Reactor Control System

Purpose: Through a combination of automatic and manual (operator) actions, maintain the NSSS’s characteristics on their targeted (programmed) values during “normal” operation.

Ex: Nuclear Power = Steam Power = Electrical Power/efficiency
Steam P
S/G (PWR) or Reactor Vessel (BWR) level
PRZ (PWR) level
PRZ P (PWR)
Primary Coolant Temp (PWR) [related to steam P]
Core Void Content (BWR)

PWR

At steady-state \( \dot{Q}_{RX} = \dot{Q}_{sg} \cong \dot{W}_T / \eta \)

\[
\dot{Q}_{RX} = U A_{RX} [T_{RX} - T_{avg}] \\
T_{avg} = \frac{T_{hot} + T_{cold}}{2}
\]

\[
\dot{Q}_{sg} = U A_{sg} [T_{avg} - T_{sat}]
\]

Reactivity: \( \rho = \rho_0 + \rho_{CR} + \rho_b + \rho_{MOD} + \rho_{RX} + \rho_{FP} \) \( \Rightarrow \rho = 0 \Rightarrow \) reactor critical and at steady state

\[
\rho_{MOD} = \alpha_{MOD} (T_{avg} - T_{avg}) \quad \alpha_{MOD} < 0
\]

\[
\rho_{RX} = \alpha_{RX} (T_{RX} - T_{RX_s}) \quad \alpha_{RX} < 0
\]
"NATURAL" RESPONSE TO POWER MANEUVERS

Power maneuvers are typically initiated by actions on the steam side. What is the "Natural" system response (no automatic control operations) to perturbations initiated on the secondary (steam) side?

Suppose we desire \( \dot{W}_T \uparrow \Rightarrow m_{st} \uparrow \Rightarrow \text{Open TCV} \)

\( P_{sg} \downarrow \Rightarrow T_{sat} \downarrow \)

If \( U_{sg} \equiv \text{constant (UTUBE)} \Rightarrow T_{avg} \downarrow \)

\( T_{avg} \downarrow \Rightarrow \rho_{MOD} \uparrow \Rightarrow \rho(+) \Rightarrow \text{RxPwr} \uparrow \)

\( \text{RxPwr} \uparrow \Rightarrow T_{RX} \uparrow \Rightarrow \rho_{RX} \downarrow \Rightarrow \rho \rightarrow 0 \)

The reactor will settle out at a new higher power level such that

\[
\text{RxPwr}_{\text{new}} = U_{A_{RX}} [T_{RX} - T_{avg}]_{\text{new}} = U_{A_{sg}} [T_{avg} - T_{sat}]_{\text{new}} = \left(\frac{\dot{W}_T}{\eta}\right)_{\text{new}} \text{ with } P_{sg}^{\text{new}} < P_{sg}^0
\]

**Continued increases in** \( \dot{W}_T \Rightarrow \text{Continued decreases in } P_{sg} \)**
Suppose we desire $\dot{W}_r \downarrow \Rightarrow m_{st} \downarrow \Rightarrow \text{Close TCV}$

$P_{sg} \uparrow \Rightarrow T_{sat} \uparrow \Rightarrow T_{avg} \uparrow$

$T_{avg} \uparrow \Rightarrow \rho_{MOD} \downarrow \Rightarrow \rho(-) \Rightarrow \text{RxPwr} \downarrow$

$\text{RxPwr} \downarrow \Rightarrow T_{RX} \downarrow \Rightarrow \rho_{RX} \uparrow \Rightarrow \rho \rightarrow 0$

The reactor will settle out at a new lower power level such that

$\text{RxPwr}^{\text{new}} = U A_{RX} [T_{RX} - T_{avg}]^{\text{new}} = U A_{sg} [T_{avg} - T_{sat}]^{\text{new}} = (\dot{W}_r / \eta)^{\text{new}}$ with $P_{sg}^{\text{new}} > P_{sg}^{0}$

Continued decreases in $\dot{W}_r \Rightarrow$ Continued increases in $P_{sg}$

Pressurized Water Reactors are natural load followers. However, this mode of operation results in relatively large swings in $P_{sg}$, and $P_{sg}$ moves in directions opposite of that desired.
Suppose we wish to keep $P_{sg}$ approximately constant over the entire power range.

\[ \dot{W}_T \uparrow \Rightarrow \dot{m}_{st} \uparrow \Rightarrow \text{Open TCV however, require } P_{sg} \rightarrow T_{sat} \rightarrow \text{and } P_{imp} \uparrow \]

\[ \dot{m}_{st} = \frac{Q_{sg}}{UA_{sg}[T_{avg} - T_{sat}]} \]

For $\Delta h$ and $T_{sat} \rightarrow \dot{m}_{st} \uparrow \Rightarrow T_{avg} \uparrow$

\[ T_{avg} \uparrow \Rightarrow \rho_{MOD} \downarrow \Rightarrow \rho(-) \]

In addition \[ \dot{Q}_{sg} \uparrow \Rightarrow \dot{Q}_{RX} = UA_{RX}[T_{RX} - T_{avg}] \uparrow \Rightarrow T_{RX} \uparrow \]

\[ T_{RX} \uparrow \Rightarrow \rho_{RX} \downarrow \Rightarrow \rho(-) \]

\[ \Rightarrow \text{To maintain } P_{sg} \text{ constant at higher powers implies negative reactivity which must be compensated for.} \]

Solution \( \Rightarrow \) Withdraw control rods.
Similarly if we desire $\dot{W}_T \downarrow \Rightarrow \dot{m}_{st} \downarrow \Rightarrow \text{Close TCV} \Rightarrow P_{imp} \downarrow$

$$\dot{m}_{st} = \frac{\dot{Q}_{sg}}{U A \sum \left( T_{avg} - T_{sat} \right)}$$

For $\Delta h$ and $T_{sat} \rightarrow \dot{m}_{st} \downarrow \Rightarrow T_{avg} \downarrow$

$T_{avg} \downarrow \Rightarrow \rho_{MOD} \uparrow \Rightarrow \rho(+) $

In addition $\dot{Q}_{sg} \downarrow \Rightarrow \dot{Q}_{RX} = U A \sum \left( T_{RX} - T_{avg} \right) \downarrow \Rightarrow T_{RX} \downarrow$

$T_{RX} \downarrow \Rightarrow \rho_{RX} \uparrow \Rightarrow \rho(+) $

$\Rightarrow$ To maintain $P_{sg}$ constant at lower powers implies positive reactivity which must be compensated for.

Solution $\Rightarrow$ Insert control rods.
CONTROLLING $T_{avg}$ IMPLIES CONTROLLING $P_{sg}$

![Graph showing the relationship between Programmed $T_{avg}$ and Electrical Power.](image)

The $T_{avg}$ program is chosen based on PRZ size and steam P considerations.

\[
\dot{Q}_{sg} \approx (UA)_{SG} \left( T_{AVG} - T_{sat} \right) \quad \text{where} \quad T_{sat} = T_{Sat}(P_{SG})
\]

Given $T_{avg}$ and $\dot{Q}_{RX} = \dot{Q}_{sg} \approx \dot{W}_T / \eta \Rightarrow \Delta T$ across S/G Fixed $\Rightarrow T_{sat}$ of steam fixed $\Rightarrow P_{SG}$ fixed

In OTSGs, $\uparrow \downarrow \dot{Q}_{SG}$ while holding both $T_{avg}$ and $T_{sat}$ constant can be accomplished by changing the steam generator level (UA). However, $T_{RX}$ still $\uparrow \downarrow$ as before requiring control rod motion.
PWR:
- Nuclear Power
  Electrical Power ⇒ Turbine Impulse Pressure ⇒ Reactor Power ($P_{rel}$)
  ⇒ Core Av. Coolant Temp. ($T_{avg}$)
Automatic Control System:

Operator sets Electrical Power (Load or Demand Setpoint) \( \Rightarrow \) Ref \( P_{\text{imp}} \)

TCV moves which automatically sets high pressure turbine impulse pressure

Impulse Pressure \( \Rightarrow \) Automatically sets Programmed \( T_{AVG} \) \( \Rightarrow \) Automatically moves control rods in or out to make \( T_{AVG} = \) Programmed \( T_{AVG} \)

Speed of rod motion \( \propto |T_{AVG} - \text{Programmed } T_{AVG}| \)

ISSUE: Time lags in system can result in undershoot/overshoot

Example: Step load increase
SOLUTION: Add an “anticipatory” signal based on the difference between turbine output and reactor thermal power

\[ E_1 = \frac{\dot{W}_{\text{load}}}{(\dot{W}_{\text{load}})_{\text{ref}}} - \frac{\dot{Q}_{\text{RX}}}{(\dot{Q}_{\text{RX}})_{\text{ref}}}, \]

\[ E_2 = \text{Programmed } T_{\text{avg}} - T_{\text{avg}} \]

\[ E = G_1 E_1 + G_2 E_2 \]

Rod Speed \( \propto |E| \)
What if control rods result in undesirable positions?

Ex:  Totally withdrawn \( \Rightarrow \) Cannot withdraw anymore \((-\)\(\rho\)

Too deep inserted \( \Rightarrow \)
- Violating control rods insertion limits \( \Rightarrow \) not enough rod
  worth to trip plant to required subcritical condition
- Power shape violates power peaking limits, e.g. \( F_{\text{sh}} \) or \( F_Q \).

How are rods repositioned? Change soluble boron concentration in the primary loop!

Rods too inserted \( \Rightarrow \) Borate
Rods too withdrawn \( \Rightarrow \) Dilute

How much should PPM be changed?

\[
\Delta \rho \left( PPM^{(0)} \rightarrow PPM^{(1)} \right) = \Delta \rho_{\text{rods}} \left( \text{Position}^{(0)} \rightarrow \text{Position}^{(1)} \right)
\]
Special situation of rapid load reduction

Electrical $P_{rel} \downarrow$ (with time) rapidly $\Rightarrow$ 
\[
\begin{cases} 
T_{AVG} > \text{Programmed } T_{AVG} \\
\text{Core } P_{rel} > \text{Electrical } P_{rel}
\end{cases}
\]
rapidly

$\Rightarrow$ Control rods insert $\Rightarrow$ Core $P_{rel} \downarrow$

Problem: Control rods don’t insert fast enough $\Rightarrow$ Core $P_{rel} >$ Electrical $P_{rel}$

$\Rightarrow$ $T_{AVG} \uparrow$ continues $\Rightarrow$ $T_{AVG} >>$ Programmed $T_{AVG}$.

What happens to steam $P$?

Electrical $P_{rel} \downarrow$ rapidly $\Rightarrow$
\[
\begin{cases} 
\text{Turbine control valves partially close} \\
T_{AVG} \uparrow
\end{cases}
\]
$\Rightarrow$ Steam $P \uparrow$

Automatic Control System Actions

Rapid decrease in Electrical $P_{rel} \downarrow$ $\Rightarrow$
\[
\begin{cases} 
T_{AVG} \uparrow \\
\text{Control rods inserted} \\
\text{Steam } P \uparrow
\end{cases}
\]

Core $P_{rel} \downarrow$

Core $P_{rel} \downarrow$ but Core $P_{rel} >$ Electrical $P_{rel}$ $\Rightarrow$
\[
\begin{cases} 
T_{AVG} \uparrow \\
\text{continues} \\
\text{Steam } P \uparrow
\end{cases}
\]

\[
\left\{ \frac{T_{AVG} - \text{Programmed } T_{AVG}}{\Delta T_{Set \text{ Point}}} \right\} > \Delta T_{Set \text{ Point}} 
\]
$\Rightarrow$ If $\left\{ \text{Steam } P > \text{Steam } P_{Set \text{ Point}} \right\}$ $\Rightarrow$ Open Steam Dump (Turbine Bypass)

Valves $\Rightarrow$ Blow Steam (to condenser or atmosphere) $\Rightarrow$ Steam $P \downarrow$.

Steam Temp $\downarrow \Rightarrow \Delta T_{SG} \uparrow \Rightarrow T_{AVG} \downarrow ...$ Steam dump valves stay open until setpoint values not exceeded.
Feedwater Pump Speed Control

![Diagram showing the flow of water from a feedwater pump through a steam generator and into a high pressure turbine, with control valves and pressure changes depicted graphically.]

Typical Pump Curve

![Graph showing the relationship between pressure change ($\Delta P_p$) and flow rate ($G$) with two distinct RPM levels (RPM 1 and RPM 2).]
Pressure Drop Across the Feed Control Valve

\[
\Delta P_{FCV} \approx P_{dis} - P_{SG} = K_{FCV}(H_{FCV}) \frac{G_{FW}^2}{2\rho}
\]

\[K_{FCV}(H_{FCV}) \approx \frac{K_{FCV_0}}{H_{FCV}^2}\]

\[G_{FW}^2 = 2\rho\Delta P_{FCV} \frac{H_{FCV}^2}{K_{FCV_0}} \Rightarrow G_{FW} \propto \sqrt{\Delta P_{FCV}} H_{FCV}\]

If the pressure drop across the feed control valve is constant, then feed flow increases linearly with valve position (linear control valve).

This simplifies the control problem.

⇒ Pump speed controller adjusts pump RPMs such that

\[P_{dis} - P_{SG} = \Delta P_{FCV} = \text{Constant}\]

⇒ For \(P_{SG} \rightarrow \text{Constant}\)

⇒ FCV \(\uparrow\downarrow\) \(G_{FW} \uparrow\downarrow\) \(P_{dis} \downarrow\uparrow\) \(\Rightarrow \Delta P_{FCV} \downarrow\uparrow\)

⇒ RPMs \(\uparrow\downarrow\) Pdis \(\uparrow\downarrow\) \(\Delta P_{FCV} \rightarrow \text{Constant}\)
Turbine Control

\[ P_{\text{steam}} \rightarrow \text{Turbine Control Valve} \rightarrow P_{\text{impulse}} \]

**P_{\text{impulse}} Controller**

Set Elec. \( P_{\text{rel}} \downarrow \Rightarrow \text{Set Prog. } P_{\text{impulse}} \downarrow \Rightarrow (P_{\text{impulse}} - \text{Prog } P_{\text{impulse}}) > 0 \Rightarrow \text{Close down on turbine control valve} \Rightarrow P_{\text{impulse}} \downarrow

How is Prog \( P_{\text{impulse}} \) determined?

Require \( \text{RPM}_{T/G} = \text{Prog. RPM}_{T/G} (1800 \, @ \, \text{all Elec. } P_{\text{rel}} \Rightarrow \text{AC frequency}) \)

With fixed \( \text{RPM}_{T/G} \) and Elec. \( P_{\text{rel}} \Rightarrow P_{\text{impulse}} \) uniquely specified

**RPM Controller**

\( (\text{RPM}_{T/G} - \text{Prog RPM}_{T/G}) > 0 \Rightarrow \text{Close down on control valve} \Rightarrow P_{\text{impulse}} \downarrow \Rightarrow \text{RPM}_{T/G} \downarrow

Error signal for T/G controller controls both \( P_{\text{impulse}} \) and \( \text{RPM}_{T/G} \) utilizing Turbine Control Valves
**S/G Level Control**  (UTUBE)

Programmed level to assure S/G tubes covered to assure adequate heat transfer and separators not flooded.

![Graph showing level % vs. Relative Power](image)

1. **S/G level correct.**

   If Steam Mass Flow Rate = F/W Mass Flow Rate \( \Rightarrow \) S/G level constant.

   If S/G level correct, adjust F/W Flow Rate such that it equals Steam Flow Rate. **Adjustment done by valve and/or variable speed F/W Pump**

2. **S/G level not correct.**

   Adjust F/W Flow Rate to bring steam generator level to programmed value.

**Issue:** Load follow maneuver

\[
\text{Electrical } P_{rel} \uparrow \Rightarrow \text{Turbine Control Valves Open}
\]

\[
\begin{align*}
\Rightarrow & \left\{ \begin{array}{l}
\text{Steam flow} \uparrow \\
\text{Steam } P \downarrow
\end{array} \right. \\
\Rightarrow & T_{sat} \downarrow \Rightarrow \text{Water in S/G Flashes} \Rightarrow \text{S/G Level} \uparrow
\end{align*}
\]

“Swell” effect (short lived phenomena)
Electrical $P_{rel} \downarrow \Rightarrow \ldots \Rightarrow S/G$ level $\downarrow \ldots$ Called “Shrink” effect

Automatic Control System Actions

\[
\begin{align*}
\text{Electrical } P_{rel} \uparrow \Rightarrow \begin{cases}
S/G \text{ swell} \Rightarrow F/W \text{ Flow} \downarrow \\
\text{Steam Flow} \uparrow \Rightarrow \text{Desire F/W Flow} \uparrow 
\end{cases} \\
\text{Conflict!}
\end{align*}
\]

How resolved?

a) Delay (lag compensation) $S/G$ level signal to automatic control system

b) Control $F/W$ flow by Steam/$F/W$ Flow mismatch

\[
\begin{align*}
\text{Electrical } P_{rel} \uparrow \Rightarrow \begin{cases}
S/G \text{ Swell} \\
\text{Steam Flow} \uparrow 
\end{cases} \Rightarrow F/W \text{ Flow} \uparrow \\
F/W \text{ Flow} \uparrow \text{ until } S/G \text{ level restored and } F/W \text{ flow} = S/G \text{ flow.}
\end{align*}
\]
**Integration of Control**

Directly Controlled: $T_{AVG}$, Level$_{S/G}$, $P_{impulse}$, RPM$_{T/G}$

Not Directly Controlled: Elec. $P_{rel}$, Core $P_{rel}$, $m_{Steam}$, $P_{Steam}$, $m_{F/W}$

Question: How do we know these not directly controlled parameters will have desired values?

Assume Steady-State

Set Demanded Elec. $P_{rel}$ $\Rightarrow$ \( \left( P_{impulse}/RPM_{T/G} \right) \) $\Rightarrow$ Elec. $P_{rel}$ $\Rightarrow$ Core $P_{rel}$ $\Rightarrow$ $\dot{Q}_{RX}$

\[ P_{impulse} \Rightarrow T_{AVG} \]

\[ \dot{Q}_{RX} = \dot{Q}_{SG} = U_{SG} [T_{AVG} - T_{SG}(P_{steam})] \Rightarrow P_{steam} \]

\[ \dot{Q}_{SG} = h_{steam}(P_{steam}) - h_{F/W} \]

\[ \Rightarrow \bar{m}_{steam} = \frac{\dot{Q}_{SG}}{h_{steam}(P_{steam}) - h_{F/W}} \]

Elec. $P_{rel}$ $\Rightarrow$ Level$_{S/G}$

Level$_{S/G}$ $\Rightarrow$ $\bar{m}_{steam}$ = $\bar{m}_{F/W}$

Conclusion: Specifying: Elec. $P_{rel}$

Directly Controlling: $T_{AVG}$, Level$_{S/G}$, $P_{impulse}$, RPM$_{T/G}$

Assures

Not Directly Controlled: Core $P_{rel}$, $\dot{Q}_{SG}$, $m_{steam}$, $m_{F/W}$, $P_{Steam}$

Have Desired Values!

Note constraints: $P_{Steam} > P_{impulse}$

$\Delta P_{F/W}$ has to be such to meet this constraint.
Response to Load Maneuver

\[ \text{Elec. } P_{\text{rel}} \downarrow \Rightarrow \text{Prog. } P_{\text{impulse}} \downarrow \Rightarrow \text{Turbine Control Valve} \downarrow P_{\text{impulse}} \downarrow \]

\[ \text{Turbine Control Valve} \downarrow P_{\text{steam}} \uparrow \Rightarrow T_{\text{Steam}} \uparrow \Rightarrow \Delta T_{\text{S/G}} \downarrow \Rightarrow \dot{Q}_{\text{sg}} \downarrow \]

\[ T_{\text{AVG}} \uparrow \Rightarrow \text{Core } P_{\text{rel}} \downarrow \]

\[ \text{Prog. } T_{\text{AVG}} \downarrow \Rightarrow \text{Control Rods Insert} \]

When \( P_{\text{WR}} < \dot{Q}_{\text{sg}} \Rightarrow T_{\text{AVG}} \downarrow \Rightarrow T_{\text{Steam}} \downarrow \Rightarrow P_{\text{Steam}} \downarrow \rightarrow \)

\[ \begin{cases} P_{\text{steam}} \uparrow \Rightarrow \text{SG}_{\text{h}} \downarrow \text{ then } \uparrow \\ TCV \downarrow \Rightarrow \dot{m}_{\text{steam}} \downarrow \end{cases} \Rightarrow \text{F/W Control Valves} \downarrow \Rightarrow \dot{m}_{\text{f/w}} \downarrow \rightarrow \]

Note: RPM_{T/G} control is also required to assure Elec. \( P_{\text{rel}} \) demanded satisfied \( \Rightarrow \)
Indirectly control \( \dot{m}_{\text{steam}} \) to correct value.
**Prz level**

Electrical $P_{rel} \Rightarrow$ Programmed $T_{AVG} \Rightarrow$ Primary loop Av. Water Density $\Rightarrow$ Primary Loop Water Volume $\Rightarrow$ Unique Prz Level (Programmed Prz Level)

Prz level maintained by CVCS

Prz level $\geq$ Prog. Prz level $\Rightarrow$ CVCS Charging Rate $\leq$ CVCS Letdown Rate.

Automatic Control System

$T_{avg} \Rightarrow$ Programmed Prz. Level $\Rightarrow$ CVCS Rate dependent upon Prz. Level $\leq$

Programmed Prz. Level

When $T_{avg} \rightarrow$ and Prz Level $=$ Prog. Prz level $\Rightarrow$ CVCS Charging Rate $=$ CVCS Letdown Rate.
Prz Pressure

- Objective: Hold Primary System P constant ⇒ $P_{\text{set point}}$
- Assume SS operation ⇒ $P = P_{\text{set point}}$

Prz Heaters on sufficient to offset heat losses from Prz and spray circulation (some to keep Prz chemistry same as rest of RCS & Minimize Thermal Shock)

Electrical $P_{\text{rel}} \uparrow \downarrow \Rightarrow T_{\text{AVG}} \downarrow \uparrow$ initially ⇒ Prz level $\downarrow \uparrow \Rightarrow \text{Prz} P \downarrow \uparrow$

Automatic Control System

\[
(Prz \ P - P_{\text{Set Point}}) > 0 \Rightarrow \text{Prz Heaters Output} \downarrow
\]
\[
< 0 \Rightarrow \text{Prz Heaters Output} \uparrow
\]

If $(Prz \ P - P_{\text{Set Point}}) > \Delta P_{\text{Set Point}}(1) \Rightarrow \text{Prz Sprays} \uparrow \Rightarrow \text{Prz Steam Condenses} \Rightarrow \text{Prz} P \downarrow$

If $(Prz \ P - P_{\text{Set Point}}) > \Delta P_{\text{Set Point}}(2) > \Delta P_{\text{Set Point}}(1) \Rightarrow \text{Prz Pilot Operated Relief Valve (PORV) Opens} \Rightarrow \text{Prz Steam blows down to Prz Relieve Tank} \Rightarrow \text{Prz} Pr \downarrow$

If $(Prz \ P - P_{\text{Set Point}}) < \Delta P_{\text{Set Point}}(3) \Rightarrow \text{Backup Heaters On}$

Longer Term Effect:

Elec. $P_{\text{rel}} \uparrow \downarrow \Rightarrow \text{Prog.} T_{\text{AVG}} \uparrow \downarrow \Rightarrow T_{\text{AVG}} \uparrow \downarrow \text{via } T_{\text{AVG}} \text{ control} \Rightarrow ...$
Figure 7-6. NSSS Integrated Plant Control System