Operational Reactor Safety
22.091/22.903

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Professor of the Practice

Safety Systems and Functions
Lecture 9
Topics to be Covered

• Fundamentals of Safety
  – Introduction to Safety Analysis
  – Defense in Depth
  – Design Basis Accidents
  – Beyond Design Basis Accidents
  – Safety Systems
  – Emergency Safeguards Systems
  – Containment
Key Safety Measures

- Prevention
  - Proper Design and Training
- Protection
  - Monitoring and Control Systems
  - Active shutdown and cooling systems
- Mitigation – limit consequences
  - Engineered Safety Systems

Called Defense in Depth Approach
Energy Sources

- Stored Energy in Fuel, Steam and Structures
- Energy from nuclear transients
- Decay Heat
- Chemical Reactions
- External events – seismic, tornadoes, hurricanes, etc.
Mission - Remove Heat

• Prevent fuel cladding failure or core melting
  – Install systems to do this under many transient and accident conditions

• If unsuccessful, keep radioactive materials in the containment
  – Assure containment function is maintained and not breached by overpressure or missiles

• If unsuccessful, limit releases

• If unsuccessful, implement emergency plan
Design Basis Accidents

- Overcooling
- Undercooling
- Overfilling
- Loss of Flow
- Loss of Coolant
- Reactivity
- Anticipated Transients without Scram
- Spent fuel or handling events
- External Events
### TABLE 13-1

Properties of Potentially Energetic Chemical Reactions of Interest in Nuclear Reactor Safety

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Temperature (°C)</th>
<th>Oxide(s) formed</th>
<th>Heat of reaction‡ with:</th>
<th>Hydrogen produced with water (l/kg R)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Oxygen (kcal/kg R)</td>
<td>Water (kcal/kg R)</td>
</tr>
<tr>
<td>Zr (liq.)</td>
<td>1852⁸</td>
<td>ZrO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-2883</td>
<td>-1560</td>
</tr>
<tr>
<td>SS (liq.)</td>
<td>1370⁸</td>
<td>FeO, Cr₂O₃, NiO</td>
<td>-1330 to -1430</td>
<td>-144 to -253</td>
</tr>
<tr>
<td>Na (solid)</td>
<td>25</td>
<td>Na₂O</td>
<td>-2162</td>
<td></td>
</tr>
<tr>
<td>Na (solid)</td>
<td>25</td>
<td>NaOH</td>
<td>-</td>
<td>-1466</td>
</tr>
<tr>
<td>C (solid)</td>
<td>1000</td>
<td>CO</td>
<td>-2267</td>
<td>+2700</td>
</tr>
<tr>
<td>C (solid)</td>
<td>1000</td>
<td>CO₂</td>
<td>-7867</td>
<td>+2067</td>
</tr>
<tr>
<td>H₂ (gas)</td>
<td>1000</td>
<td>H₂O</td>
<td>-29,560</td>
<td></td>
</tr>
</tbody>
</table>


‡ Positive values indicate energy that must be added to initiate an endoergic reaction; negative values indicate energy released by exoergic reactions.

⁸ Melting point.

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Pressurized Water Reactor Schematic

Concrete and Steel Containment

Primary Concrete Shield

Pressurizer

Primary Vessel

Control Rods

Reactor Core

Primary Coolant Pump

Steam Generator

Steam to Turbine

6.9 MPa

285°C

Turbine

Turbine Bypass

Electric Generator

Condenser

-40°C

-15°C

Cooling Tower

Turbine Bypass

High-Pressure Heaters

Low-Pressure Heaters

Feed Pump

Condensate Pump

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Specific Design Basis Accidents

- Steam line break
- Loss of Flow
- Loss of heat sink
- Steam generator tube(s) rupture
- Control rod ejection or rapid withdrawal
- Anticipated Transients without Scram
- Pressurized thermal shock
- Loss of coolant
  - Double ended guillotine break
  - Small Break
Typical PWR

FIGURE 14.2

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Severe Accidents

• Beyond Design Basis
  – Successive failures of the engineering safety systems
  – Looking for cliff edge effects that may need to be addressed if consequences are severe and scenario is plausible.
  – Core Melt scenarios - vaporization
    • Steam explosion
    • Hydrogen explosion
    • Fission product inventory for release
# Fission Products for Release

## Table 13-2

<table>
<thead>
<tr>
<th>Fission products</th>
<th>Gap</th>
<th>Meltdown</th>
<th>Vaporization†</th>
<th>Steam Explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noble gases (Kr, Xe)</td>
<td>3.0</td>
<td>90</td>
<td>100</td>
<td>90 (X)(Y)</td>
</tr>
<tr>
<td>Halogens (I, Br)</td>
<td>1.7</td>
<td>90</td>
<td>100</td>
<td>90 (X)(Y)</td>
</tr>
<tr>
<td>Alkali metals (Cs, Rb)</td>
<td>5</td>
<td>81</td>
<td>100</td>
<td>—</td>
</tr>
<tr>
<td>Te, Se, Rb</td>
<td>$10^{-2}$</td>
<td>15</td>
<td>100</td>
<td>60 (X)(Y)</td>
</tr>
<tr>
<td>Alkaline earths (Sr, Ba)</td>
<td>$10^{-4}$</td>
<td>10</td>
<td>11</td>
<td>—</td>
</tr>
<tr>
<td>Noble metals (Ru, Mo)</td>
<td>—</td>
<td>3</td>
<td>8</td>
<td>90 (X)(Y)</td>
</tr>
<tr>
<td>Rare earths (La, Sm, Pu) &amp; refractories (Zr, Nb)</td>
<td>—</td>
<td>0.3</td>
<td>1.3</td>
<td>—</td>
</tr>
</tbody>
</table>

†Adapted from WASH-1400 (1975).

‡Exponential loss over 2 h with a half-time of 30 min. If a steam explosion occurs first, only the core fraction not involved in the explosion can experience vaporization.

$X =$ fraction of core involved; $Y =$ fraction of inventory remaining for release.
FIGURE 13-1
Loss-of-coolant accident (LOCA) sequences for light-water reactors. (Adapted from A. Sesonske, Nuclear Power Plant Design Analysis, TID-26241, 1973)
Engineered Safety Systems

**Figure 14-1**
Conceptual engineered safety systems for LWRs. (Adapted from WASH-1400, 1975.)
PWR Engineered Safety Systems

FIGURE 14-2

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PWR Containment

![Diagram of PWR Containment](image)

**Figure 14-4**
Representative PWR containment. (From NUREG-1150, 1989.)
Containment Pressure Response

FIGURE 14-5
Containment pressure response for a PWR to a design-bases LOCA with assumed safety system failures.
(Adapted from WASH-1400, 1975.)
FIGURE 14-6

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Early BWR Containment Design
Later Version of BWR Containment
Containment Leakage

• Function of event and chemistry in building
• Driven by containment pressure
• Source terms
  – Noble gases – not captured
  – Elemental iodine – reactive and plated out
  – Organic iodides – not chemically reactive
  – Particulates and aerosols – heavy settle out
• What is not chemically reacted in containment, plated out or settled out is available for release.
Reading and Homework Assignment

1. Read Knief Chapter 13
