FTC Reactor Engineering

NUCLEAR REACTOR INSTRUMENTION AND CONTROL

SUDARNO

PRTRN – ORTN -BRIN

Tangerang Selatan, 19 Februari 2025

Biodata

Nama : Sudarno

Unit Kerja : PRTRN - ORTN - BRIN

Pendidikan :

- S1 Electrical Engineering
- S2 Automatic Control
- S3 Automatic Control & Signal Processing

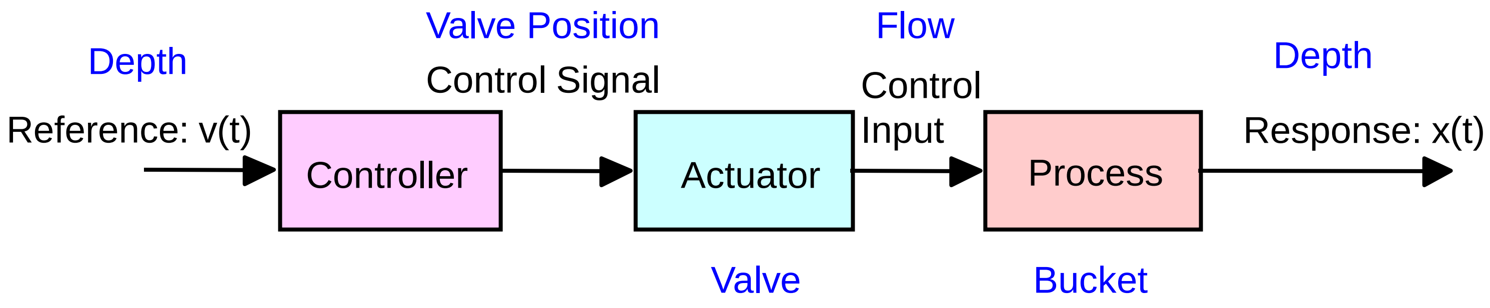
Bidang Keahlian : Instrumentation & Control, Signal Processing, Intelligent System

Outline

- Basis of Control System
- PWR Control System
- Reactor Protection System

1. Basis of the Control System

(1) Feed-forward Control System



Characteristics

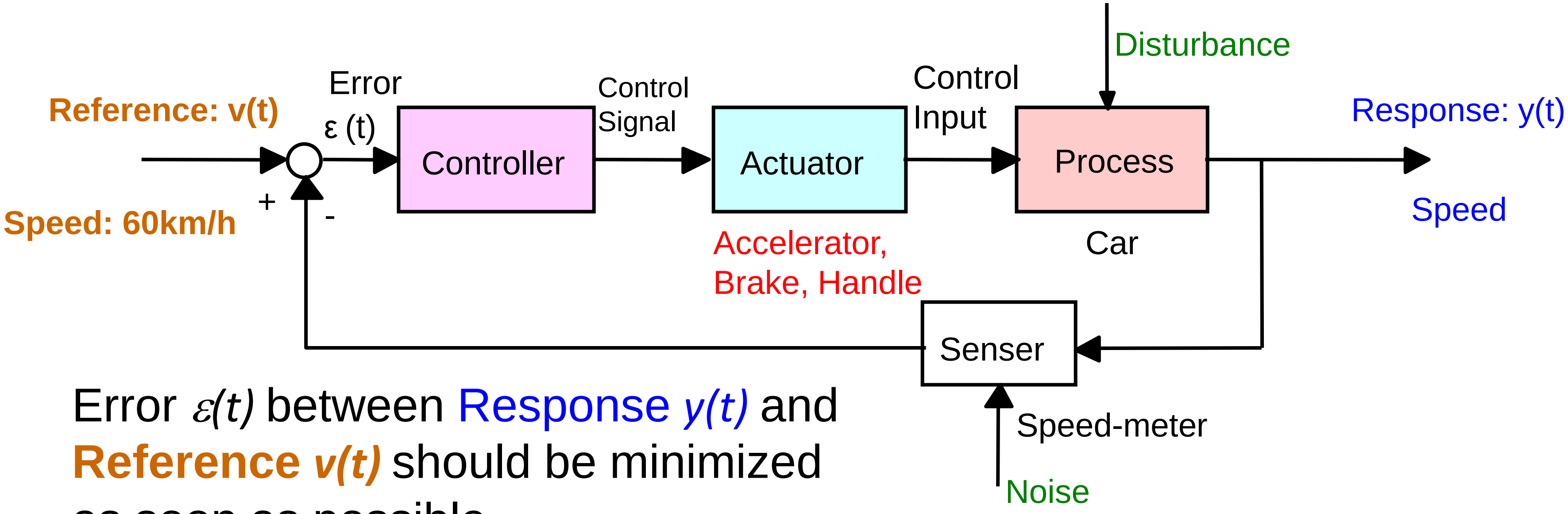
(1)Open-loop

(2)One direction

(3)Fixed Control in shortest way

(4)Good performance without Disturbance

(2) Feedback Control System



Error $\varepsilon(t)$ between Response *y(t)* and **Reference *v(t)*** should be minimized as soon as possible.

Characteristics

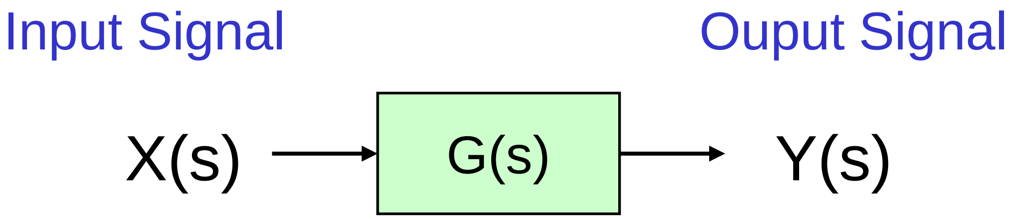
(1)Closed-loop

(2)One direction

(3)Reference value

(4)Good performance with Disturbance or Measurement Noise

Definition of Transfer Function



Transfer Function is defined as

$$G(s) = \frac{Y(s)}{X(s)}$$

Here,
X(s): Laplace transform of input x(t)
Y(s) : Laplace transform of output y(t)

Laplace Transform

The **Laplace transform** of a function *f* is defined as

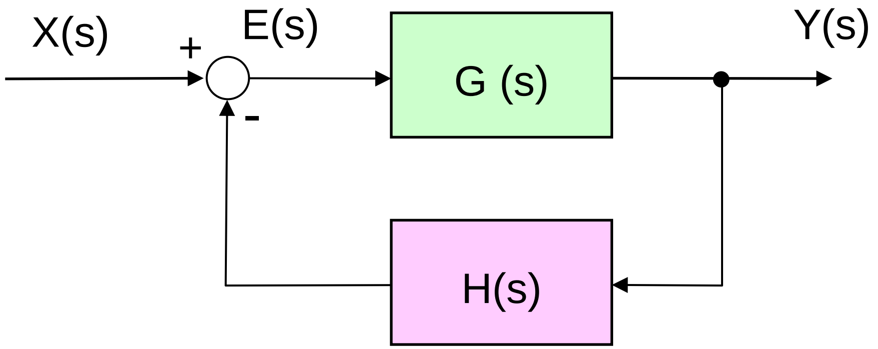
$$F(s) = \int_0^{\infty} f(t) e^{-st} dt$$

f is defined by *t>0* (*f* contains no impulse at *t = 0)*
F is a complex-valued function of complex numbers
t : the time variable (in sec)
s: the (complex) frequency variable (in sec^{-1})

The inverse of **Laplace transform** is defined as

$$f(t) = \frac{1}{2\pi j} \int_{\sigma - j\omega}^{\sigma + j\omega} F(s) e^{st} ds$$

Transfer Function of Feedback System



Block Diagram of Feedback Control System

$$Y(s) = G(s)E(s) = G(s)\{X(s) - H(s)Y(s)\} = G(s)X(s) - G(s)H(s)Y(s)$$

Transfer Function of Closed-Loop (Reactor System) *is defined as*

$$\frac{Y(s)}{X(s)} = \frac{G(s)}{1+G(s)H(s)}$$

G(s): Transfer Function

H(s): Feedback Transfer Function

G(s)H(s) : Open-loop Transfer Function

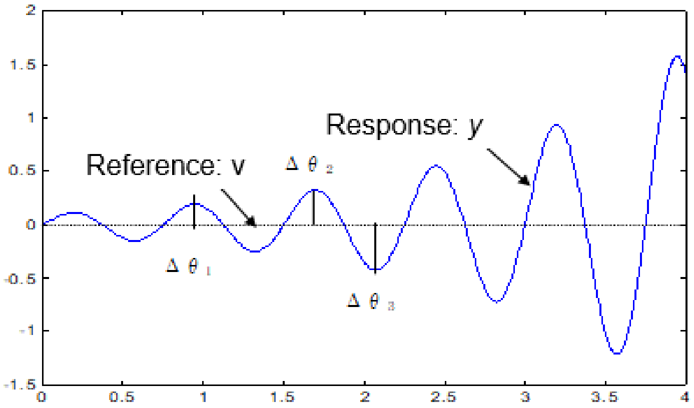
Stability

Stability in time domain

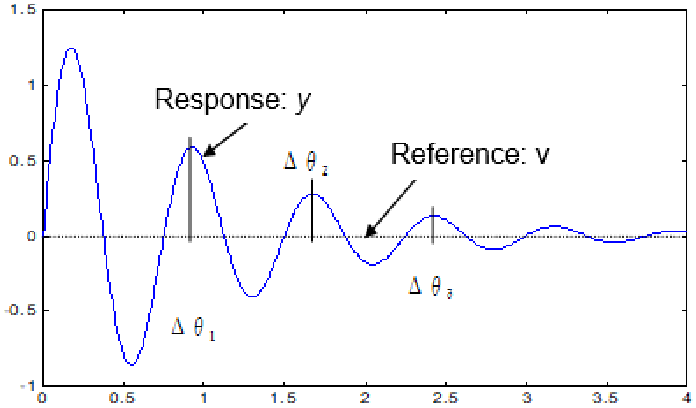
- Change of Reference
- Disturbance
- Measurement Noise

$t \rightarrow \infty$

error: $\varepsilon(t) \approx 0$



Unstable System



Stable System (y → v)

System Stability by Transfer Function

$$G(s) = \frac{b_m s^m + b_{m-1} s^{m-1} + \cdots + b_1 s + b_0}{s^n + a_{n-1} s^{n-1} + \cdots + a_m s^m + \cdots + a_1 s + a_0}$$

numerator

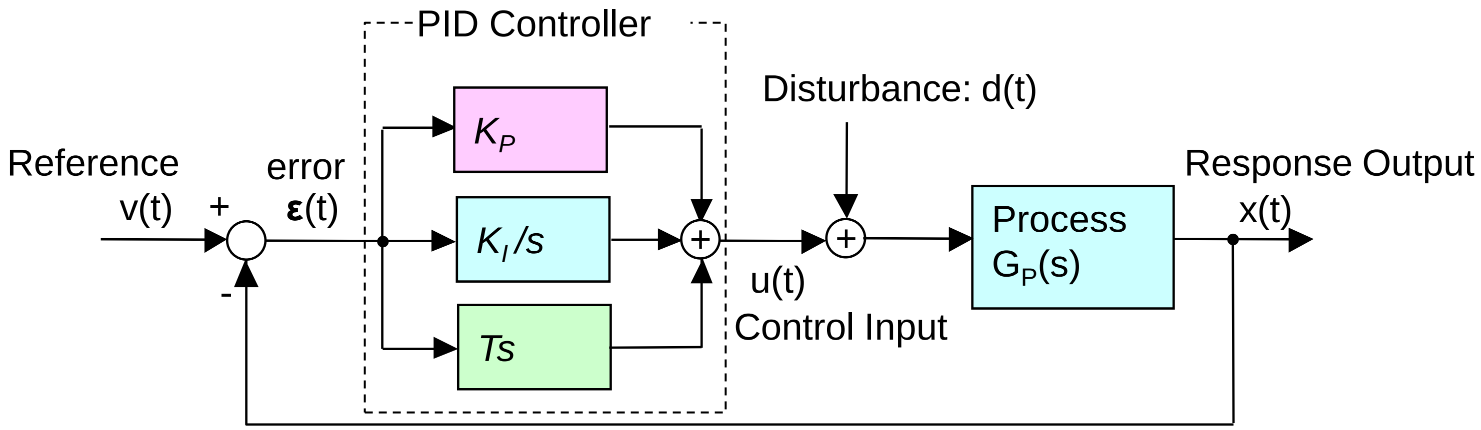
denominator

The characteristic equation is obtained by setting the denominator of the transfer function equal to zero.

$$s^n + a_{n-1} s^{n-1} + \cdots + a_m s^m + \cdots + a_1 s + a_0 = 0$$

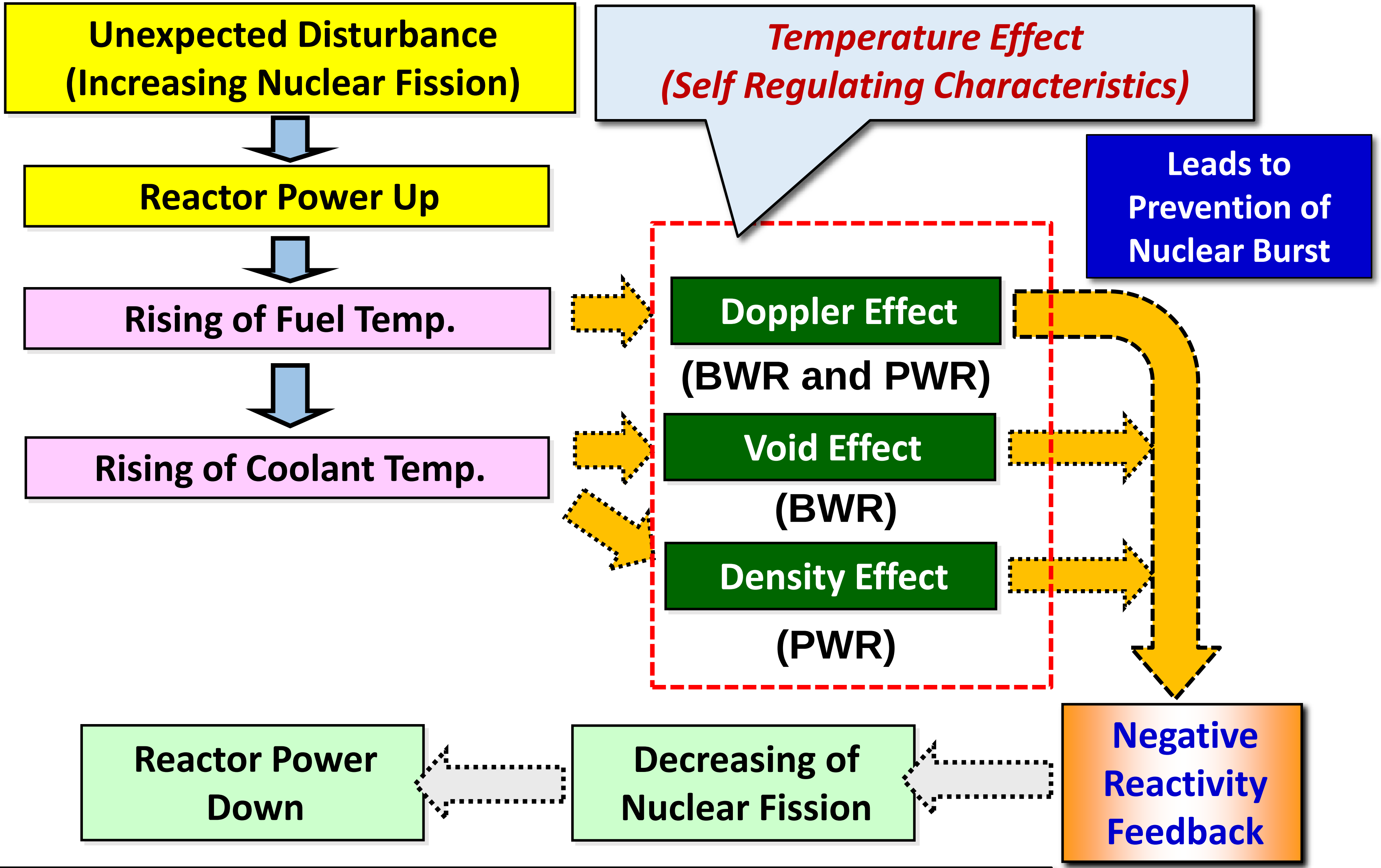
The roots (poles) of characteristic equation are usually negative or real part of conjugate complex number ($s_1 = \sigma + j\omega, s_1^* = \sigma - j\omega$) are **less than zero**, if the system is stable.

PID Controller



1. **Proportional term**
   It makes a change to the output that is proportional to the current error value. →A high proportional gain results in a large change in the output for a given change in the error.
2. **Integral term**
   Summing the instantaneous error over time (integrating the error) gives the accumulated offset
3. **Derivative term**
   The rate of change of the process error is calculated by determining the slope of the error over time

Concept of "Feedback Reactivity" (Temperature Effect)



If Temp. in a core rises, Reactor Power ***automatically goes down*** by ***Temperature Effect*** which is ***Physical Phenomenon.***

Reactor Control System of PWR

MAIN PURPOSE

- The reactor control system maintains the heat generation in the reactor and the heat transfer and steam generation in the steam generator.

- The reactor control system also attenuates transients, without reactor trip, caused by changes in the turbine load, and provides the ability to recover from transients and maintain the plant in a stable condition.

PWR: Turbine is main. Reactor follows.

When the generator power demand changes, the turbine load of the secondary system is adjusted first, and then the reactor power of the primary system follows the turbine load.

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Reactor Control System of PWR

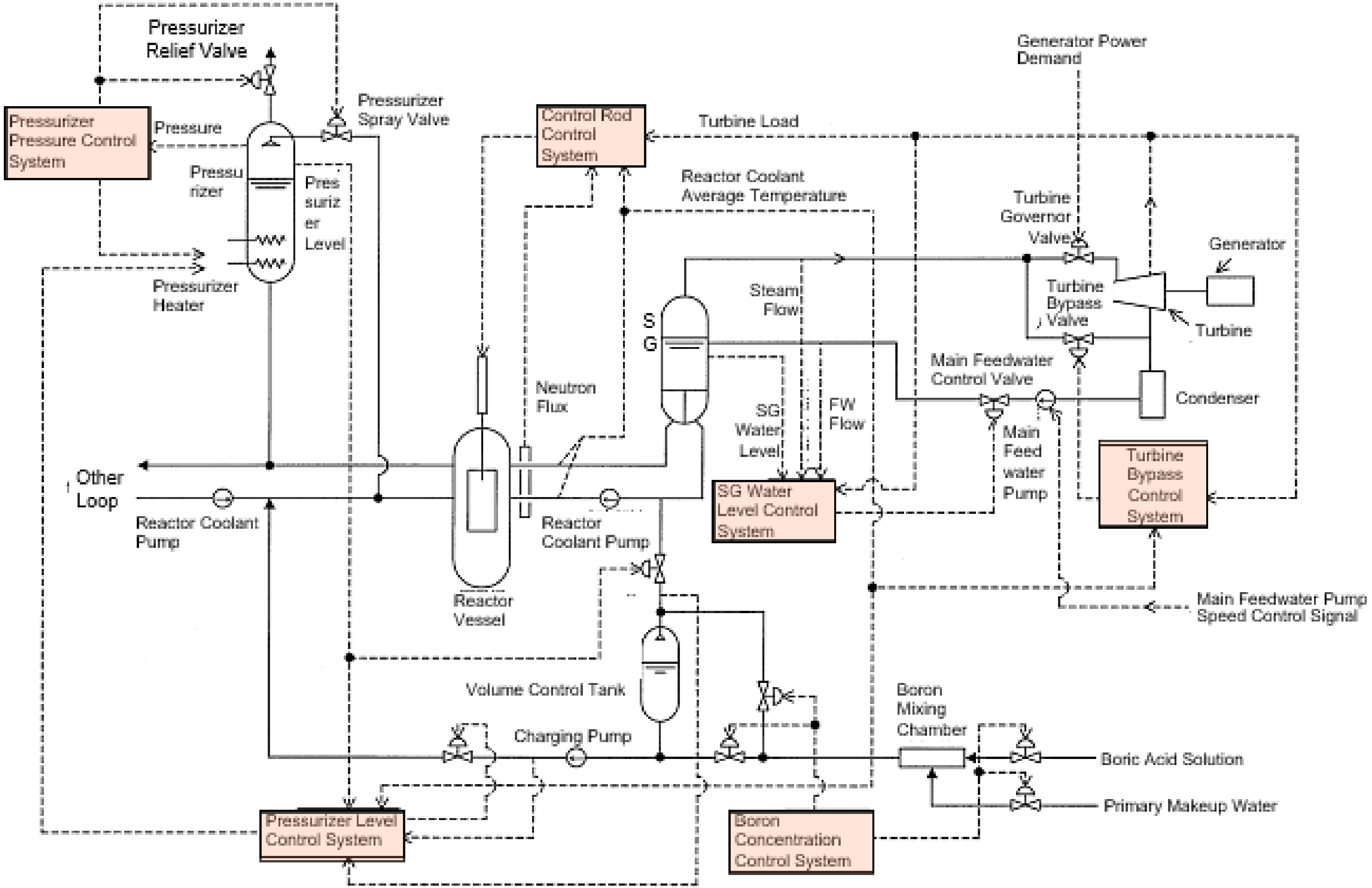
1. Control Rod Control System
2. Pressurizer Pressure Control System
3. Pressurizer Water Level Control System
4. Turbine Bypass Control System
5. Steam Generator Water Level Control System
6. Boron Concentration Control System

Reactivity Control :

Fast : Plant power changes (turbine load change, etc) → 1. Control Rod

Slow : fuel burnup and changes in the xenon concentration → 6. Boron Concentration

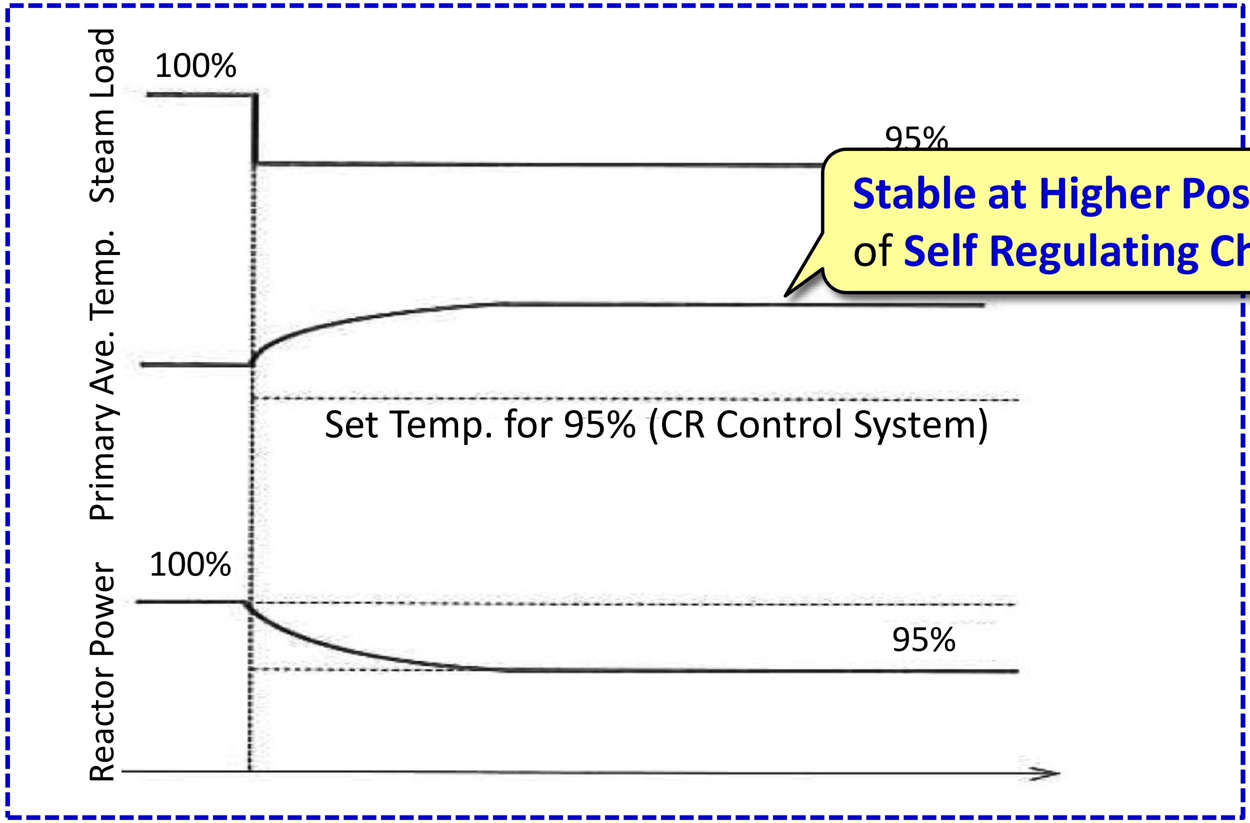
Overall Configuration of Reactor Control System in PWR



(1) Control Rod Control System

Case of without CR Control System (Only Self Regulating Characteristics)

- When turbine load decreases slightly, the Reactor power will decrease by inserting of Negative Reactivity given by Moderator Temp. Effect due to rising of Primary Average Temp..
- That to say, primary and secondary systems will be balanced by **Self Regulating Characteristics** without any control actions by the CR Control System.
- However, this T_{avg} will be stable with **higher than the initial temp**.. Which is different temp. from the Set Temp. of the CR Control System.

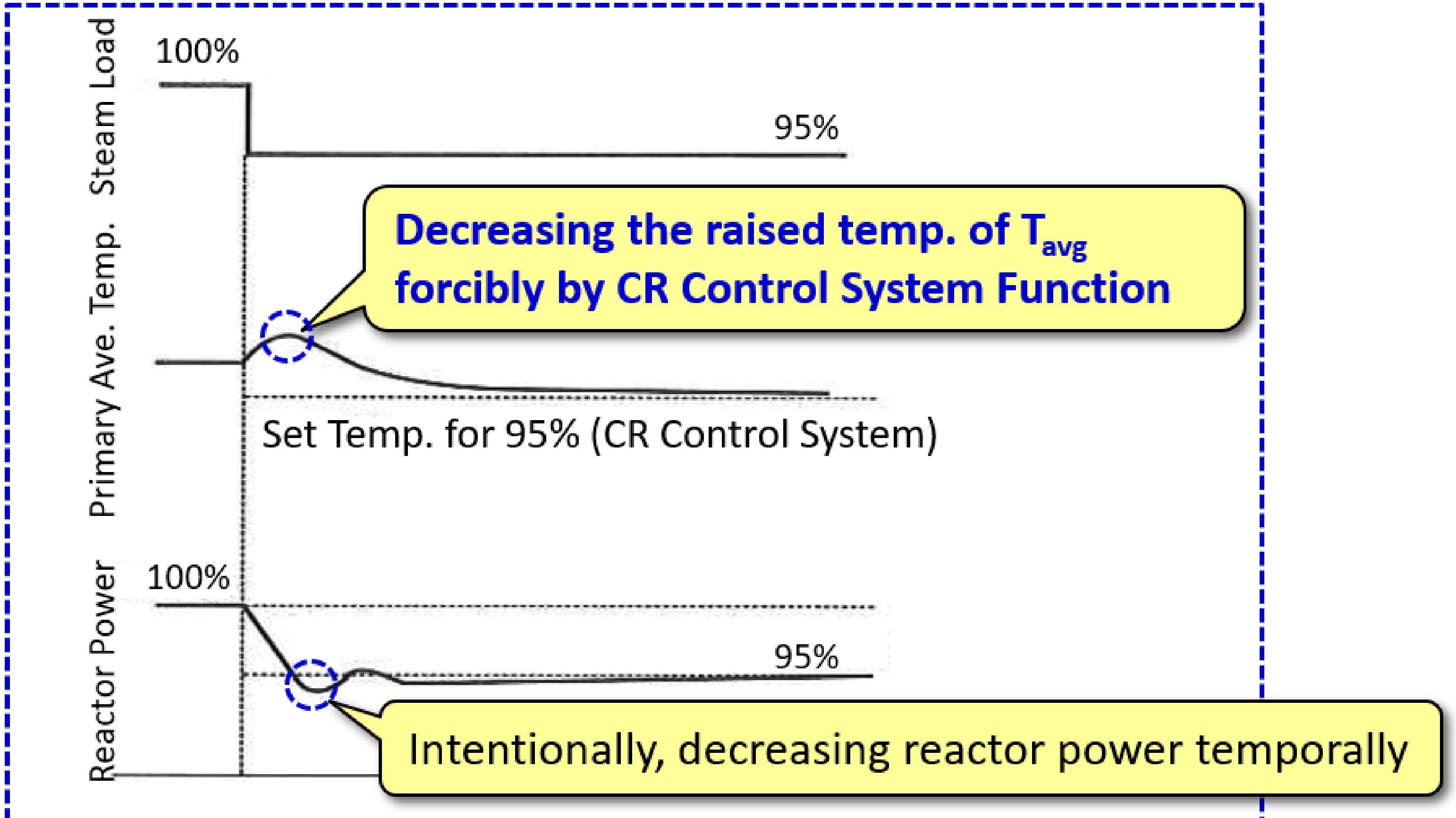


Stable at Higher Position by effect of **Self Regulating Characteristics**

Source: 編書 岡芳明・鈴木勝男、原子炉動特性とプラント制御、第4章加圧水型軽水炉の運転制御の実際、4-1PWRの運転制御方式、㈱オーム社、平成20年3月

Function of CR Control System

- To keep T_{avg} to the Set Temp. of the CR Control System, not only expecting to Self Regulating Characteristics but also taking control action by the CR Control System is required.
- By decreasing of reactor power to under than the turbine loading temporally, the T_{avg} raised transiently at the initial period decreasing of load will be decreased to the Set Temp. forcibly.
- The CR Control System is **designed** so that to **Satisfy** the function mentioned above.

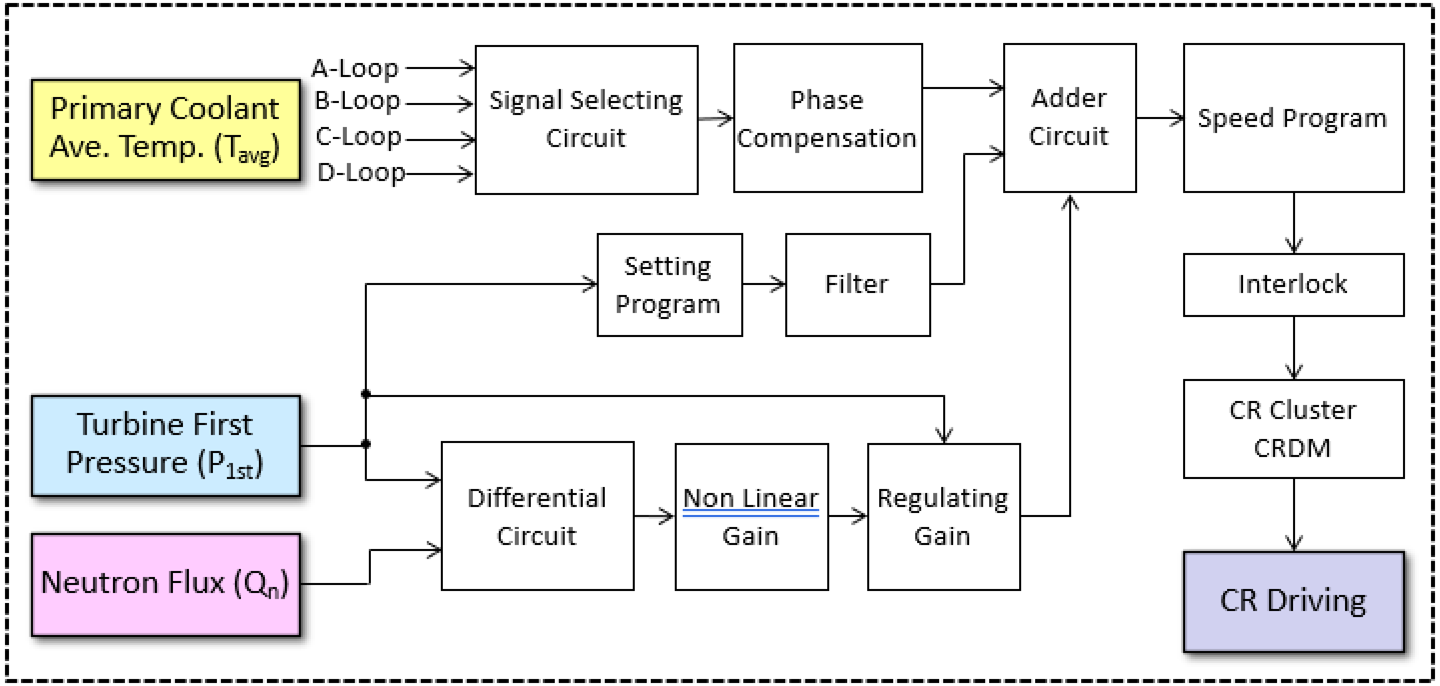


(1) Control Rod Control System

The control rod control system automatically regulates the position of control rod clusters in a control bank in order to control the reactor power by using three types of input signals: primary loop average temperature, neutron flux, and the first stage turbine impulse pressure.

Input Signals

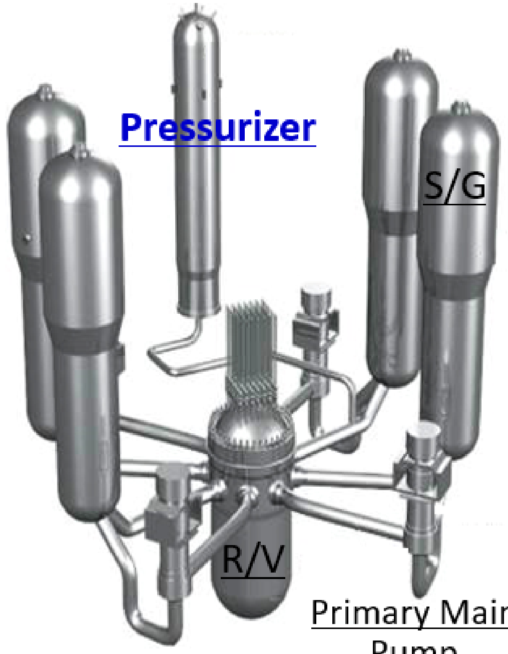
- **Primary Coolant Average Temp.**: (T_{avg}) → As Difference between Both mentioned below
- **Turbine First Pressure**: (P_{1st}) → As Consumed Heat Quantity at Turbine
- **Neutron Flux**: (Q_n) → As Generating Heat Quantity at Reactor



(2) Pressurizer pressure control system (PID)

System Function and System Configuration

- The Pressurizer Pressure Control System controls primary pressure to be **constant**.
- The system consists of: 1) **Pressurizer Proportional Heater**, 2) **Pressurizer Backup Heater**, 3) **Pressurizer Spray Valve**, 4) **Pressurizer Release Valve**



Variation of Turbine Loading → Change of Primary Coolant Temp.

↓

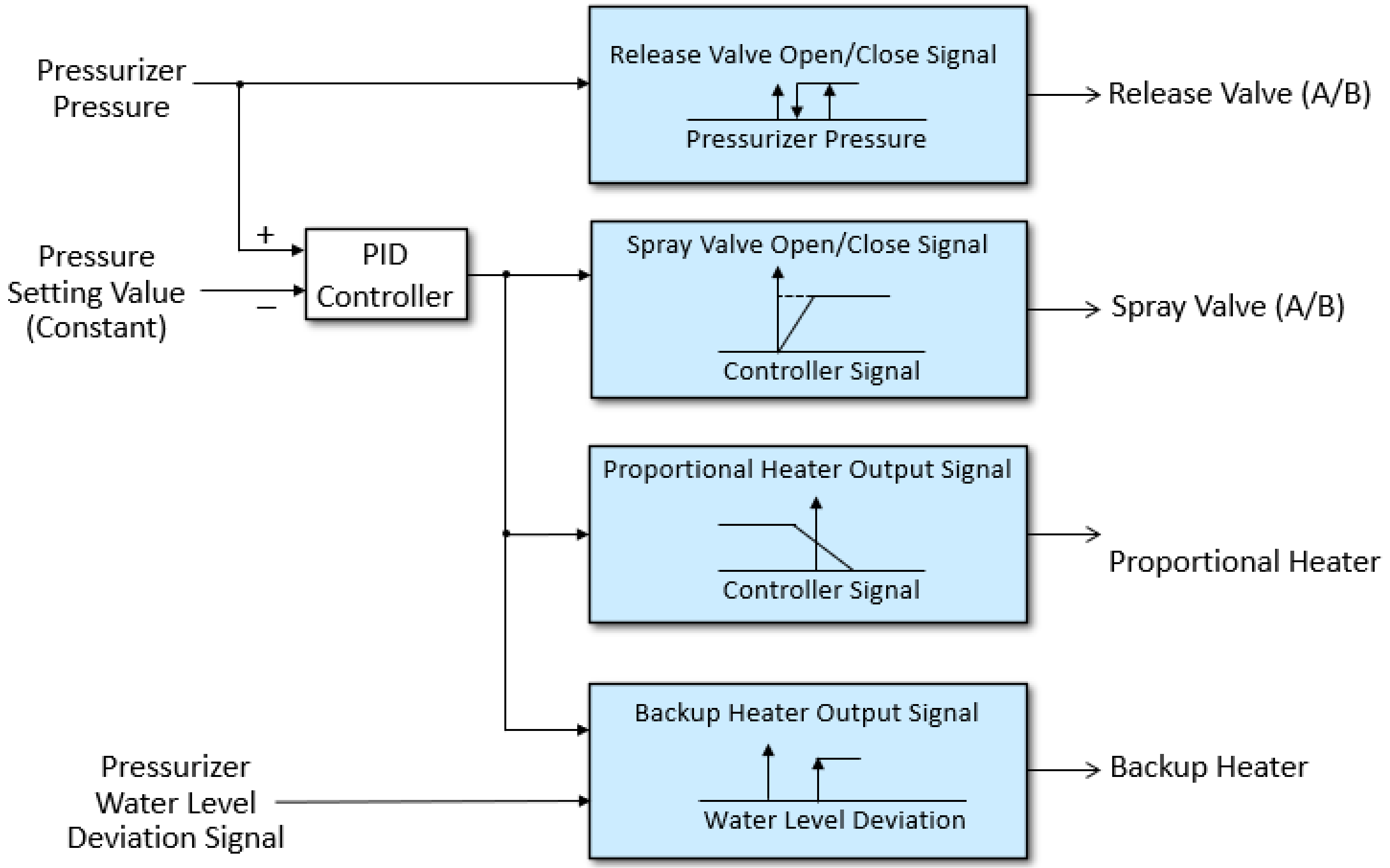
Expansion/Shrink of Primary Coolant → **Change of Pressurizer Pressure**

↓

Control of Pressurizer Pressure with **Saturated Temp. of Reactor** by **Pressurizer Pressure Control System**

- Incase of **Decreasing** of Pressure (Setting Value=15.7MPa):
  - ☞ Recovering by **Electrical Heater** provided in the liquid Phase in a Pressurizer
- Incase of **Increasing** of Pressure (Setting Value=15.7MPa):
  - ☞ Decreasing by **Condensing Steam** by Spraying of Primary Cold Leg Water
- Incase of **More Increasing** Pressure (≥16.4MPa):
  - ☞ Decreasing by **Release Valve Open**

Circuit Diagram of Pressurizer Pressure Control System



Pressurizer Water Level Control System (1/2)

Relation between Pressurizer Water Level and T_{avg} (Primary Coolant Ave. Temp.)

Variation of Turbine Loading

↓

Expansion/Shrink Primary Coolant

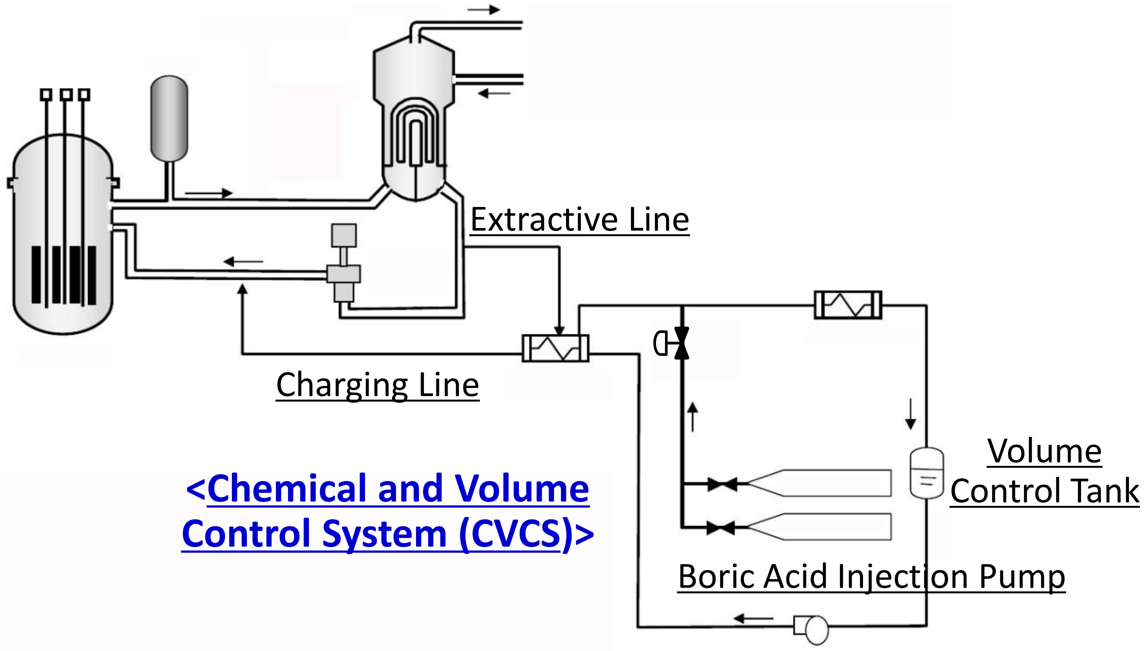
↓

Change of Pressurizer Water Level ⇔ T_{avg} ⇔ Change of Pressurizer Pressure

Proportional Relation with T_{avg}

↓

Regulating of Charge Line Flow of Chemical and Volume Control System ⇐ Pressurizer Water Level Control System



<Chemical and Volume Control System (CVCS)>

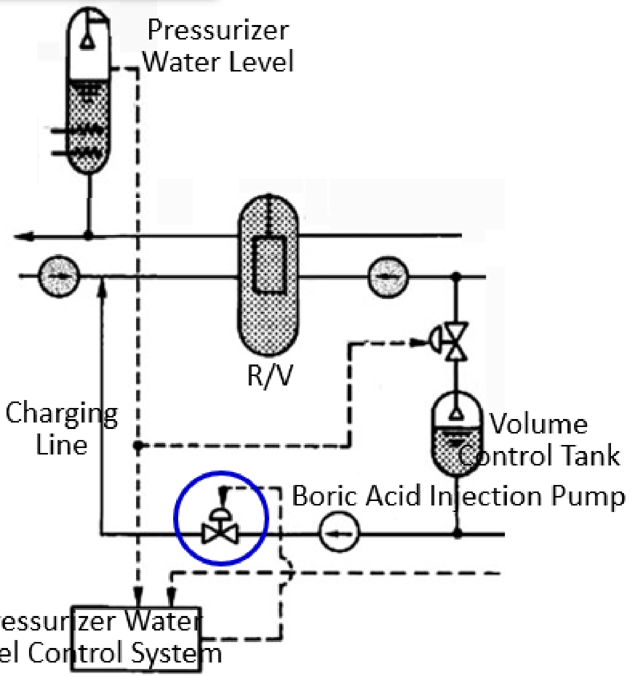
Pressurizer Water Level Control System (2/2)

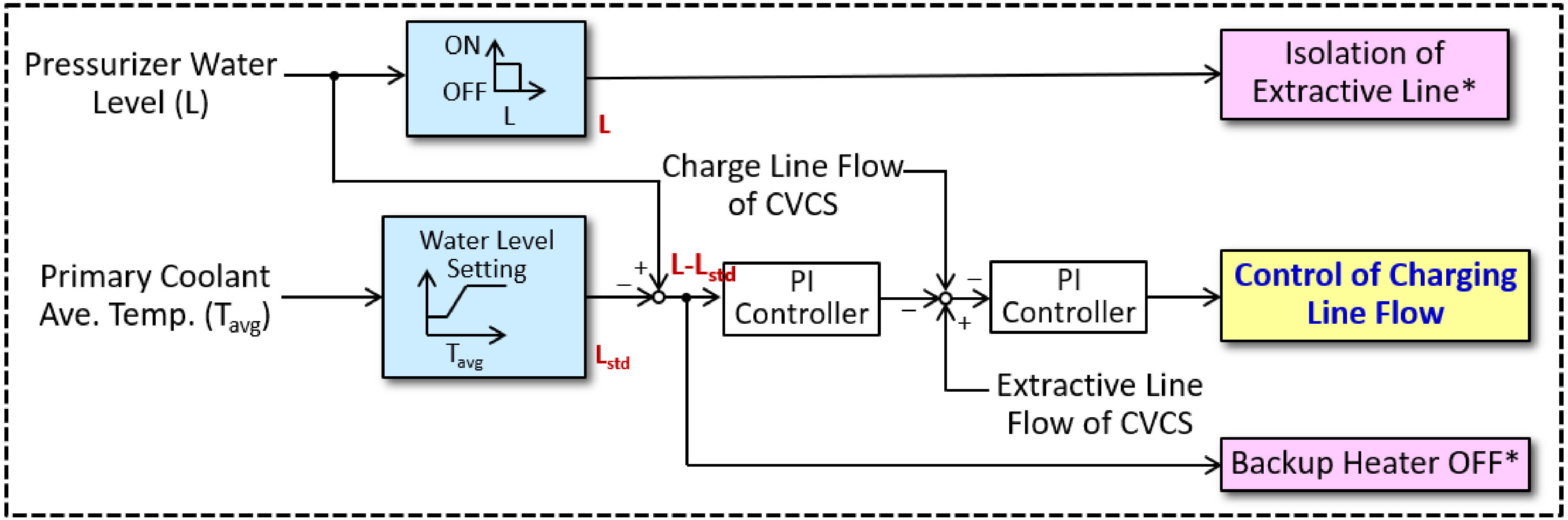
Control by Three Factors

- Deviation from Standard Water Level setting based on T_{avg} ($L - L_{std}$)
- Charge Line Flow of Chemical & Volume Control System (CVCS)
- Extractive Line Flow of CVSC

⇒ **Control of Charging Line Flow of CVCS**

*For the case of that Pressurizer Water level (L) continues to decrease:
→ Isolation of Extractive Line and Backup Heater OFF in order to prevent heater damage due to exposing of heater.





Source: 編書 岡芳明･鈴木勝男、原子炉動特性とプラント制御、第4章加圧水型軽水炉の運転制御の実際、4-1PWRの運転制御方式、㈱オーム社、平成20年3月

S/G Water Level Control System

System Function

◆Maintaining of S/G **Secondary Side Water Level to the Standard Level**

◆**S/G Water Control System of Each Loop is Independent**. (Control Each by Each)

System Configuration

S/G Water Level Control System consists of the following Three Systems controlling **depending on Reactor Power.**

1) **Main Feed-water Control System: >15% Power →Control S/G Main Feed-water Valve**

- **Deviation** between the **Standard S/G Water Level** and Actual Water Level
- **Main S/G Feed-water Flow**
- **Main Steam Flow**

2) **Main Feed-water Bypass Control System: 2-15% Power →Control S/G Main Feed-water Bypass Valve**

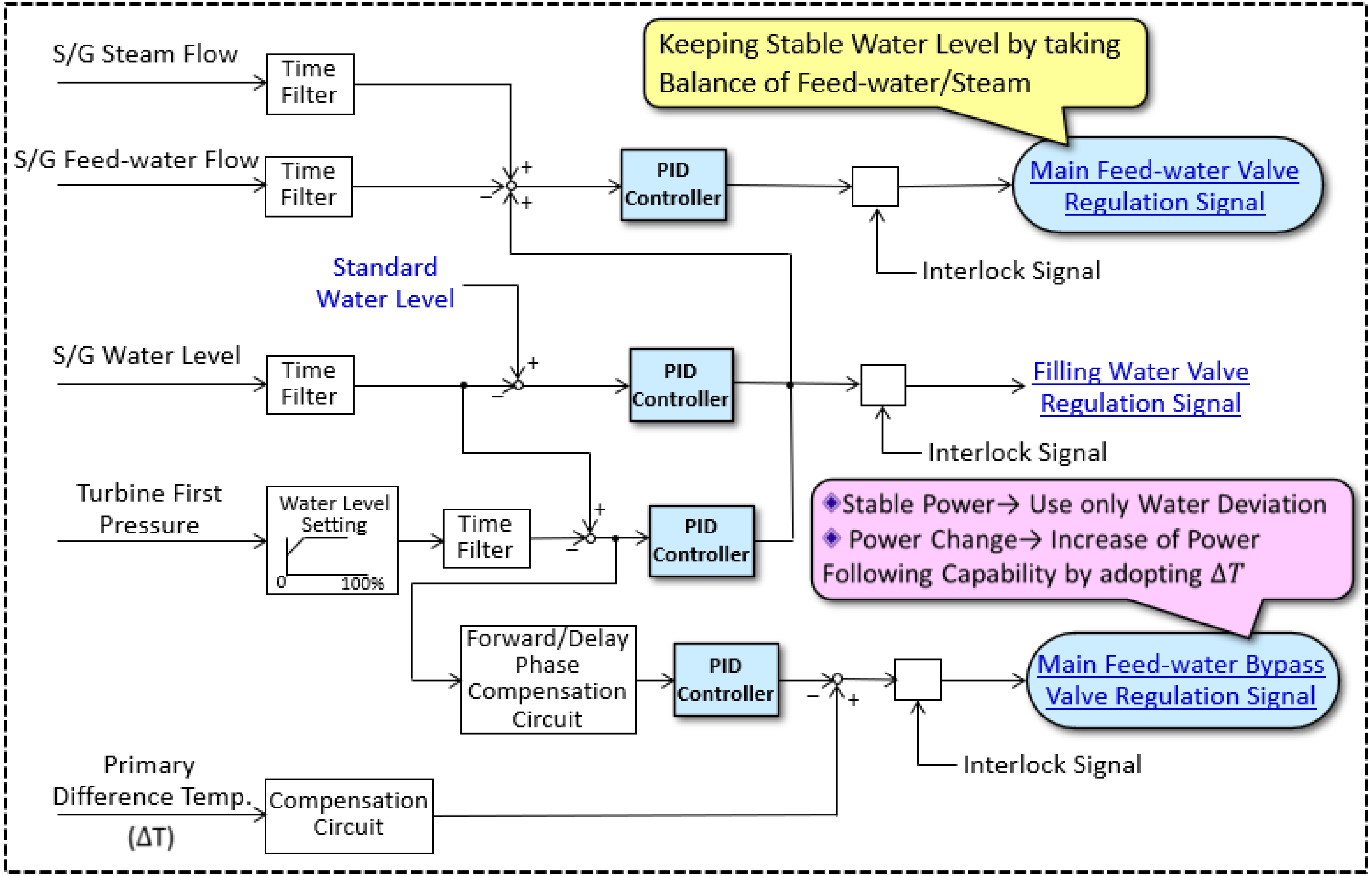
- **Deviation** between the **Standard S/G Water Level** and Actual Water Level
- Difference between Hot and Cold Leg of Primary Coolant Temp. (ΔT)

3) **Filling Feed-water Control System: <2% Power →Control S/G Filling Feed-water Valve**

- **Deviation** between the **Standard S/G Water Level** and Actual Water Level

Source: 編書 岡芳明·鈴木勝男、原子炉動特性とプラント制御、第4章加圧水型軽水炉の運転制御の実際、4-1PWRの運転制御方式、㈱オーム社、平成20年3月

Circuit Diagram of S/G Water Level Control System



Turbine Bypass Control System

System Function

◆To **mitigate Thermal Shock** for the following Thermal Transient Case, **Turbine Bypass Valve** is opened automatically.

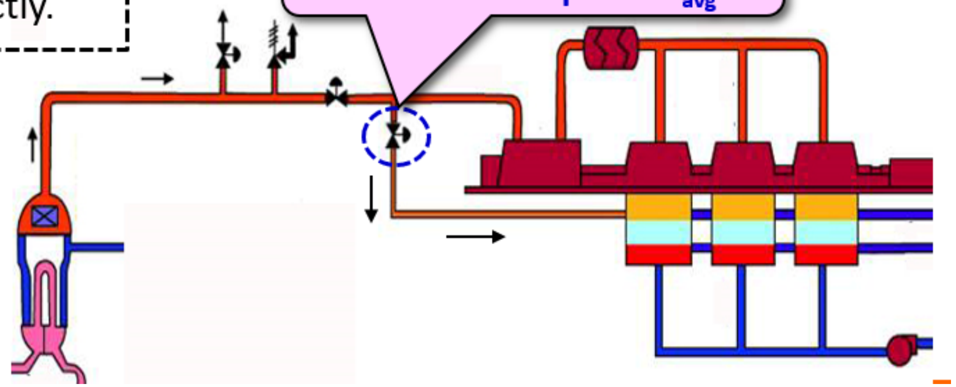
→ **Turbine Load Decreasing with over 10% Step Response**

→ **Turbine Load Decreasing with Lump Step of over 5%/min**

Control of Turbine Bypass Valve

◆Turbine Bypass Valve is controlled by the signal of **Primary Coolant Ave. Temp. (T_{avg})** and a part of main steam is dumped to a condenser directly.

T_{avg} ☞ Turbine Load Changing



(5) Turbine bypass control system

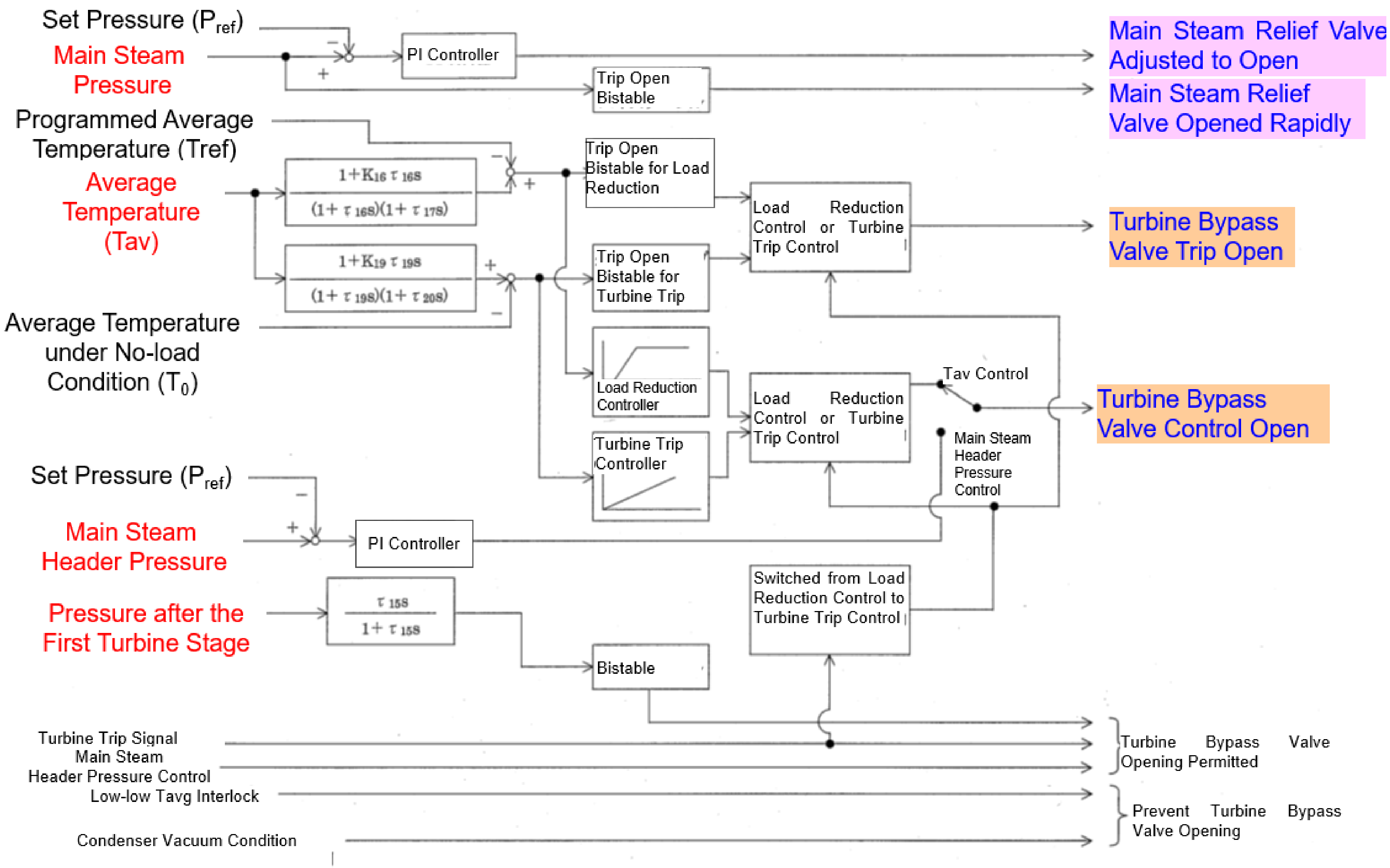
Function:

1. To operate the turbine bypass valves to ease off the temperature rise of the primary system accompanying to the reduction of load at the transition if the load is reduced over 10% stepwise or 5%/min rampwise.

2. To operate the turbine bypass valves to suppress excessive rise of the steam pressure on the secondary side and to switch the plant to the hot shutdown condition without operating the main steam safety valves at the transition in the case of a plant trip from the power operation.

3. To remove residual heat from the reactor to maintain the hot shutdown condition and to cool the reactor system during the operation for lowering temperature toward cold shutdown.

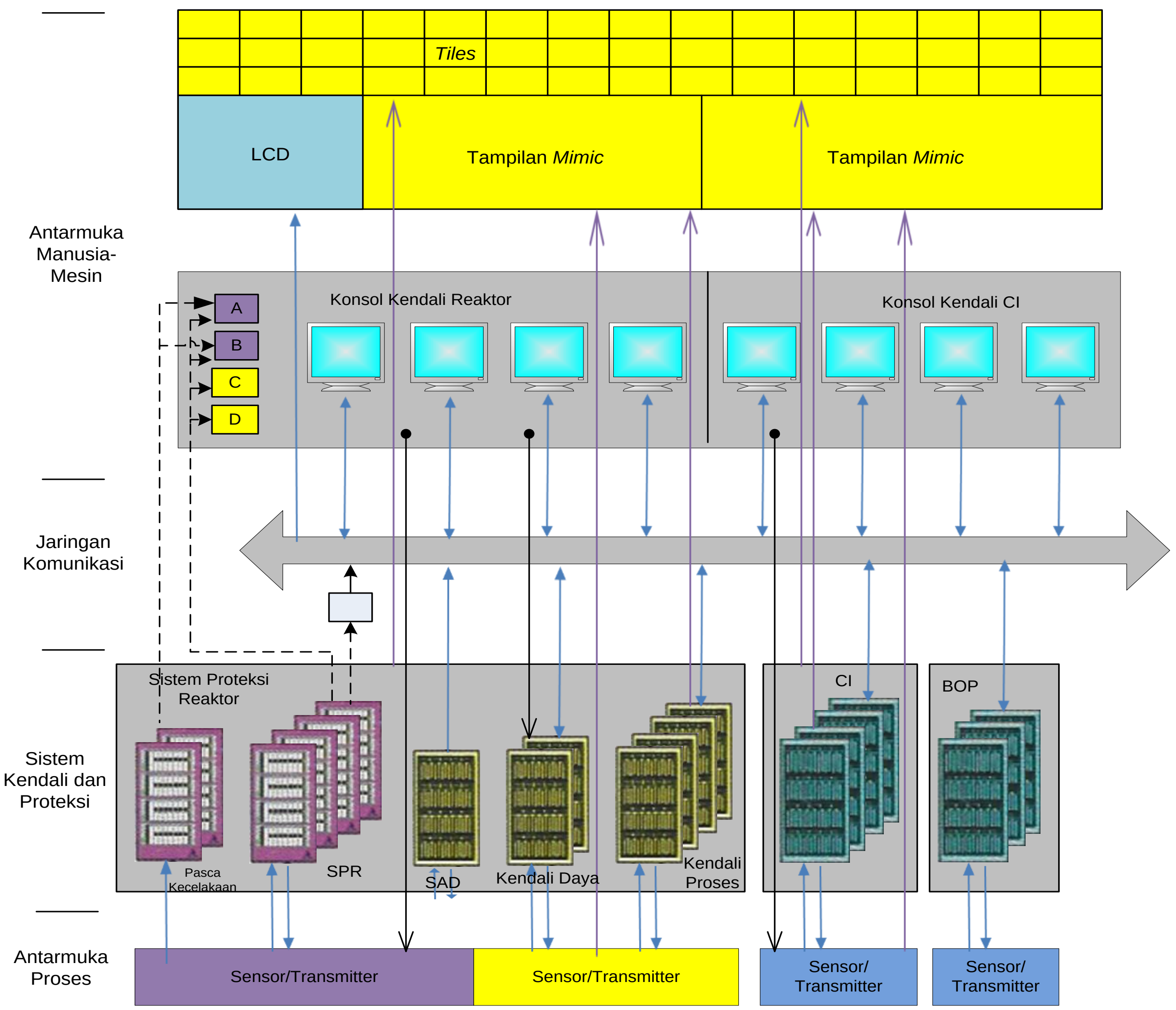
Circuit Diagram of Turbine Bypass Control System



REACTOR PROTECTION SYSTEM

(DESAIN RPS RDE)

Arsitektur I&C



Sistem Proteksi Reaktor

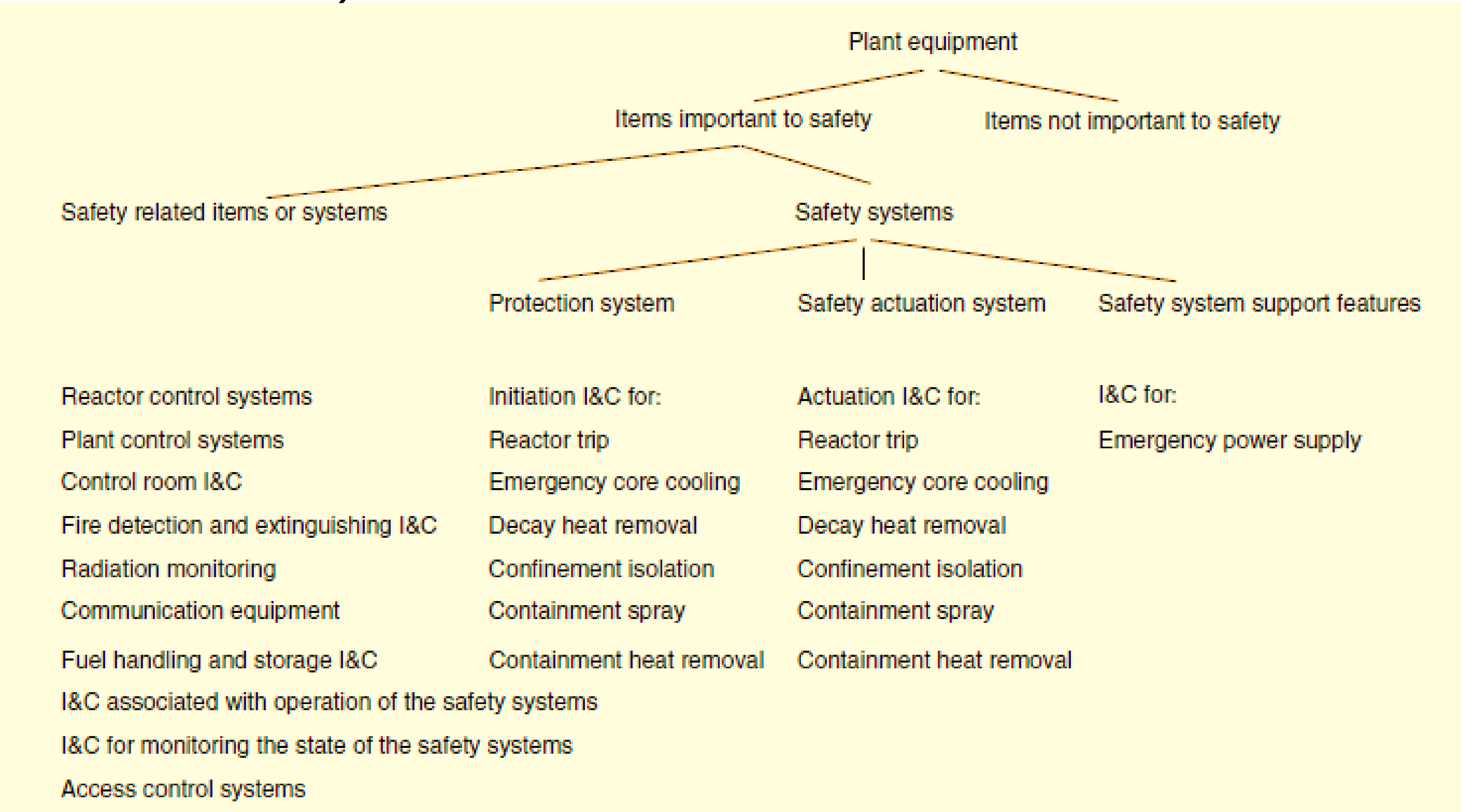
FUNGSI:

- untuk memantau dan memproses variabel-variabel yang penting bagi keselamatan reaktor dan lingkungan,
- untuk mendeteksi kecelakaan secara dini, dan
- untuk menginisiasi secara otomatis tindakan proteksi

Dalam suatu kejadian operasi abnormal, sistem proteksi reaktor melakukan *shut down* reaktor (*trip*) dan mengaktifkan tindakan proteksi yang dibutuhkan untuk mitigasi.

- RPS functions are classified as “Category A” as defined in IEC 61226
- Design criteria:
  - Redundancy
  - Fail-safe
  - Single failure criterion
  - Design simplicity
  - Well known technology
  - Separation
  - Independence
  - Diversity

Generic identification of I&C systems important to safety (IAEA NS-G-1.3)



RDE RPS Initiation criteria

Initiation criteria and their logic operators / Accidents		Reactivity accidents at Start-up	Reactivity decrease in power operation	Reactivity increase in power operation	Primary system depressurization	Steam generator tube break	Blower failure / inadvertent operation of blower damper	Feedwater line break	Main Steam line break	Emergency power operation	Earthquake
Initiation criteria	Logic operations										
Period ≤ min	1 of 2	•		•							
Intermediate-range neutron flux ≥ max	1 of 2	•									
Thermally corrected neutron flux ≥ max	2 of 3	•		•							
Neg. sliding limit for therm. corr. Neutron flux ≥ max	2 of 3		•				•			•	
Hot gas temperature ≥ max	2 of 3			•							
Cold gas temperature ≥ max	2 of 3							•			
Moisture in primary system ≥ max	2 of 3					•					
Neg. sliding limit for primary system pressure ≥ max	2 of 3				•						
Mass flow ratio, primary to secondary side ≤ min / ≥ max	2 of 3				•a)		•	•		•	
Pressure differential, primary to secondary side ≤ min	2 of 3							•	•		
Earthquake acceleration ≥ max	Detailed design										•
	Protective actions										
		1	1	1	1	1	1	1	1	1	1
						2					
					3						

1 Reactor trip
- 1.1 The reflector rods drop under gravity
- 1.2 Primary gas blower tripped
- 1.3 Secondary system isolated

2 Steam generator relief

3 Primary system isoation

a) Actuates only 1

Fig. 215-005
Reactor protection system concept

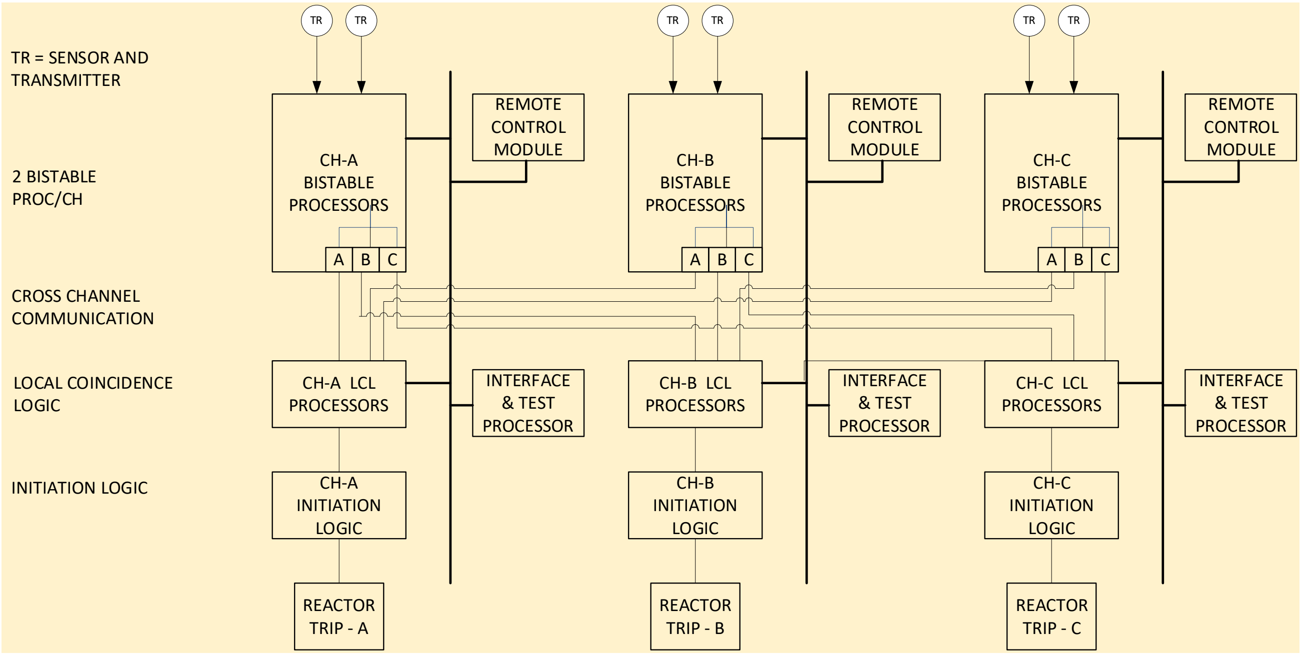
SAFETY SHUTDOWN AND PROTECTION

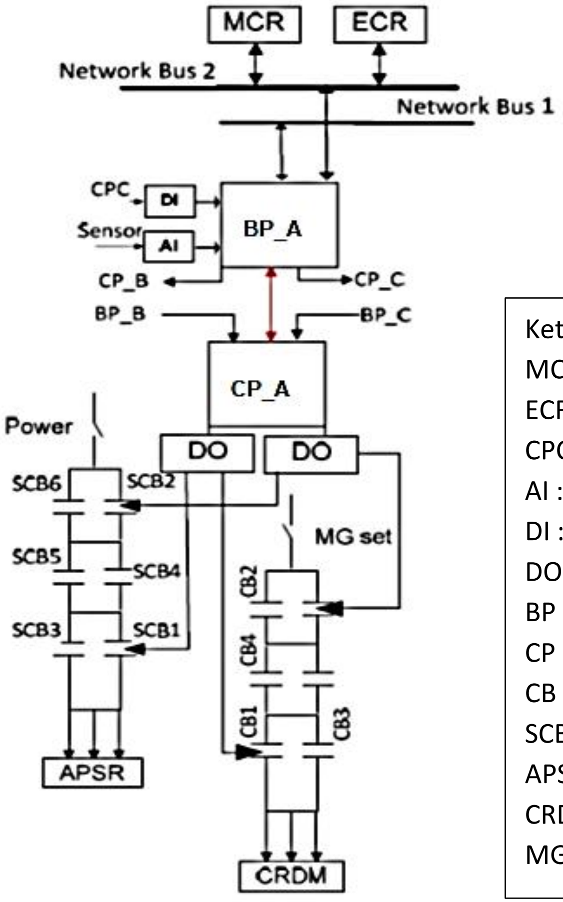
Modul Trip	Teknik Shutdown & Protection
1	• Batang kendali di reflektor disisipkan
	• Sirkulator helium dihentikan
	• Isolasi sistem untai sekunder
2	• Modul Trip 1
	• Isolasi sistem untai primer
3	• Modul Trip 1
	• Relief generator uap

Pengelompokan Kecelakaan

Kecelakaan	Kelompok 1	Kelompok 2	Kelompok 3
Kecelakaan reaktivitas positif	√		
Station black out	√		
Kegagalan sirkulator	√		
Depresurisasi untai primer	√		
Pipa uap utama pecah		√	
Tabung steam generator pecah			√

RPS Diagram





Keterangan :
MCR : Main Control Room
ECR : Emergency Control Room
CPC : Core Protection Calculator
AI : Analog Input
DI : Digital Input
DO : Digital Output
BP : Bistable Processor
CP : Coincidence Processor
CB : Circuit Breaker
SCB : Secundary Circuit Breaker
APSR : Alternate Protection System Rods
CRDM : Control Rod Drive Mechanism
MG : Motor Generator

RPS Implementation : Microprocessor vs FPGA

Microprocessors(Software) vs FPGA

Microprocessors(Software)	FPGA
Sequential execution	Parallel
Interrupts	-
Memory Access	-
Context switching	-
Operating System	-
Short product life cycles	Long term support

Time consuming and expensive V&V process

More attainable and affordable V&V process

Background of FPGA based RPS

- **FPGA advantages for RPS implementation**

– High reliability (As keep simple using only Finite State Machines and Combinational Logic)
– Parallel nature
– Portability using Hardware Description Languages (HDL)
– Long term support

- **IEC 62566 standard**

– IEC 62566 – Nuclear power plants – Instrumentation and control important to safety – Development of HDL –programmed integrated circuits for systems performing category A functions
– The design process follows a Verification and Validation process similar to software V&V process.

Thank You