“Physics and Technology of Water-Cooled Reactors through the use of PC-based Simulators”

PASSIVE PRESSURIZED WATER REACTOR

International Centre for Theoretical Physics
Trieste
6th - 10th November 2017
Passive PWR Introduction

Evolution of Nuclear Power

Generation I
- Early Prototypes
  - Shippingport
  - Dresden
  - Magnox
- 1950

Generation II
- Commercial Power
  - PWRs
  - BWRs
  - CANDU
- 1960

Generation III
- Advanced LWRs
  - CANDU 6
  - System 80+
  - AP600
- 1970

Generation III+
- Evolutionary Designs
  - ABWR
  - ACR1000
  - AP1000
  - APWR
  - EPR
  - ESBWR
- 1980

Generation IV
- Revolutionary Designs
  - Safer
  - Sustainable
  - Economical
  - More
  - Proliferation Resistant and Physically Secure
  - Secure
- 1990

Future
- 2000
- 2010
- 2020
- 2030

Generations
- Gen I
- Gen II
- Gen III
- Gen III+
- Gen IV
IAEA set the components degree of passivity based on the following:

1) no moving working fluid
2) no moving mechanical part
3) no signal inputs of 'intelligence'
4) no external power input or forces

- **A:** 1+2+3+4 (fuel rods)
- **B:** 2+3+4 (PZR surge line)
- **C:** 3+4 (ACCs, no intelligence signals, actuation just based on pressure drop instead of situation analysis)
- **D:** 4 (reactor trip: control rods drop by gravity based on signals that analyze plant conditions. Others: CMTs, PRHR, IRWST)
Passive PWR

- Proven components are used.
- Passive means as motive force:
  - Gravity
  - Compressed fluids
  - Natural Circulation
  - Evaporation/Condensation.
- Active non-safety-related components as backup.
- Greatly reduced operator dependency.
PWR NPP SYSTEMS

- Nuclear Steam Supply System (RCS)
- Primary System Auxiliaries (CVS, RNS)
- Engineered Safeguards
- Power Generation (Balance of Plant)
- Control and Protection Systems
- Main Control Room
Reactor Coolant System (RCS)

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See simulator display for reference of RCS layout
Core Components
Arrangement

The core components consist of:

- 157 fuel assemblies
- 53 Rod Cluster Control Assemblies (RCCA) - High rod worth
- 16 Gray Rod Cluster Assemblies (GRCA) - Low Rod worth
- 42 incore detectors
157 Fuel assemblies (17x17 configuration)

A fuel assembly contains 289 cells:

- 264 individual fuel rods supported by grids.
- 24 guide thimble tubes.
- 1 instrumentation thimble tube.

14 Feet in length (4.27m)

The instrumentation thimble tube provides multiple incore discrete neutron flux detectors and core exit thermocouples.
Control Rods

- Rod Control Cluster Assembly (RCCA)
  - High worth (Ag-In-Cd)
  - Shutdown Margin
  
  AND

  Axial Power Control

- Gray Rod Cluster Assembly (GRCA)
  - Low worth (Tg)
  - Power/Reactivity Control
- 7 Vanadium Self Powered Neutron Detectors
- 1 Chromel-Alumel Core Exit Thermocouple
Rod Control

Power Mismatch

Temperature Mismatch
RCS Temperature Program

NOTE: PZR Saturation temperature @ 15.41 MPa gauge (15.51 MPa abs) is 345°C

NOTE: 100% Power ΔT is 46.4°C

Temperature (°C)

Power

Steam Generator Pressure 7.52 MPa gauge
Steam Generator Pressure 5.66 MPa gauge

T Hot
T Average
T Cold
T Steam
Axial Offset Control

AO Bank Withdrawal

AO Bank Insertion
Pressurizer (PZR)

- Maintains RCS pressure
  - Pressure control during normal operation with heaters and spray.
  - Saturated environment.
  - Provides overpressure relief.
  - Pathway for initial ADS pressure reduction.
- Provides surge volume during temperature transients.
PZR Pressure Control

Backup Heaters

On

Off

Control Group Heaters

PZR Spray Valves

1915
LZ Reactor Trips

2210
B/U Heaters turn ON

2220
B/U Heaters turn OFF

2230
NORMAL OPERATING PRESSURE

2250
Ctrl Heaters fully OFF

2260
Spray Valve start

to OPEN

2310
Spray Valve Fully Open

2420
K2 Rx Trip

2485
PZR Safeties

IAEA
International Atomic Energy Agency

ICTP
International Centre for Theoretical Physics

Tecnatom
PZR Pressure Control

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Chemical and Volume Control System (CVS)

RCPs differential pressure provides driving head for purification flow to CVS

CVS suctions from cold leg 1B.

CVS discharges back to the RCS at SG1 channel head.

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See simulator display for reference of CVS layout
Chemical and Volume Control System (CVS)
CVS functions

- RCS purification
- RCS inventory control
- Chemical shim
- Borated Makeup to Auxiliary Equipment
- pH control
- Oxygen control
- Filling and Pressure Testing the RCS
- Auxiliary Pressurizer Spray
PZR Level Program

**100% Power**
(31.5 – 58)% level

**No-load**
(21 – 46.3)% level

- Makeup Pump Start
- Makeup Pump Stop
- Letdown Open
- Letdown Close

IAEA
International Atomic Energy Agency

ICTP
International Centre for Theoretical Physics

TECNATOM
Core Cooling – Heat Sink

- Normal Operation:
  - At power: Steam Generators thru *Turbine*
- Startup/Shutdown:
  - Steam Generators thru *Steam Bypass / Steam Relief Valves* (>177°C; >3.1MPag)
  - *Normal Residual Heat Removal System (RNS)* (<177°C; <3.1MPag)
- Emergency Operation
  - *Passive Core Cooling System (PXS)*
  - *Passive Containment Cooling System (PCS)*
Passive Safety Systems

- Passive Core Cooling System (PXS)
  - Passive Residual Heat Removal Subsystem
    - Natural circulation across a HX connected to the RCS
  - Passive Safety Injection Subsystem
    - Core Makeup Tanks (CMTs) injection by natural circulation
    - Nitrogen pressurized Accumulators (ACCs)
    - Gravity drained IRWST
    - Automatic Depressurization System (ADS)
- Passive Containment Cooling System (PCS)
  - Water supply by gravity, and heat removal by evaporation and natural circulation
Passive Core Cooling System (PXS)

Safety Injection Subsystem
- Core Makeup Tanks
- Accumulators
- In-Containment Refueling Water Storage Tank
- Containment Sumps
- Automatic Depressurization Valves

Emergency Core Decay Heat Removal Subsystem
- Passive Residual Heat Removal HX

http://www.westinghousenuclear.com/New-Plants/AP1000-PWR/Safety/Passive-Safety-Systems
Automatic Depressurization System (ADS)

- Three stages of ADS valves are connected to the PZR, and discharge through spargers located in the IRWST.
- They are motor operated valves (MOVs).

- The fourth stage ADS valves are connected to the RCS hot legs and discharge directly to the steam generator compartments.
- These are squib valves.

See simulator display for reference of ADS layout.
Automatic Depressurization System (ADS)

- Reduces the pressure in the RCS during loss-of-coolant accidents (LOCA) in order to permit safety injection.

- The ADS valves are designed to operate in four different stages.

- Automatic signal to open comes from CMT level, but can also be manually actuated.
Passive Core Cooling System (PXS)

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Containment Sump
Recirculation

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Severe Accident: In-Vessel Retention of Core Damage

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Passive Containment Cooling System (PCS)

Final Heat Sink for Loss of Coolant Accidents Or Steam Line Breaks Inside Containment

Normal Residual Heat Removal System (RNS)

- Remove decay heat from the core and reduces the temperature of the RCS during the second phase of plant cooldown (From ~177°C to ~51.6°C)
- Supplement the passive core cooling system (PXS) during emergencies.
- Provide RCS purification motive force when the RCPs are not operating or are operating at reduced speeds.
- IRWST cooling
One safety-related protection system:

- Redundant divisions (Logic 2 out of 4) “de-energize-to-act”
- Screens and Controls (both hard and soft) in MCR.
- Backed up by batteries (safety-related) and diesel generators (non-safety-related)
- Automatic detection of abnormal conditions and Safety Functions Actuation.
- Post-Accident Instrumentation (backed by longer endurance batteries)
One **non-safety-related** protection system

- Back-up where common mode failure is a risk
- "Diversity" (different Hardware & Software architecture)
- Backed by short endurance batteries and DGs.
- Automatic detection of abnormal conditions and "reduced" protective functions actuation.
- Independent instrumentation
- Logic 2 out of 2, "energize-to-act"
- Actuates over some equipments as regular protection system
- Signal isolation between regular protection system
- Non-Actuated
  - Solenoid 1 energized (SR Protection)
  - Solenoid 2 de-energized (NSR Protection)
- Actuated by safety-related protection
  - Solenoid 1 de-energized
  - Solenoid 2 de-energized
Actuated by non-safety-related protection

- Solenoid 1 energized
- Solenoid 2 energized
- **Non-safety-related** control system.
- Distributed Control System (modular repaired).
- Two redundant servers.
- Signal Selector Algorithms (single failure criteria).
- Isolation devices with Protection System.
- Alarm Presentation System.
- Computerized Procedures.
- Datalinks for data exchange to external systems (radiation monitors, in-core instrumentation, PLC...).
Advanced Main Control Room

- Compact Control Room
  - Designed to be operated by at least one operator and one supervisor.
- Passive ventilation during accidents:
  - Compressed air to feed the MCR.
  - Ceiling fins acting as passive heat sink.
- Controls
  - Software controls
  - Hardware switches
- Computerized Procedures
Advanced Main Control Room

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## PRA Results for a Passive PWR

<table>
<thead>
<tr>
<th>At Power, Internal Events</th>
<th>Current US</th>
<th>AP600</th>
<th>AP1000</th>
<th>Ratio (Current vs AP600</th>
<th>AP1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transients</td>
<td>1.3E-05 /yr</td>
<td>4.4E-09 /yr</td>
<td>7.3E-09 /yr</td>
<td>2959</td>
<td>1772</td>
</tr>
<tr>
<td>Loss Offsite Power</td>
<td>6.6E-06 /yr</td>
<td>1.0E-09 /yr</td>
<td>9.6E-10 /yr</td>
<td>6600</td>
<td>6889</td>
</tr>
<tr>
<td>Steam Line / Feed Line Breaks</td>
<td>-- /yr</td>
<td>6.1E-10 /yr</td>
<td>7.5E-10 /yr</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>SG Tube Rupture</td>
<td>1.7E-06 /yr</td>
<td>6.1E-09 /yr</td>
<td>6.8E-09 /yr</td>
<td>279</td>
<td>250</td>
</tr>
<tr>
<td>RCS Leak</td>
<td>-- /yr</td>
<td>2.3E-09 /yr</td>
<td>1.7E-09 /yr</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Small LOCA</td>
<td>8.0E-06 /yr</td>
<td>4.7E-09 /yr</td>
<td>1.9E-08 /yr</td>
<td>1717</td>
<td>430</td>
</tr>
<tr>
<td>Medium LOCA</td>
<td>5.0E-06 /yr</td>
<td>8.0E-08 /yr</td>
<td>1.1E-07 /yr</td>
<td>63</td>
<td>44</td>
</tr>
<tr>
<td>Large LOCA</td>
<td>8.0E-07 /yr</td>
<td>5.0E-08 /yr</td>
<td>7.5E-08 /yr</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>ATWS</td>
<td>2.2E-06 /yr</td>
<td>1.0E-08 /yr</td>
<td>4.4E-09 /yr</td>
<td>218</td>
<td>496</td>
</tr>
<tr>
<td>Loss Support Sys (CCW/SW, ...)</td>
<td>-- /yr</td>
<td>2.9E-10 /yr</td>
<td>1.0E-09 /yr</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Inter-System LOCA</td>
<td>1.0E-06 /yr</td>
<td>5.0E-11 /yr</td>
<td>5.0E-11 /yr</td>
<td>20000</td>
<td>20000</td>
</tr>
<tr>
<td>Vessel Rupture</td>
<td>3.0E-07 /yr</td>
<td>1.0E-08 /yr</td>
<td>1.0E-08 /yr</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td><strong>3.9E-05 /yr</strong></td>
<td><strong>1.7E-07 /yr</strong></td>
<td><strong>2.4E-07 /yr</strong></td>
<td><strong>228</strong></td>
<td><strong>160</strong></td>
</tr>
<tr>
<td>Total without Operator Actions</td>
<td>~ 2 E-03 /yr</td>
<td>1.8E-05 /yr</td>
<td>1.4E-05 /yr</td>
<td>111</td>
<td>146</td>
</tr>
<tr>
<td>Total without Nonsafety Systems</td>
<td>~ 2 E-03 /yr</td>
<td>7.7E-06 /yr</td>
<td>7.4E-06 /yr</td>
<td>260</td>
<td>270</td>
</tr>
</tbody>
</table>
QUESTIONS?