Lecture 7

Design Issues

Power Cycles for Nuclear Plants
Topics to be Covered

• Design Issues for nuclear plants Kneif (8,9 10)

• Rankine Cycle
  – Basic
  – Superheat
  – Multi-fluid cycles
  – Brayton cycle

• Pressure Ratios
Reactor Design Interactions

FIGURE 8-3
Reactor design interactions. (From A. Sesonske, Nuclear Power Plant Design Analysis, TID-26241, 1973.)
Reactor Core Design

• Thermal Analysis
  – Set inlet and outlet temperature
  – Assume radial peaking factor to calculate hot channel coolant temperature
  – Assume axial flux profile and engineering factors to calculate hot channel coolant temperature
  – Calculate clad surface temperature profile for hot channel assuming a clad surface heat flux and empirical heat transfer coefficient
Design Process (2)

- Set clad and gap conductance materials and dimensions
- Calculate fuel surface temperature profile

- Fuel Pin Composition and diameter selection
  - For a given fuel material use thermal conductivity and peak temperature to determine limiting heat rate for hot channel
  - Set pellet diameter based on fuel fabrication cost
  - Recalculate heat fuel and temperature
Reactor Design (3)

- Core sizing
  - Calculate number of fuel pins from core power and length
  - Chose geometry and spacing
  - Calculate physics parameters – axial and radial power profiles
  - Assess safety (reactivity coefficients) and power conversion factor (core lifetime)
  - Calculate required coolant velocity
Reactor Design (4)

- Fuel Cycle Economic Analysis
- Fuel Pin Structural Analysis
- Hydraulic Analysis
  - Pressure drops, flow distributions
  - Pumping power requirements
- Safety Analysis
  - Reactivity coefficients for accident analysis
- Fuel element reliability analysis – fuel stress etc.
- Post Irradiation handling considerations – cooling needs
Fuel Performance

**Figure 9-4**
Mixed-oxide fuel restructuring versus linear heat rate. (Photograph courtesy of the Hanford Engineering Development Laboratory, operated by Westinghouse Hanford Company for the U.S. Department of Energy.)
### TABLE 9-1
Representative Fuel Design Parameters for Water-Cooled Reactor Systems

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>PWR</th>
<th>BWR</th>
<th>CANDU</th>
<th>RBMK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 x 15</td>
<td>17 x 17</td>
<td>7 x 7</td>
<td>8 x 8</td>
</tr>
<tr>
<td>Rod diameter (mm)</td>
<td>10.7</td>
<td>9.50</td>
<td>14.3</td>
<td>12.5</td>
</tr>
<tr>
<td>Active fuel height (m)</td>
<td>3.66</td>
<td>3.66</td>
<td>3.66</td>
<td>3.66</td>
</tr>
<tr>
<td>Clad thickness (mm)</td>
<td>0.61</td>
<td>0.58</td>
<td>0.81</td>
<td>0.86</td>
</tr>
<tr>
<td>Pellet-clad diametrical gap (mm)</td>
<td>0.19</td>
<td>0.17</td>
<td>0.28</td>
<td>0.23</td>
</tr>
<tr>
<td>Average linear heat rate (kW/m)†</td>
<td>23.1</td>
<td>17.8</td>
<td>23.3</td>
<td>19.8</td>
</tr>
<tr>
<td>Average power density (kW/l)‡</td>
<td>106</td>
<td>105</td>
<td>51</td>
<td>56</td>
</tr>
</tbody>
</table>

† Calculated from core thermal power and total length of fuel.
‡ Calculated from core thermal power and active core volume (for CANDU and RBMK, volume is that for pressure tubes only.).
FIGURE 1-6
Fuel assembly for a representative boiling-water reactor. (Adapted courtesy of General Electric Company.)
Fuel Rod Design Interactions

FIGURE 9-6
Flow chart for representative fuel-rod design interactions. (From D. R. Olander, Fundamental Aspects of Nuclear Reactor Fuel Elements, TID-26711-P1, 1976.)
Typical Protective System

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Daya Bay PWR – French Design

FIGURE 8-4
Cut-away drawing of the Guangdong pressurized water reactor [Courtesy of Nuclear Engineering International (Sept. 1987), with permission of the editor.]
Schematic of Plant Design

FIGURE 8-5
Schematic diagram of the fluid subsystems of the Ringhals, Units 3 and 4 pressurized water reactors [Courtesy of the Swedish State Power Board.]
Key Reactor Systems

- Reactor Coolant System
- Heat Removal Systems
- Nuclear Support Systems
- Plant Service Systems
- Nuclear Safety Systems
- Balance of Plant
Power Conversion Systems

- Carnot Efficiency
- Rankine Cycle Fundamentals
- Superheat
- Multi-Fluid Cycles
- Choices for Efficiency and Cost
ENERGY IN THE FORMS OF HEAT AND WORK

Heat: Energy of a system associated with the unordered motion of the system’s molecules (indicated by the system’s temperature).

Work: Energy of a system associated with the ordered motion of the system’s molecules (Work = Force * Displacement).
IDEAL HEAT ENGINE
VAPOR-POWER CYCLES

• Carnot Cycle (Ideal, Reversible Engine)
  - Heat addition and rejection at constant temperatures
  - System expansion and compression at constant entropies

• Rankine Cycle (Two-Phase Working Fluid)
  - Heat addition and rejection at constant temperatures
  - System expansion and compression at constant entropies

• Brayton Cycle (Single-Phase Working Fluid)
  - Heat addition and rejection at constant temperatures
  - System expansion and compression at constant entropies
REVERSIBILITY AND IRREVERSIBILITY

Reversible Process: A process involving the change from system State A to State B, such that the system can be restored to State A with no net change in the status of any other system in the universe.

Irreversibility: Net work that must be supplied by an external system in order to restore the system of interest from State B back to its initial state, A.

Sources of Irreversibility:

• Heat not converted to work in association with heat from a hot body to a colder body.

• Work that is transferred from one system to another without being preserved in the form of work (i.e., work that is converted to heat via friction during a process).
Temperature Entropy Diagrams

Fig. 2-1. TS diagram of Carnot cycle.

Fig. 2-6. TS diagram of cycle with irreversible expansion and irreversible constant-temperature heat addition.
IRREVERSIBILITY IN HEAT TRANSFER

Heat Source
Temperature = T_1

\[ Q \]

Carnot Engine \[ W = \eta_{\text{Carnot}} Q \]

\[ (Q - W) \]

Heat Sink
Temperature = T_2

\[ \eta_{\text{Carnot}} = \frac{T_1 - T_2}{T_1} \]

Irreversibility, I, in transferring heat, Q, is the work not performed, \( W = \eta_{\text{Carnot}} Q \), due to absence of a perfect heat engine.
Basic Rankine Cycle

Some Thermodynamic Aspects of Nuclear I

Primary coolant  Working fluid  Load

Heat exchanger  Condenser

FIG. 2-5. Schematic of two-loop nuclear power plant.

FIG. 2-4. Internally reversible Rankine cycle with saturated vapor.
Steam Generators

**FIG. 2-10.** Heat addition to vaporizing fluid with a variable-temperature source; counter-flow heat exchanger.

**FIG. 2-11.** Heat addition to vaporizing fluid with a variable-temperature source; parallel-flow heat exchanger.
Rankine Cycle with Feedwater Heaters

FIG. 2-9. Schematic of Rankine cycle with two closed-type feedwater heaters.
REFINED RANKINE CYCLE USING SUPERHEATING AND REGENERATIVE HEATING

Thermal Efficiency $\approx \frac{\text{Heat Added} - \text{Heat Rejected}}{\text{Heat Added}} \equiv 0.42_{\text{max}}$
Power Cycles

FIG. 2-12. Internally reversible Rankine cycle with superheat and a variable-temperature heat source.

FIG. 2-13. Ts diagram of internally reversible supercritical and reheat cycles.
Binary Cycle Plants

**FIG. 2-16.** Schematic of a mercury-steam binary-vapor power plant.

**FIG. 2-17.** TS diagram of internally reversible mercury-steam cycle.
Gas Reactor Cycles

• Brayton Cycle
• Brayton-Rankine Dual Cycle
• Real Example – Pebble Bed
• Choices for Efficiency and Cost
  – Materials
  – Costs
  – Efficiency Trade-offs
Brayton Gas Cycle - Open

Fig. 7-1. The direct open cycle. (a) Cycle diagram; (b) $T-s$ diagram.
# Perfect Gas Relationships

## Table 2-1

<table>
<thead>
<tr>
<th>Process</th>
<th>$p$, $v$, $T$ relationships</th>
<th>$u_2 - u_1$</th>
<th>$h_2 - h_1$</th>
<th>$s_2 - s_1$</th>
<th>$W$ (nonflow)</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isothermal</td>
<td>$T = \text{const}$</td>
<td>0</td>
<td>0</td>
<td>$(R/J) \ln (v_2/v_1)$</td>
<td>$(p_1v_1/J) \ln (v_2/v_1)$</td>
<td>$(p_1v_1/J) \ln (v_2/v_1)$</td>
</tr>
<tr>
<td>Constant pressure</td>
<td>$p = \text{const}$</td>
<td></td>
<td></td>
<td>$c_p(T_2 - T_1)$</td>
<td>$p(v_2 - v_1)/J$</td>
<td>$c_p(T_2 - T_1)$</td>
</tr>
<tr>
<td>Constant volume</td>
<td>$v = \text{const}$</td>
<td>$c_v(T_2 - T_1)$</td>
<td>$c_p(T_2 - T_1)$</td>
<td>$c_v \ln (T_2/T_1)$</td>
<td>0</td>
<td>$c_v(T_2 - T_1)$</td>
</tr>
<tr>
<td>Isentropic</td>
<td>$s = \text{const}$</td>
<td>$c_v(T_2 - T_1)$</td>
<td>$c_p(T_2 - T_1)$</td>
<td>0</td>
<td>$p_2v_2 - p_1v_1$</td>
<td>0</td>
</tr>
<tr>
<td>(adiabatic</td>
<td>$p_1v_1^r = p_2v_2^r$</td>
<td></td>
<td></td>
<td></td>
<td>$J(1 - \gamma)$</td>
<td>0</td>
</tr>
<tr>
<td>reversible)</td>
<td>$T_2/T_1 = (v_1/v_2)^{r-1}$</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Throttling</td>
<td>$h = \text{const}$</td>
<td>0</td>
<td>0</td>
<td>$(R/J) \ln (v_2/v_1)$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Constant pressure</td>
<td>$T = \text{const}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polytropic</td>
<td>$p_1v_1^n = p_2v_2^n$</td>
<td>$c_v(T_2 - T_1)$</td>
<td>$c_p(T_2 - T_1)$</td>
<td>$c_v \ln (p_2/p_1)$</td>
<td>$p_2v_2 - p_1v_1$</td>
<td>$c_v \left( \frac{\gamma - n}{1 - n} \right) (T_2 - T_1)$</td>
</tr>
</tbody>
</table>
Indirect Brayton Open Cycle

FIG. 7-2. The indirect open cycle.
Direct Closed Brayton Cycle

![Diagram of Direct Closed Brayton Cycle]

**FIG. 7-3.** The direct closed cycle.
Indirect Closed Cycle – Gas to Gas
Indirect Gas to Steam Generator

Fig. 7-5. The indirect closed cycle, gas to water.
FIG. 7-6. Variation of molar $c_p$ with temperature for various gases.
Ideal Brayton Cycle

FIG. 7-7. An ideal Brayton cycle.
Non-Ideal Brayton Cycle

FIG. 7-12. Closed nonideal Brayton cycle with regeneration.
BRAYTON CYCLE WITH REGENERATIVE HEATING

T

S

Heat Added

Heat Rejected

Prof. Andrew C. Kadak, 2008

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FIG. 8-1. Schematic of a simple-cycle gas-steam-reactor power plant.

FIG. 8-2. Temperature-enthalpy diagram of a gas-steam heat exchanger in simple cycle.
COMBINED CYCLE BRAYTON (Topping), RANKINE (Bottoming)

Gas Turbine Brayton Cycle

Steam Rankine Cycle

Heat Added

Heat Rejected

Temperature

Entropy

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VARIOUS VAPOR POWER CYCLES OPERATING BETWEEN THE SAME TEMPERATURE LIMITS
Reading and Homework Assignment

1. Read Knief Chapter 8, 9, 10
2. Outside Reading El-Wakil Chapter 2
3. Problems 2.7, 7.4