/mole} \]