NSSS Design (Ex: PWR)

Reactor Coolant System (RCS)

Purpose:
- Remove energy from core
- Transport energy to S/G to convert to steam of desired pressure (and temperature if superheated) and moisture content (if not superheated)

Common Design Objectives
- Minimize volume to reduce cost.
- Minimize leakage of core coolant
- Capability to withstand static and dynamic loadings
  - Component weight, content weight, thermal stresses, fluid forces, seismic loads and accidents loads (pipe break)
- Material compatibility (corrosion resistance)
- Capability to withstand thermal cycling
- Capability to withstand radiation damage.
- Serviceability and reliability

Components
- Reactor pressure vessel and contents
- Reactor coolant pumps
- Pressurizer
- Steam generator
Simplified Diagram of a Four-Loop NSSS with U-Tube Steam Generators
Simplified Diagram of a Two-Loop NSSS with Once Through Steam Generators
Reactor Pressure Vessel and Contents

Purpose:
- Provide mechanical support for fuel, control elements and incore instrumentation.
- Provide flow path for coolant to remove energy from fuel

Design considerations beyond common design objectives
- Minimize pressure vessel penetrations to reduce failure modes
- Desire multi-inlet and outlet flow nozzles to minimize
  - Loop equipment space requirements
  - Accident consequences of single loop failure
- Desire uniform core inlet flow
- Desire low cross flows on internals.

Pressure Vessel Characteristics
- Low alloy carbon steel ≈ 9” thick ⇒ good strength
- Inner cladding of 1/8” austenic SS ⇒ good corrosion resistance
- # of Nozzles:
  - Dependent on power rating and NSSS vendor

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Rating</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/Areva</td>
<td>600MWe</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>W/Areva</td>
<td>900MWe</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>W/Areva</td>
<td>1150MWe</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>C-E</td>
<td>1150MWe</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>B&amp;W</td>
<td>1150MWe</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
Reactor Pressure Vessel and Internals
Reactor Coolant Pumps

Purpose: Provide forced circulation of primary coolant around reactor coolant system
Note: has little to do w/ system pressure!

Design Considerations Beyond Common Design Objectives
- Sufficient coast down capability
- Desire single speed pump to reduce cost.

Example: (See Figure)
- (7000-9000)HP per pump
- Centrifugal pump/vertical shaft
- Three-phase induction motor
- Multi-seal arrangement
- Large flywheel
- RPM=1189
Reactor Coolant Pump
Figure 3-8. RCP Typical Shaft Seal Arrangement
Pressurizer

Purpose: Provide primary side pressure control during:
- Part of cold to hot startup
- Normal operation
- Accident conditions

Design considerations
- Accommodate primary water volume changes over power operation range
- Provide pressure control during load follow operation.
- Limit maximum primary system pressure.

Example: (see Figure)

**Longer Term Pressure Control**
- Pressure low ⇒ Turn on Electric Heaters ⇒ Increased void formation ⇒ Increased pressurizer energy content ⇒ Increased system pressure
- Pressure high ⇒ Turn on sprays (cold leg water) ⇒ Condense steam ⇒ Decreased pressurizer energy content ⇒ Decrease system pressure.
Typical Pressurizer
Principles of Prz Operation

Initial State → A

Instantaneous Prz level ↓ → B

Why Prz level ↓?

1. Leak in RCS
2. RCS av. Temp ↓ ⇒ $\rho_{H_2O}$ ↑ ⇒ $V^H_{RCS}$ ↓

Consider first the case of a non-condensable gas in the vapor space and incompressible liquid in the liquid space ⇒ Pressure behavior governed by the compressible gas.

Ideal Gas: $P^k = P\left(\frac{V}{M}\right)^k = \text{constant}$ for a reversible adiabatic process with an ideal gas ($k>1$)

$$P\left(\frac{V}{M}\right)^k = P_0\left(\frac{V_0}{M}\right)^k \Rightarrow P = P_0\left(\frac{V_0}{V}\right)^k$$

In addition

$$\frac{T}{T_0} = \left(\frac{V_0}{V}\right)^{k-1} \Rightarrow T = T_0\left(\frac{V_0}{V}\right)^{k-1}$$
\[ P = P_0 \left( \frac{V_0}{V} \right)^k \quad T = T_0 \left( \frac{V_0}{V} \right)^{k-1} \]

Volume Increase (outsurge): Level \( \downarrow \Rightarrow V_{\text{gas}} \uparrow \Rightarrow T_{\text{gas}} \downarrow \Rightarrow P_{\text{gas}_{\text{PRZ}}} \downarrow \Rightarrow P_{\text{sys}} \downarrow \)

Gas Expands \( \Rightarrow T_{\text{gas}^{-(B)}_{\text{PRZ}}} < T_{\text{gas}^{-(A)}_{\text{PRZ}}} \) due to expansion work

Volume Decrease (insurge): Level \( \uparrow \Rightarrow V_{\text{gas}} \downarrow \Rightarrow T_{\text{gas}} \uparrow \Rightarrow P_{\text{gas}_{\text{PRZ}}} \uparrow \Rightarrow P_{\text{sys}} \uparrow \)

Gas Compresses \( \Rightarrow T_{\text{gas}^{-(B)}_{\text{PRZ}}} > T_{\text{gas}^{-(A)}_{\text{PRZ}}} \) due to compressive work
Consider next the case of a saturated liquid vapor system where vapor can exist in the liquid space.

In this case, the liquid vapor mixture acts as a single compressible fluid in a fixed volume with behavior

\[ m \uparrow \downarrow \Rightarrow P_{PRZ} \uparrow \downarrow \]

\[ E \uparrow \downarrow \Rightarrow P_{PRZ} \uparrow \downarrow \]

Volume Increase (outsurge): \[ m \downarrow \Rightarrow P_{PRZ} = P_{sat} \downarrow \Rightarrow P_{sys} \downarrow \]

If \( P_{steam}^{(B)} < P_{PRZ}^{prog} \) \( \Rightarrow \) turn on PRZ heaters \( \Rightarrow \) Increases the boiling (vapor generation)

\[ E \uparrow \Rightarrow P_{PRZ} \approx P_{sys} \uparrow \]

Volume Decrease (insurge): \( V_{Steam} \downarrow \Rightarrow P_{Steam}^{PRZ} \uparrow \Rightarrow T_{Steam}^{PRZ} \uparrow \) due to compression work

\[ T_{CPRZ}^{Steam(B)} > T_{Sat}^{(B)} \) so no condensation

If \( P_{steam}^{(B)} > P_{PRZ}^{prog} \) \( \Rightarrow \) turn off PRZ heaters (usually on to offset heat losses) and if necessary turn on sprays. Sprays add “cold” water to the pressurizer condensing steam.

\[ E \downarrow \Rightarrow P_{PRZ} \approx P_{sys} \downarrow \]

Excessive High Pressure

1st: Open Pilot Operated Relief Valve (PORV)

2nd: Open Pressurizer Safety Valves
Heater Operation

Time (seconds)

Pressure (psia)

0 50 100 150 200 250 300

1980 2000 2020 2040 2060 2080 2100
Heater Operation

**Table:**

<table>
<thead>
<tr>
<th>Time (Seconds)</th>
<th>Vapor Volume Fraction</th>
<th>Vapor Mass Fraction</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0.318</td>
<td>0.0630</td>
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<tr>
<td>50</td>
<td>0.318</td>
<td>0.0635</td>
</tr>
<tr>
<td>100</td>
<td>0.322</td>
<td>0.0640</td>
</tr>
<tr>
<td>150</td>
<td>0.324</td>
<td>0.0645</td>
</tr>
<tr>
<td>200</td>
<td>0.326</td>
<td>0.0650</td>
</tr>
<tr>
<td>250</td>
<td>0.328</td>
<td>0.0655</td>
</tr>
<tr>
<td>300</td>
<td>0.330</td>
<td>0.0660</td>
</tr>
</tbody>
</table>

**Graphs:**

1. **Vapor Volume Fraction vs. Time (Seconds):**
   - Line 1: Steam Volume Fraction
   - Line 2: Steam Mass Fraction

2. **Liquid Density vs. Time (Seconds):**
   - Line 1: Liquid Density
   - Line 2: Vapor Density

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<table>
<thead>
<tr>
<th>rhof</th>
<th>rhog</th>
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<tbody>
<tr>
<td>38.2</td>
<td>5.2</td>
</tr>
<tr>
<td>38.4</td>
<td>5.3</td>
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<td>38.6</td>
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<tr>
<td>38.8</td>
<td>5.5</td>
</tr>
<tr>
<td>39.0</td>
<td>5.6</td>
</tr>
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</table>
```
Spray Operation

Time (seconds) | 0  2  04  06  08  10  10
Pressure (psia) | 2200 2250 2300 2350 2400 2450 2500 2550

![Graph showing the decrease in pressure over time for a spray operation.](image)
Spray Operation

Time (Seconds) vs. Vapor Volume Fraction and Vapor Mass Fraction

- Vapor Volume Fraction
- Vapor Mass Fraction

Time (Seconds)

Liquid Density vs. Vapor Density

- Liquid Density
- Vapor Density

Time (Seconds)
Reactor Coolant System Flow Diagram
Steam Generators

Purposes:
- Transport energy from primary loop to secondary loop and produce steam of given pressure and moisture content.
- Provide radioactive barrier for fission products and other activated materials.

Design Considerations
- Capability to transport energy for warranted load follow within moisture content spec. (not a concern for superheated type S/G).
- Provide as integral part of S/G means of limiting steam flow if steam line breaks.

Example: (see figure)
- Tube Side: Primary Loop
- Shell Side: Secondary Loop
- Carbon Steel Vessel/Inconel Tubing

Design Types
- U-Tube: Compact, large shell side water inventory, recirculation type S/G
- Once-Through: Counter flow, superheater section, relatively small shell side water inventory
U-Tube Steam Generator
Auxiliary Systems

Chemical and Volume Control System (CVCS)

Purposes:
- Maintain proper water level in pressurizer
- Control primary coolant chemistry including pH
- Adjust soluble boron concentration consistent with reactivity requirements
- Initially pressurize system.

Design Considerations
- Capability to rapidly isolate CVCS letdown upon initiation of certain accidents since located outside containment building.

Product (see Figure)
Residual Heat Removal System (RHRS)

Purpose:
Remove energy from core (stored and decay heat) and coolant system (stored) to allow plant cooldown when S/G no longer available for:
- Normal operation
- Accidents

Safety System ⇒ Single Failure Criteria applies (must assume one single active failure of a component called upon to mitigate accident consequences)
Implies ⇒ ≥ 2 Independent Systems (2 Trains) ⇒ Runs off emergency power.

Design Considerations
- High reliability and maintainability in radiation environment
- Automatic isolation from primary system when pressure too high (RHRS lower pressure system [≤~300 psia])
- Testable

Example: (See Figure)
Residual Heat Removal System Flow Diagram
Safety Injection System (SIS)

Purpose:
- Provide emergency coolant to the reactor core to remove stored and decay heat.
- Inject borated water to assure subcriticality following a steamline break accident or LOCA
- Safety System $\Rightarrow$ 2 Trains $\Rightarrow$ Runs off emergency power

Design Considerations
- Automatically activated by plant protection system.
- Testable
- High Reliability

Example: (see Figure)

Reality of Water Injection via Pumps
- High Pressure $\Rightarrow$ Low Volume
- Low Pressure $\Rightarrow$ High Volume

Example: W 4 loop plant

<table>
<thead>
<tr>
<th>Pressure (psig)</th>
<th>Source of Flow</th>
<th>Flow Rate (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1525</td>
<td>2 Centrifugal Pumps (CVCS)</td>
<td>150/each</td>
</tr>
<tr>
<td>&lt;1525</td>
<td>2 Centrifugal Pumps (SI)</td>
<td>425/each</td>
</tr>
<tr>
<td>&lt;650</td>
<td>4 Accumulators</td>
<td>-</td>
</tr>
<tr>
<td>&lt;200</td>
<td>2 RHRS Pumps</td>
<td>3000/each</td>
</tr>
</tbody>
</table>

Water Sources
1) CVCS (Boron Injection Tank) $\Rightarrow$ 900 Gallons
2) Refueling Water Storage Tank $\Rightarrow$ 400,000 Gallons
3) Accumulators $\Rightarrow$ 3,400 Gallons
4) Sump Recirculation
Safety Injection System (SIS)
Main Feedwater System (F/W)

Purpose
- Provide F/W to S/G at desired temperature, pressure, and mass flow rate such that:
  - F/W Flow = Steam Flow
  - S/G water level on programmed value.

Design Considerations
- Can handle load follow transients
- Can isolate F/W flow from S/G (needed for steamline break accident)
- Partially operable in a degraded state

Example: (See Figure)
- Dual F/W pumps
- Startup and main F/W regulating valves
Auxiliary (Emergency) F/W System

Purpose
- Provide alternative source of F/W
  - During no or low power operation
  - During emergency conditions when Main F/W is lost. ⇒ Safety System ⇒≥ 2 Trains

Design Considerations
- Automatic activated by plant protection system
- Testable
- High Reliability
- Easy to isolate to prevent excessive cooldown (steamline accident).

Example: (See Figure)
- Dual Aux F/W pumps (motor driven)
- Dual turbine driven pumps using S/G produced steam
- Aux F/W pumps- S/G paired so failed S/G will not affect intact S/G

Note: Still need electrical power for turbine controls
Figure 5.2-1. Emergency Feedwater System, Flow Diagram
Emergency Electrical System

Purpose
- Provide AC and DC power when on-site and off-site power lost in order to power essential equipment and instruments ⇒ safety system ⇒ ≥ 2 trains

Design Considerations
- Automatic activated by plant protection system
- Testable
- High reliability

Example:
- Two diesel generators (Oconee is hydro)
- Battery Bank
- Two electrical trains
- Load shed & loading features
- Invertors (DC to AC and AC to DC)
Figure 15.3.1. Typical Steam, Condensate and Feedwater System, Flow Diagram