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# **Design Description of the 4S Instrumentation and Control System**

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**TOSHIBA CORPORATION**

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**LIST OF ACRONYMS AND ABBREVIATIONS**

4S	Super-Safe, Small and Simple
AC	air cooler
AOO	anticipated operational occurrence
ATWS	anticipated transients without scram
BDBA	beyond-design-basis accident
BOP	balance of plant
CDF	cumulative damage fraction
CFR	Code of Federal Regulations
DA	Design Approval
DBA	design basis accident
EM	electromagnetic
EMF	electromagnetic flow meter
ESFAS	engineered safety features actuation system
FP	fission product
FR	fast reactor
GV	guard vessel
I&C	instrumentation and control
IC	inner core
IHX	intermediate heat exchanger
IHTS	intermediate heat transport system
IRACS	intermediate reactor auxiliary cooling system
IRS	interface reactor system
ISI	in-service inspection
IFCS	Intermediate sodium flow control subsystem
LIBS	laser induced breakdown spectroscopy
LMFR	liquid metal fast reactor
LOCA	loss-of-coolant accident
LOF	loss of flow
LWR	light water reactor
MC	middle core
MG	motor generator
MLD	master logic diagram
NRC	Nuclear Regulatory Commission
OC	outer core
OISRS	other instrument system required for safety
PAM	post accident monitoring
PCS	plant control system
PHTS	primary heat transport system
PFCS	Primary sodium flow control subsystem
RCS	reactor power control subsystem
RHRS	residual heat removal system
RPS	reactor protection system

**LIST OF ACRONYMS AND ABBREVIATIONS (cont.)**

RSP	remote shutdown panel
RV	reactor vessel
RVACS	reactor vessel auxiliary cooling system
S/A	subassembly
SG	steam generator
SGCS	steam generator control subsystem
SR	shutdown rod
SSC	structures, systems, and components
SWR	steam-water reaction
TGCS	turbine generator control subsystem
ULOF	unprotected loss of flow

## **1 INTRODUCTION**

The purpose of this report is to inform the United State Nuclear Regulatory Commission of the instrumentation and control system of the 4S Plant. This technical report describes the overview of the instrumentation and control system of the 4S

The instrument and control system is composed of system related to safety and the system related to non-safety. The system related to safety includes reactor protection system (RPS), engineering safety feature actuation system (ESFAS), remote shutdown system (RSS) and other instrumentation system required for safety (OISRS). As for RPS, the two out of three voter logic is adopted. Sensor, cable and actuator switching breaker associated with RPS are grouped into three groups and they are electrically and physically separated. These systems have the safety class 1E instrumentations. The instrumentation and control system related to non safety system consists of plant control system (PCS) and interfacing reactor system (IRS).

The 4S plant is operated by using this instrumentation and control system.

## **2 DESIGN FEATURES OF THE 4S REACTOR**

### **2.1 Plant Description**

A pool type sodium-cooled fast neutron reactor, the 4S, when coupled to power generation equipment, has a primary electrical output of 10MWe (30MWt). Figure 2-1 is a schematic drawing of the overall 4S based power generation facility depicting its major components. The reactor vessel is located in the below-grade reactor building structure, and its primary sodium loop contains the intermediate heat exchanger (IHX), electromagnetic (EM) pumps, reactor internal structures, core and shielding. A containment system consisting of a top dome and guard vessel surrounds the reactor vessel and the reflector drive equipment. Heat is transferred from the primary loop to the single loop of the intermediate heat transport system (IHTS), and is then exchanged in a steam generator (also located below grade) to produce steam, which drives the conventional steam turbine-generator equipment in the water-steam loop.

### **2.2 Reactor**

The 4S uses a pool-type, sodium cooled reactor. The reactor structure is shown in Figure 2-2 [1]. The reactor structure includes the fuel assemblies, primary EM pumps, an IHX, a reactor core support structure, a vertical shroud, radial shields, reflectors, a fixed absorber, and reactor instrumentation, which are all installed inside the reactor vessel. The primary heat transport system is completely enclosed within the reactor vessel. The two sequential primary EM pumps are installed suspended from the bottom of the IHX, which is itself supported from the top of the reactor vessel. These pumps are immersed in sodium, and circulate the sodium coolant. The pumps are annular in configuration, and are located in the perimeter of the core shroud near the reactor vertical center. A motor-generator set for the EM pumps supplies residual power to provide flow coastdown when the normal power supply is lost. The 4S core is reflector controlled. Figure 2-3 shows the core cross section and the reflector configuration [1]. The core consists of 18 hexagonal fuel assemblies and one central assembly containing a shutdown rod and fixed absorber. Reactivity and power are controlled by the six-segment cylindrical reflectors surrounding the core. The reflecting region of the reflector assembly is positioned to cover the core partially to maintain criticality, by reflecting neutrons back into the fuel. Fall of the reflector assembly to below the core region by gravity provides shutdown. The reflector has sufficient negative reactivity worth to enable shutdown without using any additional means assuming one stuck reflector segment. Fall of the shutdown rod into core by gravity also provides shutdown. The fixed absorber is fan shaped hafnium-sheeted element fabricated of stainless steel surrounding the shutdown rod and compensating a large excess reactivity at the beginning of life, which is necessary to maintain criticality for 30 years [1]. At approximately the middle of core life, the fixed absorber is retracted from the core, adding positive reactivity, and allowing repositioning of the reflector lower on the core, so that sufficient reflector movement is available to maintain criticality until EOL. During normal operating conditions, reactor core power is controlled by the movable reflector. The reflector drive consists of a combination of fine and fast adjustment mechanisms. The fast adjustment mechanisms are used to position the reflector for startup and shutdown, and the fine adjustment mechanisms are used incrementally and automatically to compensate for core burnup reactivity swing. To shutdown the reactor, the clutch of the fast adjustment mechanism is released and the reflector falls by gravity causing the

reactor to shutdown. The shutdown rod at the core center position is also inserted upon a scram to provide an independent and redundant means of shutting down the reactor. Either the reflector or the shutdown rod is capable of inserting enough negative reactivity by itself to shut the reactor down. Burnup reactivity compensation and margins for uncertainties in temperature effects, criticality, and fissile enrichment are considered in the reflector and fixed neutron absorber design. The radial reflector segments are incrementally raised very slowly during the service life of the core using the fine adjustment mechanism to maintain neutron flux and power levels as burnup progresses. Figure 2-4 illustrates the reflector drive mechanisms and their movement. Power cylinder (A) initiates the startup and shutdown motion (fast motion) of the reflector [1], [2]. In the case of startup, power cylinder (A) raises the reflector to the position just before criticality is reached. The mechanical rod stop (A) restricts the motion of plate (A) to limit the potential total reactivity inserted by this range of the movement. A separate power cylinder (B) for power control continues to raise the reflector (fast motion) from just below criticality to rated power. Another mechanical rod stop (B) restricts the motion of plate (B) to limit the total reactivity inserted by this power cylinder. A burnup swing compensation (fine motion) drive incrementally raises the reflector during reactor operation to compensate for reactivity over core life. This drive system consists of a ball screw, motor, and reduction gear. Power cylinder (A) is used for rapidly lowering the reflector by releasing the brake to accomplish reactor shutdown in an emergency.

### **2.3 Heat Transport System**

The 4S uses a pool-type reactor primary sodium loop, an intermediate sodium loop, and a conventional steam-water balance of plant (BOP) configuration to produce electric power. Figure 2-5 shows the diagram of the heat transport system. The coolant from the core flows up through the central part of the reactor vessel, and then is drawn down into the IHX. At the exit of the IHX, the coolant reaches the suction of the primary EM pumps, and is pumped further down the annular flow path between the lower vertical shroud and the reactor vessel (RV) wall, after which it is redirected upwards at the bottom of the reactor vessel and returns to the core. The EM pump is a single stator type annular linear induction pump. Two sequential EM pumps are installed in series in the reactor. These pumps are immersed in, and circulate, the sodium coolant. One IHX is installed in the reactor to transfer the 30 MWt generated in the core to the intermediate sodium loop. The IHX is a vertical, shell and tube type heat exchanger with an annular configuration. The top of the IHX is suspended from the flange of the reactor vessel, and the EM pumps are attached to its bottom. The primary coolant flows down inside the straight heat transfer tubes, which are arranged in several concentric circles of different diameters within the annular heat exchanger shell. The IHTS consists of the intermediate sodium heat transport loop, a steam generator, an air cooler, an EM pump, an electromagnetic flow meter, piping, and associated equipments. The steam generator is a helical coil type with double wall tubes and serves to transfer heat from the intermediate sodium loop to the water-steam system. The steam generator tubes are double wall construction to prevent a sodium-water reaction in the event of tube failure. A leak detection system for the steam generator provides indication of either side of the double wall tube failure before occasion of a sodium-water reaction. Detail of leak detector is described in chapter 4.

## **2.4 Residual Heat Removal Systems**

The 4S design incorporates two independent, redundant residual heat removal systems. Figure 2-6 shows a schematic diagram of these systems [1]. The redundant residual heat removal systems consist of the Intermediate Reactor Auxiliary Cooling System (IRACS), which removes decay heat using an air cooler installed in the IHTS, and the Reactor Vessel Auxiliary Cooling System (RVACS), which removes heat transferred from the sodium coolant to the air between the guard vessel and a cylindrical steel heat collector located inside the cylindrical underground concrete wall. Ambient cold air that descends between the concrete wall and the heat collector, is redirected up at the lower end of the heat collector, and rises between the heat collector and the guard vessel. Heat from the reactor is thereby removed with natural convection of the air in the gap between the guard vessel and the heat collector. The heated air rises through the reactor building and is discharged above grade level via redundant exhaust stacks. This process takes place under all plant conditions and for all design events, entirely by natural phenomena without the intervention of operators or any active equipment. IRACS is operated by utilizing the natural circulation flow of sodium in the primary and intermediate loops. Heat is transferred from the primary to the intermediate loop via the IHX, just as during normal operation. An air cooler in the IHTS removes the heat to atmosphere after the flow path for natural circulation of the cooling air is completed by the opening of two fail-safe dampers. IRACS is only used for plant shutdown and accident conditions. Either the RVACS or IRACS operating alone by natural circulation can remove the residual heat necessary to ensure that the fuel acceptance criteria are satisfied. When using IRACS for a normal shutdown, the residual heat is removed by forced convection of sodium with the EM pumps (in both the primary and intermediate loops) and also forced air flow using a blower associated with the IHTS air cooler. IRACS maintains steady cold shutdown conditions by controlling the heat removal rate to match the decay heat of the reactor.

## **2.5 Containment System**

The containment system surrounding the reactor vessel consists of a guard vessel, top dome, airlock, cable penetrations, and piping penetrations. The steel guard vessel closely surrounds the reactor vessel. If the reactor vessel should leak at any point below the sodium pool surface level, the guard vessel retains the sodium. Considering the maximum volume that could leak into the void between the reactor and guard vessels, the core will remain covered, and the sodium flow circuit would be maintained. Containment monitoring is provided by a radiation monitor in the top dome. Temperature monitors, pressure gages, and sodium leak detectors are also provided in containment to detect failures of the primary heat transfer system (PHTS) or IHTS.

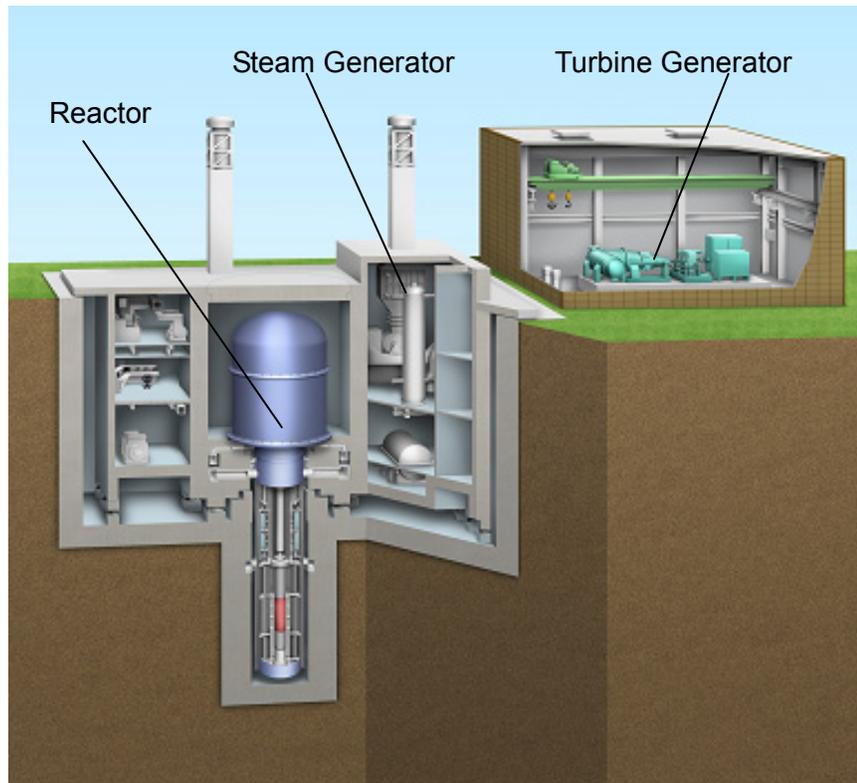
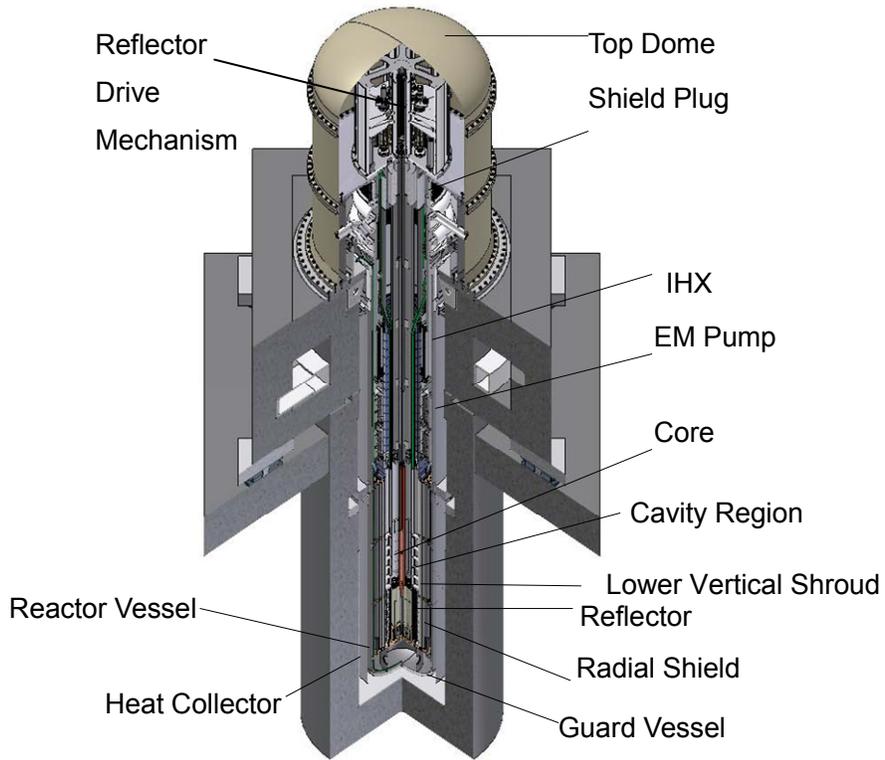


Figure 2-1 Schematic Drawing of 4S Plant



**Figure 2-2 Reactor Structure**

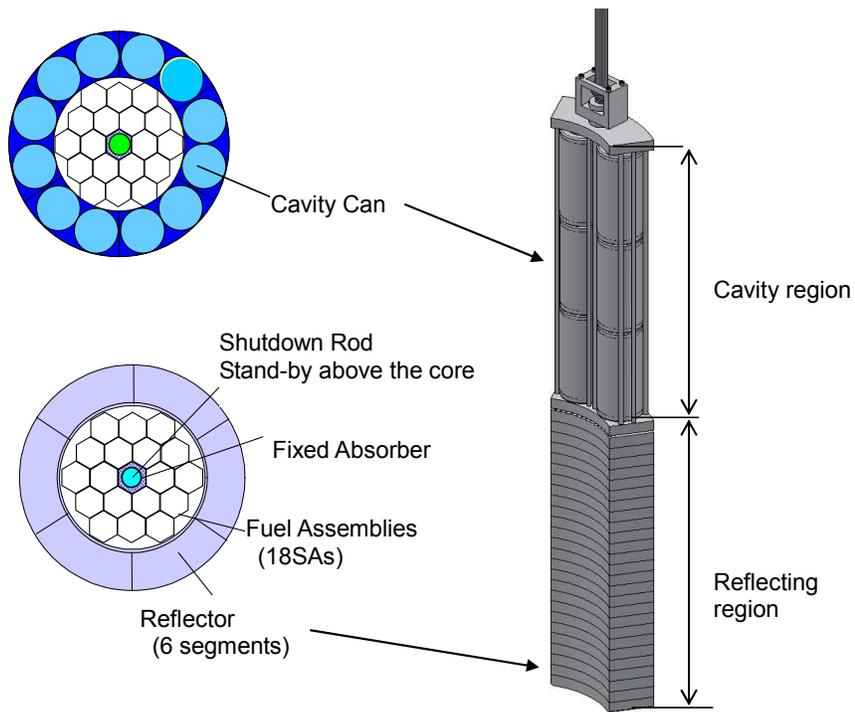


Figure 2-3 Reflector and Cross-section of Core

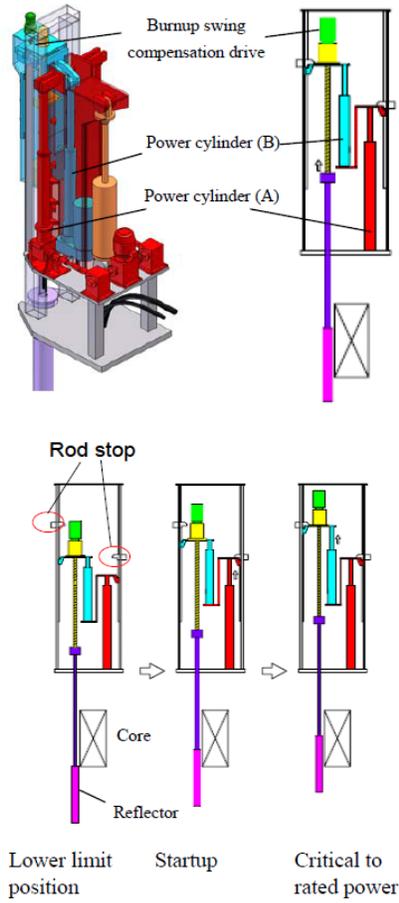


Figure 2-4 Reflector Drive Mechanisms

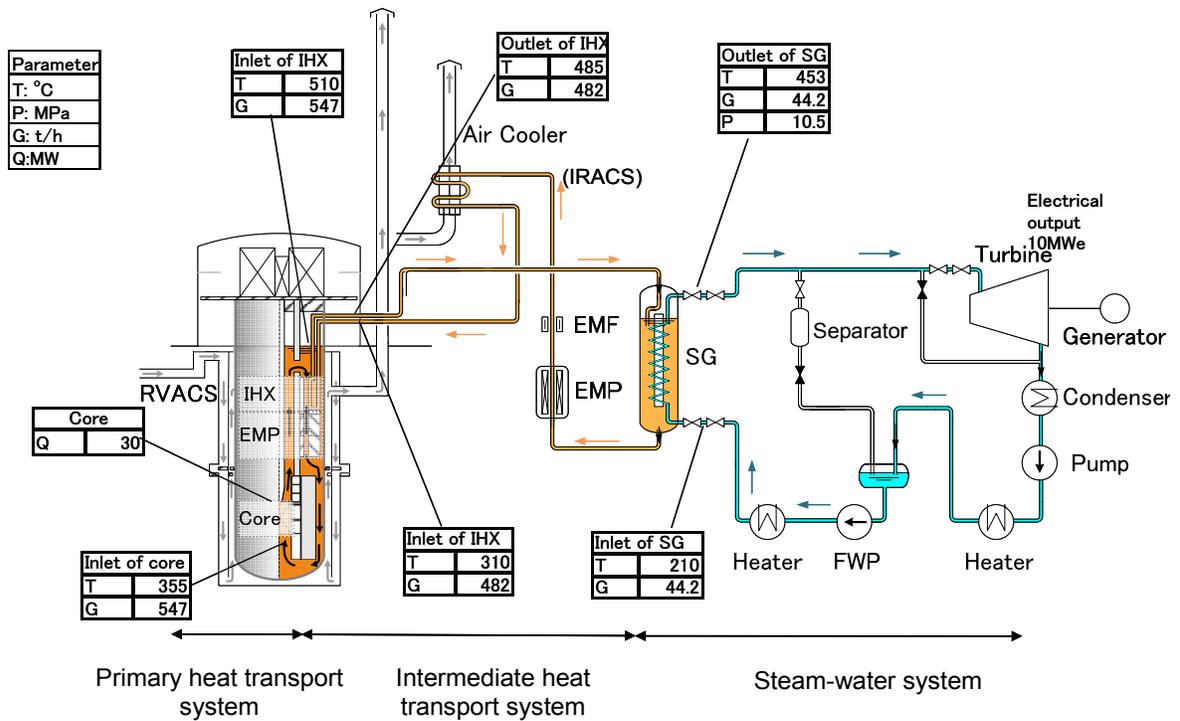


Figure 2-5 Heat Transport System Flow Diagram

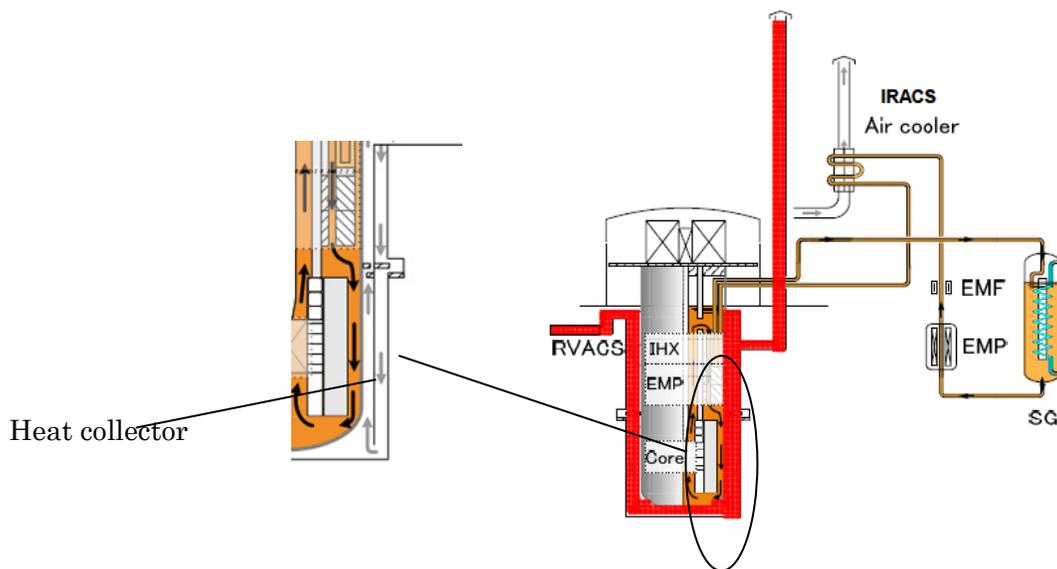


Figure 2-6 Residual Heat Removal Systems

### **3 OVERVIEW OF INSTRUMENTATION AND CONTROL SYSTEM**

This chapter describes the overview of the 4S instrumentation and control system. Figure 3-1 shows the system structure of the 4S instrument and control system. The system related to safety includes Reactor Protection System (RPS), Engineering Safety Feature Actuation System (ESFAS) and Remote Shutdown System (RSS). RSS provides a mean to carry out the reactor shutdown function outside the main control room. Those systems have the safety class 1E instrumentations. The system related to non-safety includes Plant Control System (PCS) that includes instruments such as process sensors and Interface Reactor System (IRS) .The IRS include instrumentations of supporting systems, monitoring and diagnostics systems of plant condition such as fire protection system, leak-detection system of sodium. The monitoring and indication system indicates information of systems related safety and non-safety including the information of post accident monitoring (PAM).

The control room will be described in another report.

#### (1) Instrumentation and control system related to safety

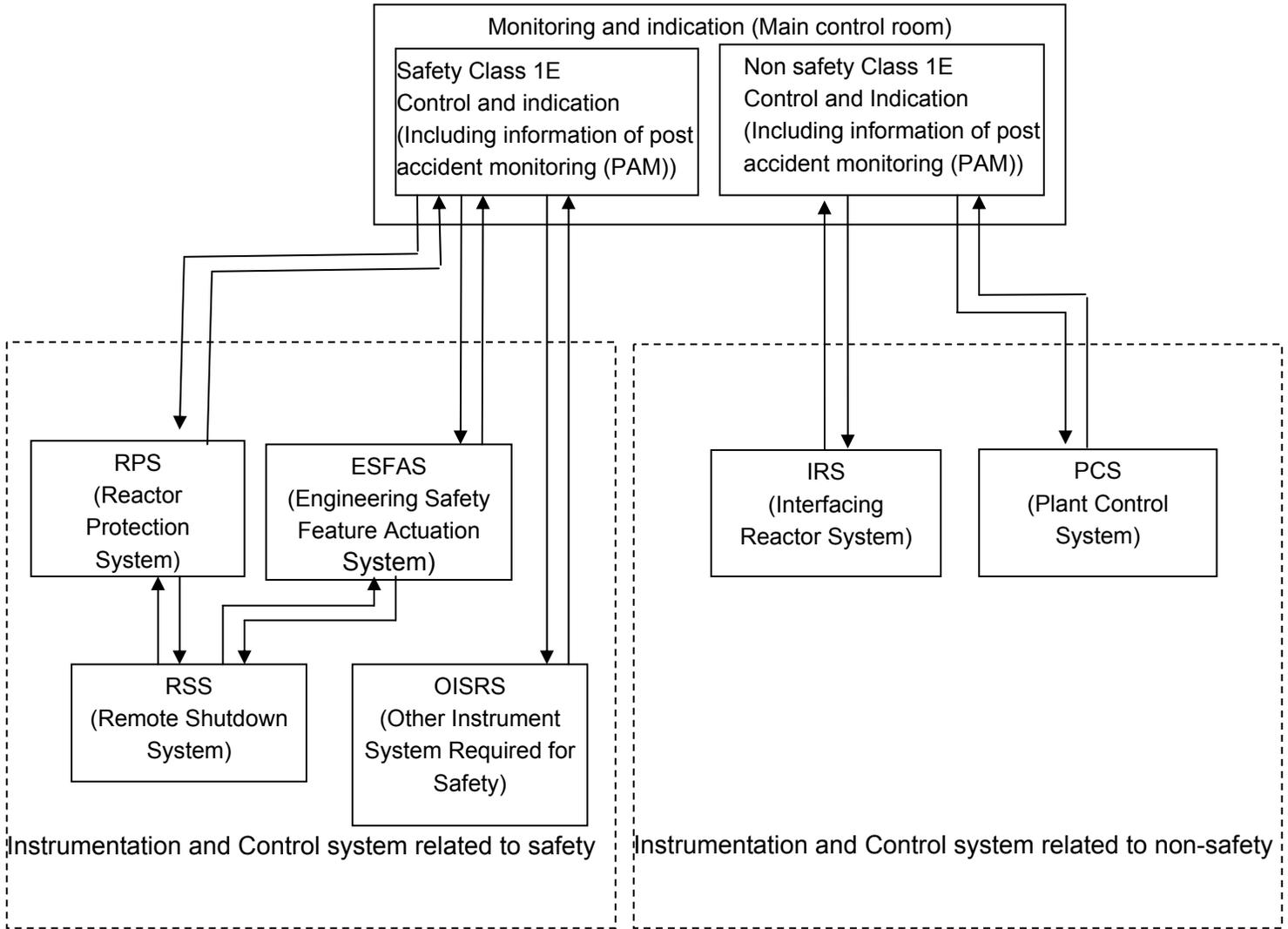
The instrumentation and control systems related for safety are following:

- Reactor Protection System (RPS),
- Engineering Safety Feature Actuation System(ESFAS),
- Remote Shutdown System (RSS)
- Other Instrumentation System Required for Safety (OISRS)

#### (2) Instrumentation and control system related to non-safety

The control systems not required for safety are following;

- Plant Control System (PCS)
- Interface Reactor System (IRS)



**Figure 3-1 System Structure of 4S Instrumentation and Control System**

## **4 INSTRUMENTATION AND CONTROL SYSTEM RELATED TO SAFETY SYSTEM**

### **4.1 Reactor Protection System**

#### **4.1.1 General Functional Requirement**

The reactor protection system (RPS) is a plant protection system to initiate reactor trip at an abnormal plant operation condition so that radioactive release guidelines and the public protection are maintained. The RPS has two major functions. One is to detect a plant abnormality by sensing process parameter changes over its set-points, and other is to initiate reactor trip after detection of plant abnormality with having sufficient reactivity margin against safety limit of reactor. The RPS of 4S plant consists of two reactor shutdown systems which are 1) the main reactor shutdown system by reflectors free falling out of the core and 2) the backup reactor shutdown system by shutdown rod free-falling insertion into the core.

The RPS consists of sensors, signal condition circuit, logics, trip breakers and actuators. Functional diversities are served to the sensors and the actuators between main shutdown system and backup shutdown system. For the logics and the trip breakers, same type systems are used for both shutdown systems. The signal conditioning circuits, and trip actuators are designed to be physically separated and independent each other.. So the reactor trip function has redundancy and diversity.

#### **4.1.2 System Identification and Classification**

Figure 4-1 shows an overview of the RPS. The RPS consists of sensors, logic circuits, trip breakers, and actuators, configured as three separate identical sensors and logic channels each for both the main and backup systems.

#### **4.1.3 Initiating Signals**

The representative design basis events (DBE) for the RPS are listed in Table 4-1. As for representative external event, seismic is considered. Figure 4-2 shows that these abnormalities are categorized to trip initiating parameters of RPS. Sensors for the main shutdown system are different from that for the backup shutdown system to have diversity between two systems.

The following signals initiate the RPS are assigned into two groups which are the main reactor shutdown system and the backup reactor shutdown system. This provides diversity to the RPS.

##### **(1) Main reactor shutdown system**

- High neutron flux level at reactor power range monitor
- High neutron flux increasing rate at reactor power range monitor
- Low neutron flux level at reactor power range monitor
- High neutron flux decreasing rate high at reactor power range monitor
- Low IHX primary outlet temperature
- High IHX primary outlet temperature

- Low power line voltage
- High seismic acceleration
- Low reactor vessel sodium liquid level
- Manual

(2) Backup reactor shutdown system

- High neutron flux level at wide power range monitor
- High neutron flux increasing rate at wide power range monitor
- Low neutron flux level at wide power range monitor
- High neutron flux decreasing rate at wide power range monitor
- Low primary main circulation EM pump voltage and current
- High seismic acceleration
- Manual

Assigned trip signals actuate both main and backup shutdown system for the events of AOOs (Anticipated Operational Occurrence) in Table 4-1.

#### **4.1.4 Logic**

The RPS has three signal sensing channels (channels I, II, and III), which are physically and electrically separated from each other. The various process signals, which are grouped into the three channels, are gathered into the separate signal conditioning panels designated for each channel. When a signal exceeds its setpoint, scram signals from bi-stable circuit outputs are transmitted to the RPS voter logic panel. In the RPS voter logic panel, those scram signals are input to the two out of three voter logic circuit so that if two or more signals come into this voter, reactor trip initiating signals (divided into three logic train signals that are A train logic signal, B train logic signal, and C train logic signal) are sent to the reactor trip breakers of each shutdown system.

The signals of de-clutch for the reflector drive system are also transmitted to the primary and intermediate loop EM pump drive systems, the IRACS air cooler damper drive circuits, and the feedwater pump drive system. After the trip initiation, the reactor will shut down, the primary and intermediate loop EM pumps and feedwater pumps will trip, and the IRACS dampers open. The safety analysis [3] shows the core fuel keeps the integrity under the DBE and it means this logic is adequate for the 4S plant. In addition, the reactor can be manually tripped by the operator from the control room or remote shutdown system

#### **4.1.5 Bypass**

When the periodic surveillance tests (See 4.1.10) are performed against the RPS instrumentation channel circuits, a channel circuit should be bypassed. The bypassed channel out of three channels should be compulsorily changed into scram condition. In this condition, the RPS covers other two channels so that it acts as if it has one out of two logic voters.

#### **4.1.6 Trip Breaker**

Trip breaker circuit is hardwired as two out of three logics which are shown in Figure 4-1. If the electrical current for two or more sets of divisional breaker trip coil is interrupted, the breaker contacts interrupt the each current of the electromagnetic clutch of main reactor shutdown system and of the shutdown rod latch coils of backup reactor shutdown system to release the reflectors and the shutdown rod.

#### **4.1.7 Actuator Devices**

##### **(1) Main reactor shutdown system**

After more than two trip breaker of the main reactor shutdown system open, the electro magnetic clutch of the reflector drive system shown in Figure 4-3 will be de-energized so that the reflectors fall freely out of the core. Confirmation of reflector's falling out the core is done by reading the indication of its position. In the case of failing de-clutch, the reflector will be lowered fully by a driving motor.

##### **(2) Backup reactor shutdown system**

In case of backup reactor shutdown system, after trip breakers action, the electromagnetic of the reactor shutdown rod shown in Figure 4-4 will be de-energized and the rod will be de-latched so that the shutdown rod is inserted into the core.

#### **4.1.8 Redundancy, Diversity and Separation**

Sensors, cables, and actuator switching breakers associated with the RPS are grouped (or divided) into three groups (or divisions) and they are electrically and physically separated each other because the RPS consists from three systems including electrical equipments. Having two out of three voters logic, even if one signal fails, it does not prevent a reactor shutdown. Equipments associated with the RPS are designed to be replaceable or repairable. Functional diversity is provided by monitoring dependent process parameters such as neutron flux (wide range and power range), IHX outlet temperature, reactor vessel sodium level, EM pump's supplied voltage and currents, and so on.

The sensor devices are separated each other and signal lines from sensor devices to signal conditioner cabinets are run in independent conduits. Trip signals by bi-stable circuits of signal conditioner panels to the two out of three voter logic cabinets are also run in independent conduits or segregated cable tray divided into the RPS channel divisions. Those are called as "channel" division. The outputs from the logic cabinets to the shutdown switching breakers are run in same number of conduits as logic trains which are divided into three "Train" divisions for redundancy. The shutdown switching breakers are installed to be also divided into three logic "Train" divisions.

#### **4.1.9 Power Supply**

Power of safety related system is supplied by uninterruptable power source of Class 1E with DC power and AC power.

#### **4.1.10 Testability**

The RPS is designed to be testable by the surveillance tests during plant operation. In surveillance test, it can be performed under plant operation condition because the one system of three systems is bypassed. When the surveillance test is performed on the RPS instrumentation channel circuits, bypassed channel should be compulsorily changed into scram condition. In this half scram condition, the RPS covers other two channels so that it will act as if it had one out of two voters logic. Before performing the tests on trip breaker, bypass breakers are energized to close the trip circuit manually so that the trip breaker test can be done without causing actual reactor trips. Thus, reliability is maintained.

#### **4.1.11 Instrumentation of Reactor Protection System**

The RPS-related instrumentations provide signals for initiating reactor trips and information on the state of the reactor in the event of an accident. The sensors, signal conditioning equipment, and logic systems are Class 1E equipment.

The RPS is actuated when a threshold is attained by any one of the safety function parameters as follows:

- Reactor core neutron flux
- Liquid sodium level of the reactor vessel
- Supply voltage/current of primary EM pumps
- Primary outlet temperature of IHX
- Voltage of power line
- Seismic acceleration

Figure 4-5 shows the monitors of reactor protection system.

##### **(1) Neutron flux monitor**

Neutron flux leaking from the core provides a measure of the core neutron flux, and it is monitored to detect both the flux level and the rate of change in the core. Measured values are used after calibration of the reactor power obtained from a heat balance evaluation.

The neutron flux monitor instrumentation measures the neutron flux level from a reactor shutdown condition up to 130 percent of the rated reactor power, initiates reactor trip signals when appropriate, and informs operators of the reactor power level during normal operation and any abnormal transients.

Three kinds of instruments are used for neutron flux monitor instruments. The first one is the source range monitor system. It is installed in the reactor vessel by setting in a well that penetrates the shielding plug of reactor. Its radial position is between fuel assemblies and the core barrel. It monitors the core subcritical condition during reactor shutdown and the neutron flux during reactor startup. The second is the wide range monitoring system and the third one is the power range monitoring system. They are installed outside the reactor vessel in the concrete

adjacent to the RVACS flow path. The wide range monitor system measures the neutron level from subcriticality to the power range, whereas the power range monitor system is restricted to measure the power range only.

Fission counter tube, of which electrode is coated by  $U_3O_4$  is used as neutron detector. This detector can endure the high temperature and high level neutron flux. The power monitoring system is used for the RPS signals to prevent excessive reactivity insertion and overpower in the reactor core. The axial position for both wide and power ranges is in the upper region of the fuel assemblies. The 4S design has power range/wide range monitors installed in at least three locations.

### (2) Reactor vessel sodium level monitor

The sodium level of the reactor vessel is monitored to confirm the core cooling function. The sensor is an induction type, which uses the high conductivity of liquid sodium. The system of level meter is composed of a detector and a converter. The detector has an exciting coil and a sensing coil, which are wound in parallel and close to each other, consisting of a solenoid. The liquid sodium level indicator for the safety protection system is required to initiate a reactor trip signal when the level is reduced below a threshold as well as to measure the reactor sodium liquid level during normal operation.

### (3) Supply voltage of primary EM pumps and its electrical current monitor

A low voltage power or electrical current interruption for the EM pumps is detected by volt/current meters.

### (4) Primary outlet temperature of intermediate heat exchanger monitor

The outlet temperature of sodium leaving the IHX is measured by monitor of the primary outlet temperature of the IHX. If the outlet temperature exceeds a threshold, a reactor trip is initiated. The temperature is measured by thermo couple settled in well.

### (5) Voltage of power line monitor

The voltage of power line is measured by voltmeter settled on the power line.

### (6) Seismic acceleration monitor

Seismic acceleration monitors supply a reactor trip signal for acceleration above a certain threshold. In addition, to determine whether the reactor facility is in safe operation and to take appropriate measures after an earthquake, appropriate monitoring equipment (separate from that used for the RPS) is installed at locations that meet the requirements of Regulatory Guide 1.12.

### (7) Parameters for post accident monitoring

As for monitoring and indication at main control room, the information of post accident monitoring (PAM) required by RG 1.97 [4] includes a part of information for RPS, a part of

information for ESFAS and the information related non-safety to indicate that plant safety function are accomplished. The objectives of PAM are to monitor the condition of reactor trip, to monitor the core cooling and to monitor the atmosphere in containment. The selected information for PAM is described at each section of RPS, ESFAS and IRS.

The following is information for PAM of the RPS.

As for the post accident monitoring, reactor core neutron flux, liquid sodium level of reactor and primary outlet temperature of IHX are monitored when accidents occur. The core neutron flux is used to confirm the shutdown. The liquid sodium level of reactor is used to confirm the sodium inventory in reactor. The primary outlet temperature of IHX is used to confirm the function of RHRS.

## **4.2 Engineered Safety Feature Actuation System**

The engineering safety feature actuation system (ESFAS) consist of the residual heat removal system (RHRS) and the containment isolation system. The RHRS consists with Intermediate reactor auxiliary cooling system and reactor vessel auxiliary cooling system. When the leakage of radioactive material inside the containment occurs, some valves of pipes should be closed to prevent the radioactive material release.

### **4.2.1 System Configuration**

#### (1) Intermediate reactor auxiliary cooling system

The Intermediate Reactor Auxiliary Cooling System (IRACS) removes decay heat using an air cooler (AC) installed in the IHTS. The dumper of AC is opened by receiving the signal of de-cutch of the reflector drive system.

#### (2) reactor vessel auxiliary cooling system

The reactor vessel auxiliary cooling system (RVACS) removes heat transferred from the sodium coolant to the air between the guard vessel and a cylindrical steel heat collector located inside the cylindrical underground concrete wall. Ambient cold air that descends between the concrete wall and the heat collector, is redirected up at the lower end of the heat collector, and rises between the heat collector and the guard vessel. Heat from the reactor is thereby removed with natural convection of air in the gap between the guard vessel and the heat collector. The heated air rises through the reactor building and is discharged above grade level via redundant exhaust stacks. This process takes place under all plant conditions and for all design events, entirely by natural phenomena without the intervention of operators or any active equipment.

#### (3) Isolation system of containment

The containment is isolated by the signal of high radiation level by radiation monitor settled in containment. As for the piping penetrating the TOP dome and guard vessel excluding main coolant piping, piping of gas system, piping of containment atmosphere conditioning system, and auxiliary sodium penetrate the TOP dome.

During steady state operation, piping of auxiliary sodium system, the nitrogen gas system and argon gas system is closed. When the signal of high radiation level occur during steady state operation, the valve of coolant transfer tube for containment atmosphere cooling system is only closed.

#### **4.2.2 Instrumentation of Engineered Safety Feature Actuation System**

##### **(1) Radiation monitoring system**

The radiation monitoring system monitors radiation levels inside TOP dome during all plant operating, shutdown, abnormal, and accident conditions.

##### **(2) Monitoring of residual heat removal system**

In order to obtain the quantity of heat transferred from the reactor vessel via the intermediate heat exchanger (IHX) to air cooler of IHTS, information on the primary sodium flow through each heat exchanger is required. It is, however, impractical to measure this information directly. Therefore, an indirect measurement of the heat transfer is made using of the increased enthalpy on the intermediate flow side of IHX. For this reason, the temperatures at the inlet and outlet of the IHX are monitored. The quantity of heat transferred in the RVACS is estimated from the enthalpy change in the air flowing through the duct system. The change in enthalpy is calculated from the mass flow rate of air, its humidity, and the temperature differential between the inlet and outlet flows. Air mass flow rate is dependent on the air density (temperature), air velocity, and duct cross-sectional area (fixed by the mechanical design of the system). The present concept for monitoring the air flow rate through the RVACS is based upon a pitot-tube dynamic and static air pressure measurement system with two sensors located in the chimney exit of each of the two RVACS stacks. The air mass flow rate in each stack is determined from the differential pressure measurement and the air density obtained from air temperature measurement.

##### **(3) Parameters for post accident monitoring**

As for the post accident monitoring information, following parameters are selected. The IHX inlet and outlet temperature is used to confirm the function of IRACS. The radiation monitor is used to monitor the containment area radiation level. Air temperature and air flow rate in stack are used to confirm the function of RVACS.

#### **4.3 Remote Shutdown System**

The remote shutdown system (RSS) is settled by the following requirement based on 10CFR part 50 Appendix A criterion 19 [5] and appendix R criterion 12 L [6]. When the event necessitating control room evacuation occur, the operator can shutdown the reactor from the control room before evacuation or switch off the power source of the electromagnetic clutch of main reactor shutdown system at clutch control panel outside the room of RSS after evacuation. The operating dumper and monitoring IHX primary/intermediate inlet/outlet temperatures to confirm the operation of IRACS can be done from RSS. Switches for opening the dumper are located on

both the control room and the RSS and they can be operated from the both control room and RSS.

#### **4.4 Other Instrumentation System Required for Safety**

This section describes the safety systems which are excluded PRS, ESFAS, and RSS. The sodium-water reaction is important for safety of fast reactor. The 4S adopts the double wall tube steam generator and its failure detection system that is important for preventing the sodium-water reaction.

Leak detection system of steam generator is system required safety and described in this section.

##### (1) Double wall tube steam generator (DWSG)

The SG is a heat exchanger that transports heat from the intermediate system to the water-steam system. Figure 4-6 shows the section view of steam generator. The SG shell has a free surface of liquid sodium outside the helical coil double-wall tubes. The free surface level is maintained during normal operation and transients, such as plant shutdown, by overflowing and pumping the sodium to/from a dump tank. The steam generator tubes have double-wall with a wire mesh layer between the inner and outer tubes. Double-wall tubes are used to prevent a sodium-water reaction during a steam generator tube failure [7]. Sodium flows onto the top of the tube bundle through a distribution header at the top of the SG. While flowing down over the tube bundle, sodium exchanges heat with water and steam inside the tubes and flows out from the outlet nozzle at the bottom of the SG. Water flows into the steam generator tubes from feedwater nozzles on the lower part of the steam generator. While rising through the helical tube bundle, water is heated by the intermediate sodium and becomes superheated steam. The steam then flows out from steam nozzles on the upper part of the SG. If tube leakage is detected, the plant is shut down by manual and the tube is plugged.

##### (2) Tube-failure monitoring system

As shown in Figure 4-6, the heat transfer tubes of the DWSG have wire mesh layer in the gap between the inner and outer tube. The wire mesh layer, as it is structurally separating the inner and the outer tube, reduces the failure probability of a tube caused by a common factor because a crack in the tube in one side does not propagate directly to the other tube. In addition, the wire mesh layer has a high permeability and is filled with helium gas, to enable continuous leak detection. This continuous monitoring detects a failure of one of the double-wall tubes and prompt operator action before a second failure of the other tube wall results in a sodium-water reaction. This enhance high reliability of the overall system. In this section, the configuration of the leak detection systems for the inner and outer tubes and the detection characteristics of these systems are described.

The configuration of the measurement instruments of the tube failure monitoring system are shown in Figure 4-7 [7]. During normal operation, helium plenum pressure is kept constant at an intermediate value below that of the water-steam side and above that of the sodium side. In case of inner tube failure, moisture leaks into the helium in the wire mesh layer. This leaking moisture migrates into the helium plenum from the feedwater header or the steam header and displaces helium. The moisture migrating into the helium plenum is detected by a moisture

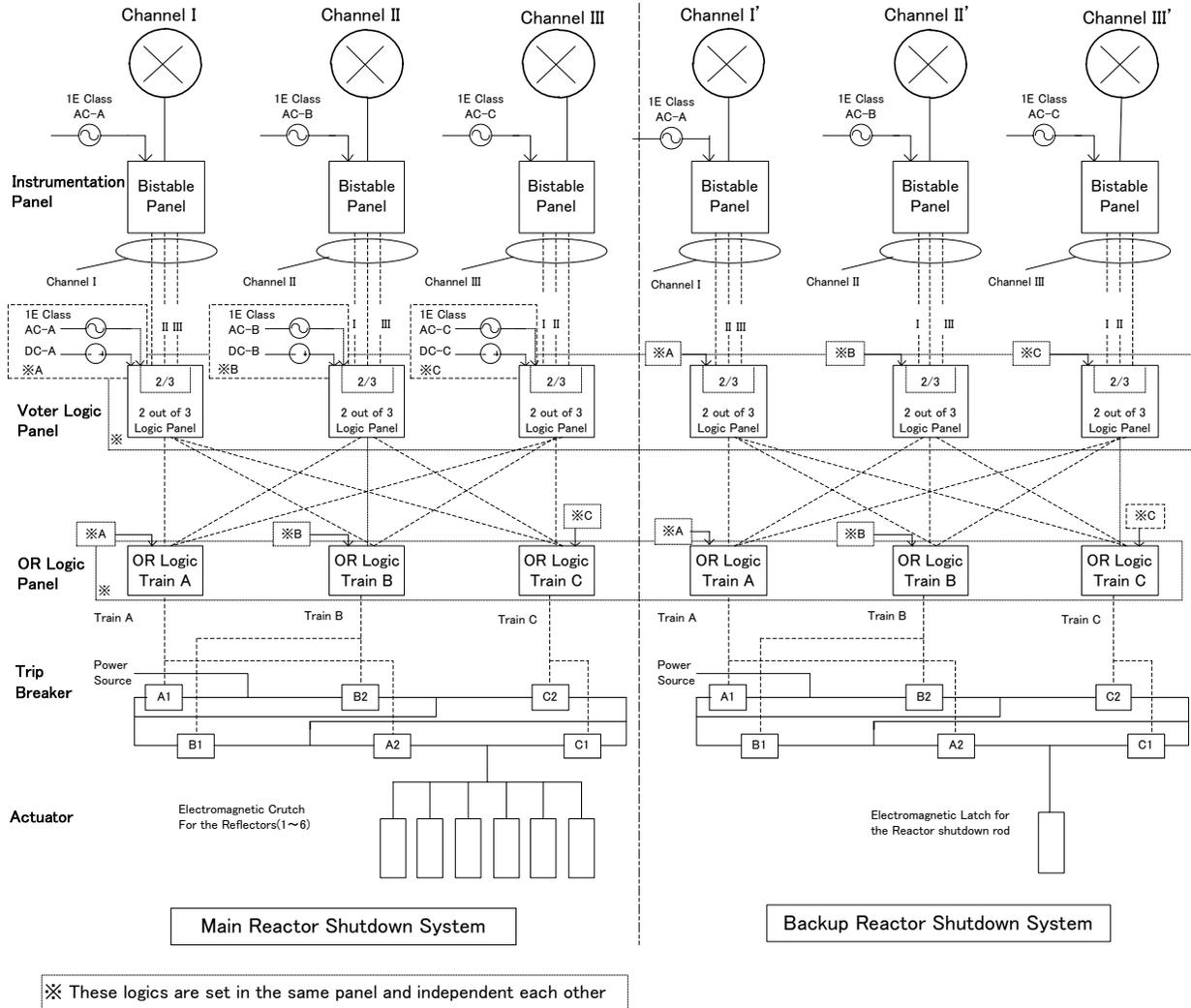
gauge in the sampling system because of increasing moisture concentration. In addition, the abnormality is detected by pressure increasing in the helium plenum. The sampling system is composed of a cooler, moisture gauge, circulator, and heater in both the feedwater side and steam side. The outer tube leak detection system is designed to detect a penetrating failure of the outer tube. If an outer tube failure occurs, the helium in the wire mesh layer leaks into the intermediate sodium loop. The pressure drop of the helium plenum caused by the outflow of helium is detected as an outer tube failure. A small portion of helium flowing into the sodium is dissolved in the sodium and the rest migrates into the cover gas area as a gas. The outer tube leak detection system consists of SG cover gas monitoring for helium content in the cover gas to detect an initial small-scale and subsequent medium-scale helium leakage promptly. This system is designed to prevent double tube failure, which would result in a sodium-water reaction, by permitting shutdown of the plant in case of prompt detection of a small-scale and medium-scale failure of either side of the double-wall tube. If a sodium-water reaction caused by double tube failure occurs, the cover gas pressure system and rupture disk failure detection system are used as an alarm signal and interlock signal, respectively.

**Table 4-1 DBE (Design Basis Events) for the RPS**

<b>Anticipated Operational Occurrences ( AOOs )</b>
Reactivity insertion by uncontrolled motion of segments of reflector at full-power operation
Reactivity insertion by uncontrolled motion of segments of reflector at startup
Decrease of primary coolant flow
Decrease of intermediate coolant flow
Increase of primary coolant flow
Increase of intermediate coolant flow
Increase of feedwater flow
Decrease of feedwater flow
Loss of offsite power

<b>Design Basis Accidents (DBAs)</b>
Failure of a cavity can
Reactor vessel leakage
One primary EM pump failure (instantaneous loss of power to one pump, equivalent to a mechanical pump seizure)
Sodium leakage from intermediate piping

# Design Description of the 4S Instrumentation and Control System



**Figure 4-1 Reactor Protection System Logic Circuit**

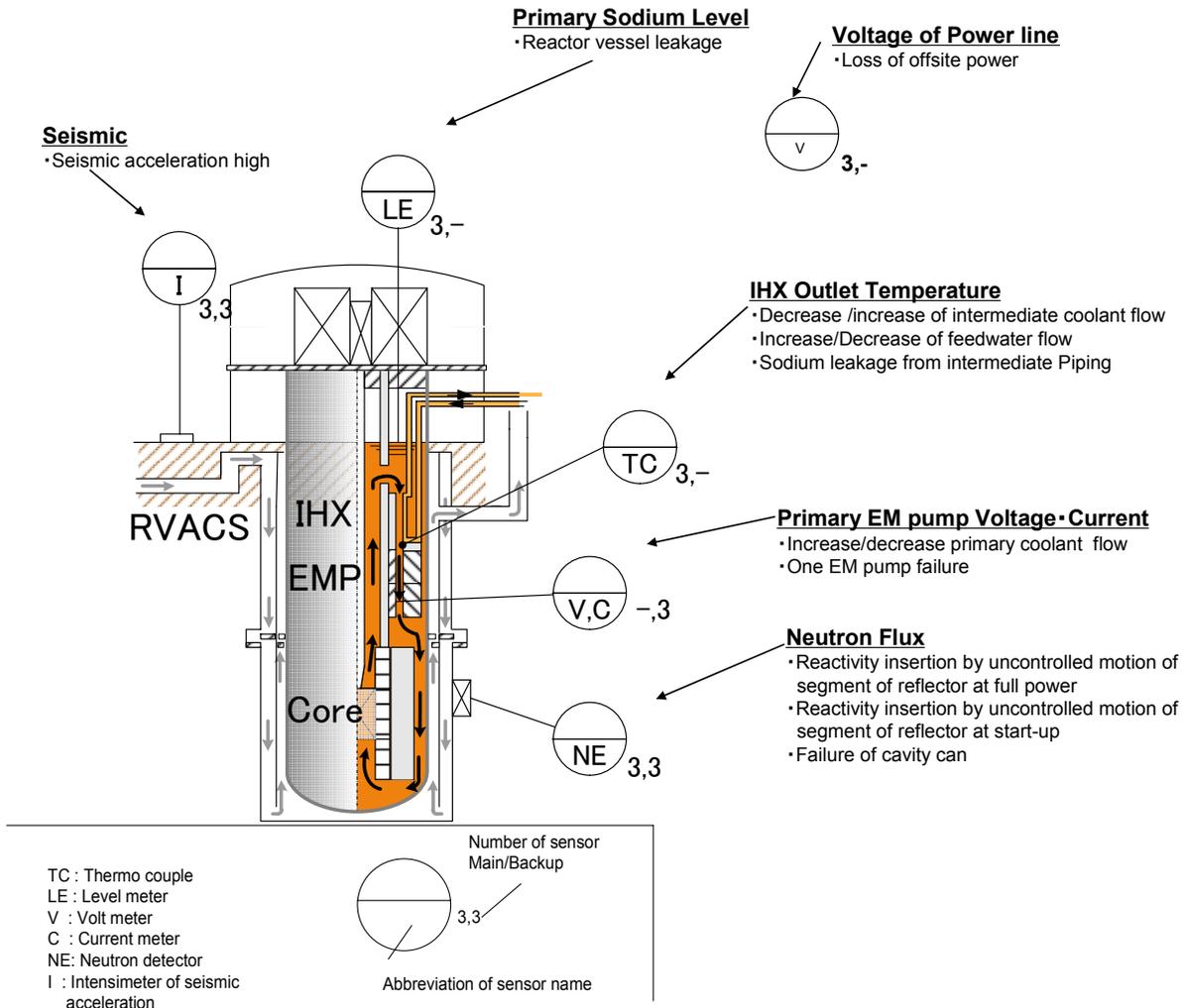


Figure 4-2 Trip Parameter vs. Design Basis Event

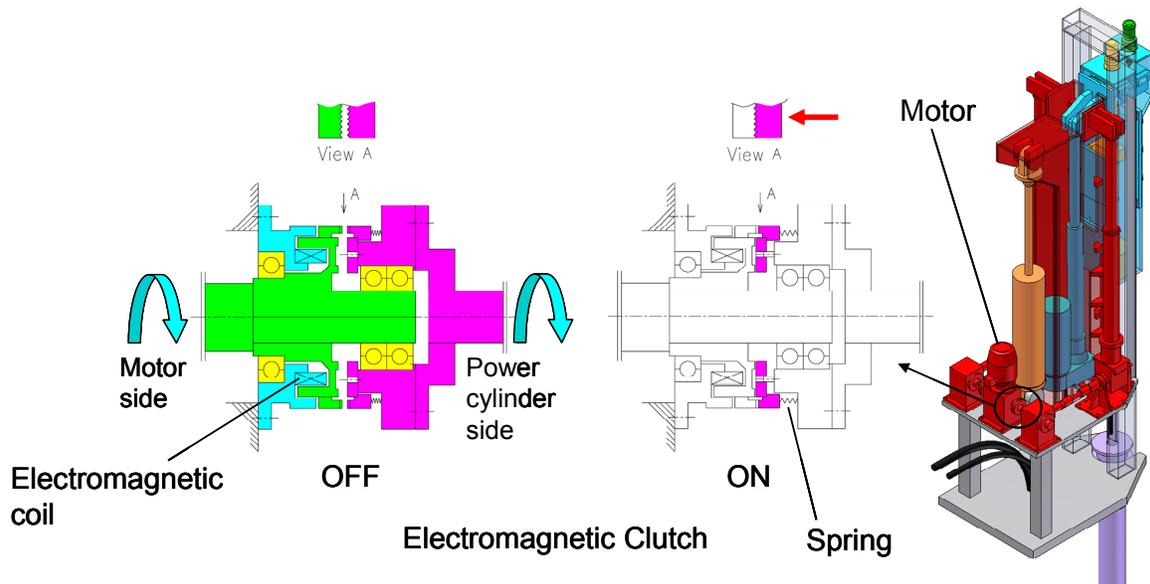


Figure 4-3 Actuator Device of Main Reactor Shutdown System

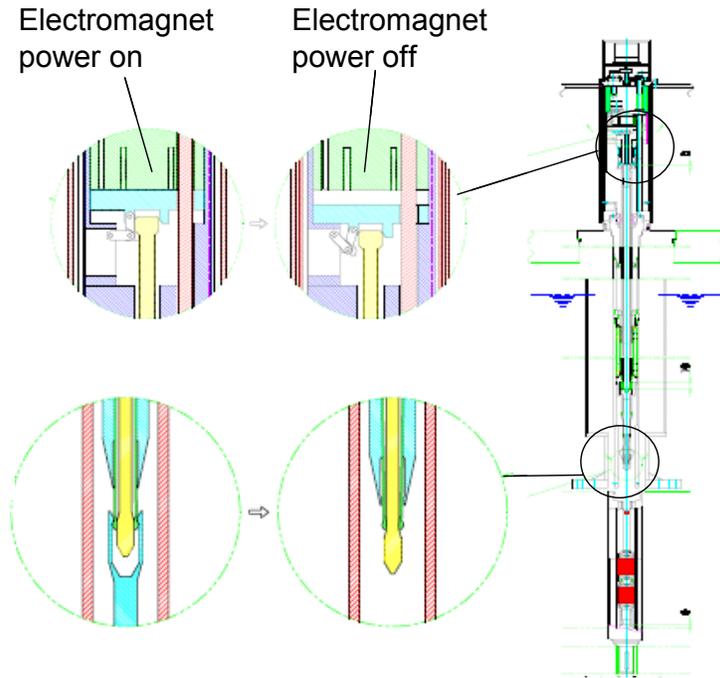


Figure 4-4 Actuator Device of Backup Reactor Shutdown System

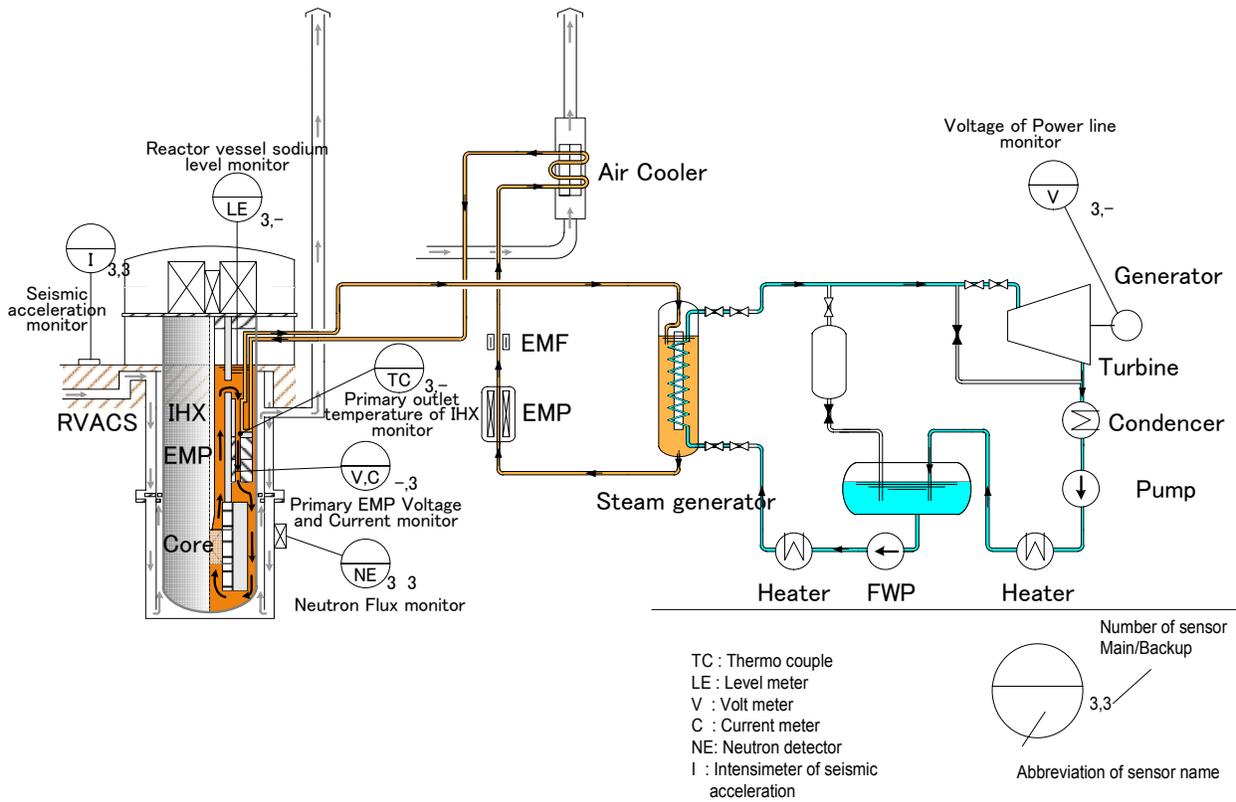


Figure 4-5 Monitors of Reactor Protection System

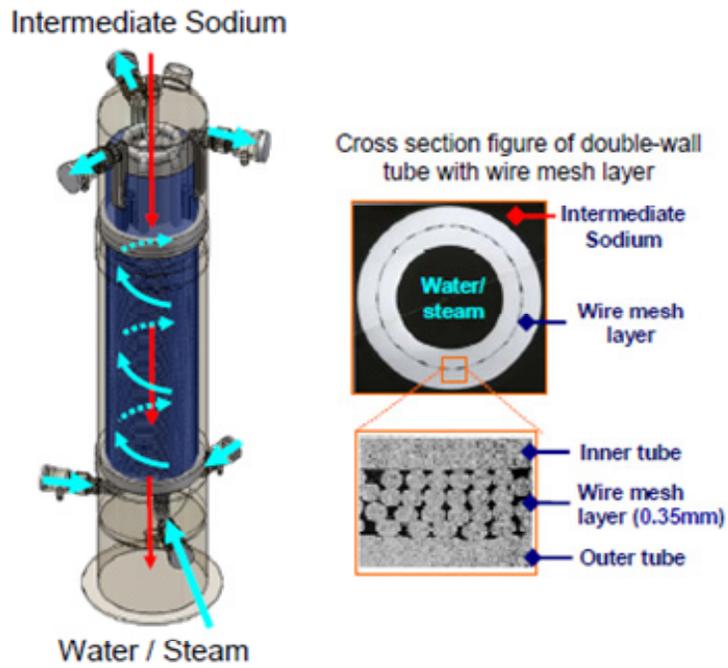


Figure 4-6 Section View of Double –Wall tube and Steam Generator

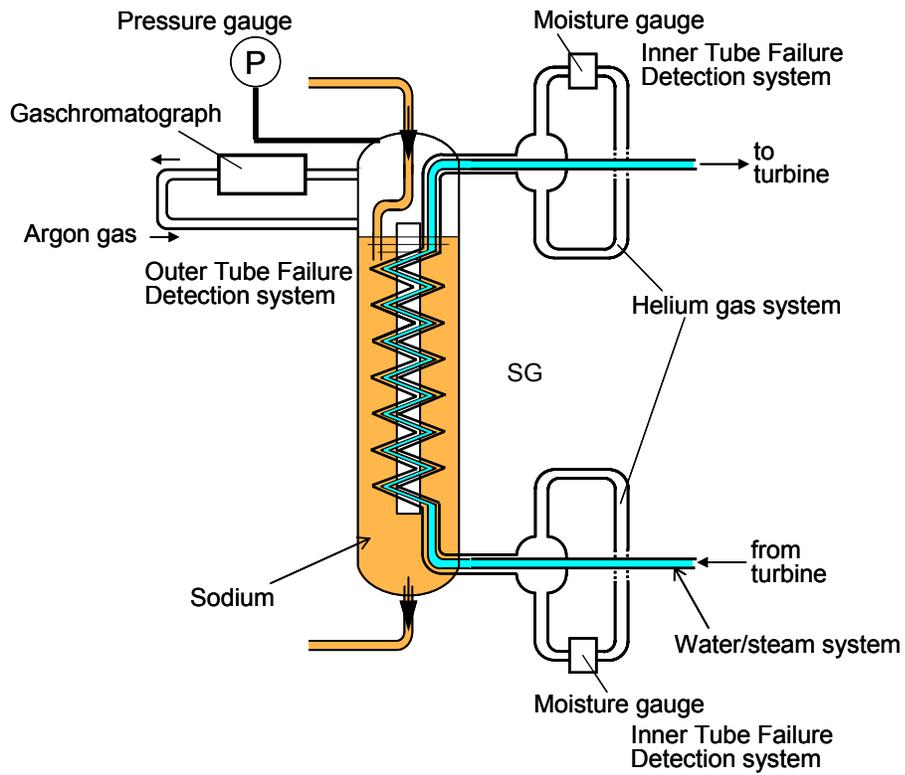


Figure 4-7 Detection Tube Failure in Double Wall Tube SG

## 5 INSTRUMENTATION AND CONTROL SYSTEM RELATED TO NON-SAFETY SYSTEM

### 5.1 Plant Control System

#### (1) Plant operation

Plant operation is directed from the control room. Normal startup and shutdown operation of plant systems is automatically sequenced and directed between predetermined hold points by the plant control system (PCS), as monitored by the plant operators. An operator-controlled permissive circuit is required to be actuated to continue the sequence at each hold point.

Most sequential plant operations are automated. The planned startup curve of temperature, power and flow is shown in Figure 5-1. In system heat up operation, initial flow rate of each primary, intermediate sodium coolant are maintained at 30% and feedwater is 10%. All initial major temperature such as reactor outlet, IHX primary outlet temperature, the SG inlet and outlet sodium temperature and main steam temperature are 200 deg C. Next step, the primary coolant is heated to 300 deg C by intermediate pre-heating system through IHX. After that operation, the operation of approaching the criticality is performed. The reflector drive system by motor driven power cylinder is manipulated automatically to the predetermined point of its cylinder position and to the set-point of wide range neutron monitor signal. After reaching the criticality, the reactor power increases with same increase rate of primary flow to 100% power. The reactor inlet and outlet temperature reaches 355 deg C and 500 deg C at 100% power.

#### (2) Plant control system (PCS)

The plant control system (PCS) provides the proper coordination of the reactor power, primary sodium coolant flow, intermediate sodium coolant flow, steam generator feed water flow, the main steam flow of turbine-generation system from plant startup through 100% power range. Proper coordination consists of producing the best load response to the load demand under recognizing the capabilities and limitations of the 4S plant.

The PCS provides limiting actions to ensure proper relationship between the reactor power and generator load.

The PCS consists of the following subsystems as shown in Figure 5-2:

- Reactor power control subsystem (RCS)
- Primary sodium flow control subsystem (PFCS)
- Intermediate sodium flow control subsystem (IFCS)
- Steam generator control subsystem (SGCS)
- Turbine generator control subsystem (TGCS)

The optimal power coordination function along with the feed forward is a part of the PCS. This controller provides optimal direction to the distributed control subsystems. Hierarchically below the feed forward demand control system, subsystem controllers manipulate the local subsystems such as reflector drive control system, EM pumps, feed water pumps, valves. When the communication between the feed forward demand controller and those subsystems, these

subsystems continue to operate the plant at fixed load set point or initiate plant shutdown if needed. An operator can override manually the automatic control mode, this operation results in removal of the appropriate portion of the system from coordinated automatic control. This is recognized by the remaining portions of the system which are on automatic control. The manual commands by an operator are transmitted to the appropriate local controller. The major subsystems which comprise the NSSS control system and turbine generator and BOP control system have multiple redundancy. Fault diagnosis and appropriate protection actions for plant investment are also performed.

Each subsystem's function is following;

Reactor power control subsystem (RCS):

The reactor power control subsystem (RCS) provides local control the reactor power level and primary outlet temperatures by positioning the reflectors to meet power demand. The RCS controls the reflector position to the demand by driving the power cylinder which is driven by motor. This driving pattern of the power cylinder is predetermined. The reflector position is monitored and driving speed is adjusted to meet the requirement of power level. Thus the RCS does not have a feature of fast runback. Display of the reflector positions, core power and temperature distribution assists the operator in monitoring the performance of the RCS.

Primary sodium flow control subsystem (PFCS):

The primary sodium flow control subsystem (PFCS) is the controller of primary heat transport. Sodium flow actuators are two EM pumps which are driven by motor-generator sets having fly-wheel with large inertia necessary to gain flow-coast down characteristic when reactor trip and especially at the hypothetical event of unprotected loss of flow (ULOF). Thus this function of flow coast down characteristic is related to safety and the M-G set should be designed as Class-1E equipment. To get variable flow rate by EM pump, this pump is driven with some constant ratio of applied voltage and frequency (so called V/F ratio) from its power source, M-G set. However the M-G set can varies only its output voltage by controlling its magnetic field DC exciting current, thus the adjustable speed driver (ASD) will be installed as a power source of the M-G set to vary its rotating speed corresponding to output frequency of the M-G set. The electro magnetic flow meters provide the flow rate to PFCS. The electromagnetic flow meters are settled at the outlets of EM pump.

Intermediate sodium flow control subsystem (SFCS):

The intermediate sodium flow is also driven by an EMP. Driving system of that intermediate EM pump is same as the primary system and has also adding fly-wheel to get flow coast down characteristic at reactor trip but this function is not required for safety. Thus, this driving system including M-G set is not classified to Class-1E equipment. The electro magnetic flow meters settled on the pipe provide the intermediate sodium flow rate.

Steam generator control subsystem (SGCS):

The steam generator feedwater flow rate and sodium outlet temperature are controlled by the steam generator control subsystem (SGCS). The feedwater flow rate is controlled by adjusting feedwater pump power.

Turbine generator control subsystem (TGCS):

The turbine generator control subsystem has two local subsystems. One is main steam pressure control system and the other is turbine control subsystem.

Main steam pressure control system controls the steam pressure by adjusting the main steam control valve.

Turbine control subsystem controls the rotational speed of turbine by adjusting the bypass valve of main steam pipe.

These controllers control the load of generator by following the load.

## **5.2 Interfacing Reactor System**

An overview of the instrumentation systems of plant supporting system, refueling system and monitoring systems performing specialized diagnostic functions, are included in this section. The systems are categorized into radiation monitoring system, fire protection system, impurity monitoring system, In-service inspection system, refueling system and diagnostic system (fission gas monitoring and leak detection system of intermediate piping, trip action and function completing sensing system, impurity monitor).

The refueling system of 4S is temporary system because it is used at the end of 30 year core life. it is not described in this report.

ISI system will be described in another report.

### **(1) Radiation monitoring system**

The radiation monitoring system monitors radiation levels during all plant operating, shutdown, abnormal, and accident conditions. The radiation monitoring systems include area monitoring, process monitoring, and environmental radiation monitoring systems; and a radiation monitoring panel. The monitors will be positioned in the areas surrounding the plant, at the site boundaries, in the head access area, and other appropriate locations.

### **(2) Fire protection system**

Fire protection monitoring is provided in accordance with 10 CFR 50.48 and 10 CFR 50, Appendix R.

### **(3) Impurity monitoring**

The 4S reactor does not require refueling during its entire plant life. Normal operation is conducted with the reactor cover gas isolated. The sodium coolant is, therefore, not exposed to impurities during normal plant operation. The impurity is monitored periodically to confirm the purity of primary coolant during plant life time. The primary sodium processing subsystem uses a cold trap for purity control and a plugging meter as a purity monitoring system. The cold trap purifies the sodium coolant by nitrogen gas cooling and excludes impurity sediments from the

coolant. The primary auxiliary system purifies sodium of the PHTS during plant initial startup and periodic maintenance when the impurity concentration monitor find the value exceed the limit. When the impurity concentration in the reactor coolant decreases below the predetermined values as determined by the plugging temperature, the cold trap operation will be terminated. The cold trap is installed in the room adjacent to the containment top dome in the reactor building, and it is surrounded with a radiation shield.

An impurity monitoring system called the plugging indicator measures the sodium temperature at an orifice in the system when the orifice is being plugged by impurities in the sodium coolant, such as oxygen and hydrogen. Sodium crystallizing temperature rises with an increase in the impurities, and the empirical relationship between impurity concentration and temperature change is used to determine the impurity concentration. The plugging indicator measures the impurity concentration in the PHTS sodium, and after the sodium purity becomes high enough, purity monitoring is not continuously performed during normal operation. When the plant is subsequently shut down for maintenance requiring opening of the reactor coolant system, the plugging indicator would again be placed in service to monitor the purity of the reactor coolant.

The intermediate sodium processing subsystem uses a cold trap for purity control and a plugging indicator as a purity monitoring system. The cold trap purifies the sodium coolant by nitrogen gas cooling and excludes impurity sediments from the coolant. The intermediate auxiliary system purifies sodium of the IHTS during plant normal operation using the sodium overflow and make-up systems for the steam generator to and from the sodium dump tank. The impurity concentration in the IHTS coolant is continuously monitored by the plugging indicator in the sodium make-up line. The cold trap is installed in the sodium dump tank to which the IHTS sodium overflows from the steam generator.

#### (4) Fission gas monitoring

The fission gas monitor detects a fuel failure by continuously measuring the gamma rays released from noble gas fission products released to the reactor cover gas due to a comparatively small fuel pin failure (pin hole failure) incident, and transmits the information to the operators. Fission gases in the cover gas, released from failed fuel pins, are transported from the cover gas to the detector by diffusion. The fission gas monitor samples the cover gas and measures the concentration of fission gas with a gamma ray detector. Data from the fission gas monitor is processed to inform the operator of the state of the reactor core.

Large scale fuel failure detection is made using detectors installed outside the reactor vessel to measure the gamma radiation from noble gases in the fission products in the cover gas space.

#### (5) Leak detection system of intermediate piping

Sodium leak detecting system is prepared to detect the sodium leak from the equipment and piping that contain the sodium. The detecting system is composed of two kinds of systems.

One system is for very little amount of sodium leak and the other is for large amount of sodium leak. As for detecting very little sodium leak, the atmosphere gas is sampled from the gap between equipment and heat insulating material surrounding the equipment. When the aerosol is contained in the sampled gas, aerosol is detected by detecting system. The laser induced breakdown spectroscopy (LIBS) is used for detecting small amount of sodium aerosol. In LIBS, the aerosol is made into plasma by irradiation of laser and inherent radiated light is detected

and distinguished as the sodium inherent light by spectroscopy. As for detecting a large amount of sodium leaks, the contact type sodium leak detector is used. The detector detects the sodium when the leaked sodium contacts the electrodes of detector.

(6) Trip action and function completion sensing system

Sensors are provided to give an indication of a trip action completion. Operators are informed that the required actions have been taken. Any device that performs a trip function is monitored to confirm the completion of its action. The reactivity control system consists of 2 systems; 1) the reflectors around the core barrel for the main reactor shutdown system and 2) the reactor shutdown rod in the center of the core for the backup reactor shutdown system. Drive shafts are installed in the reflector upper region and are coupled to the reflector drive mechanism on the shielding plug. Reflectors tripping action actuates the trip breaker open to be electrical current interrupted. In case of failure of its action, motor-driven power cylinder is backed up and inserts the reflector into the emergency-shutdown position together with the drive shaft. In an emergency case of loss of power supply, the electro magnetic crutch of reflector drive system are de-energized so that the reflectors fall freely by its own weight. This insertion motion to the emergency shutdown position is monitored by the position detectors (rotary encoder) for the reflector. Moreover, the reactor shutdown rod is equipped with the handling head, which is held with latch fingers at the lower end of the extension pipes which are moved up and down by the reactor shutdown rod drive mechanism on the shielding plug. The trip actuation for the reactor shutdown rod de-energizes holding magnet in the drive mechanism, which closes the latch fingers, and then, only the reactor shutdown rod gets separated and drop under by its own weight. This insertion motion is monitored by measuring electric current produced when the permanent magnet embedded in the handling head of reactor shutdown rod is passing the coil attached to the top guide tube.

(7) Parameters for post accident monitoring

As for the post accident monitoring information, above reflector position information and shutdown rod position information are used to confirm the completing the trip action.

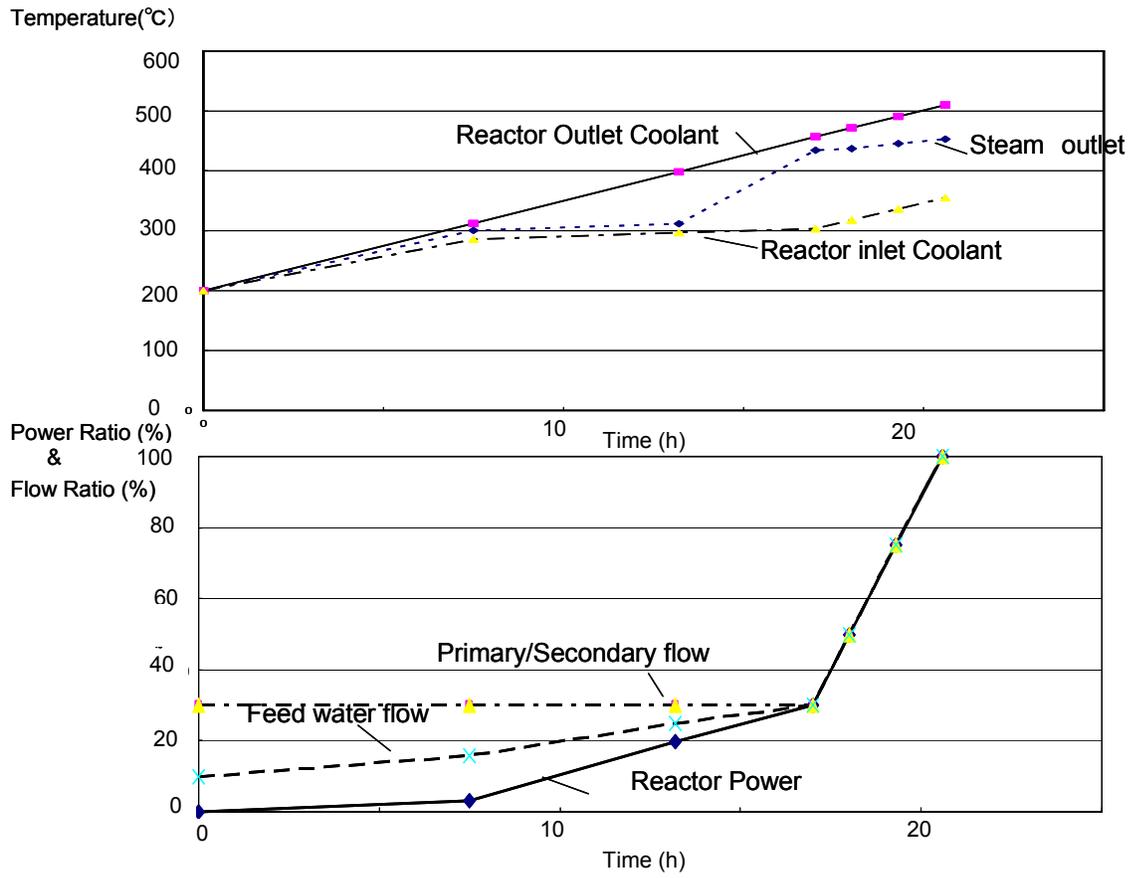


Figure 5-1 Start-up Curve

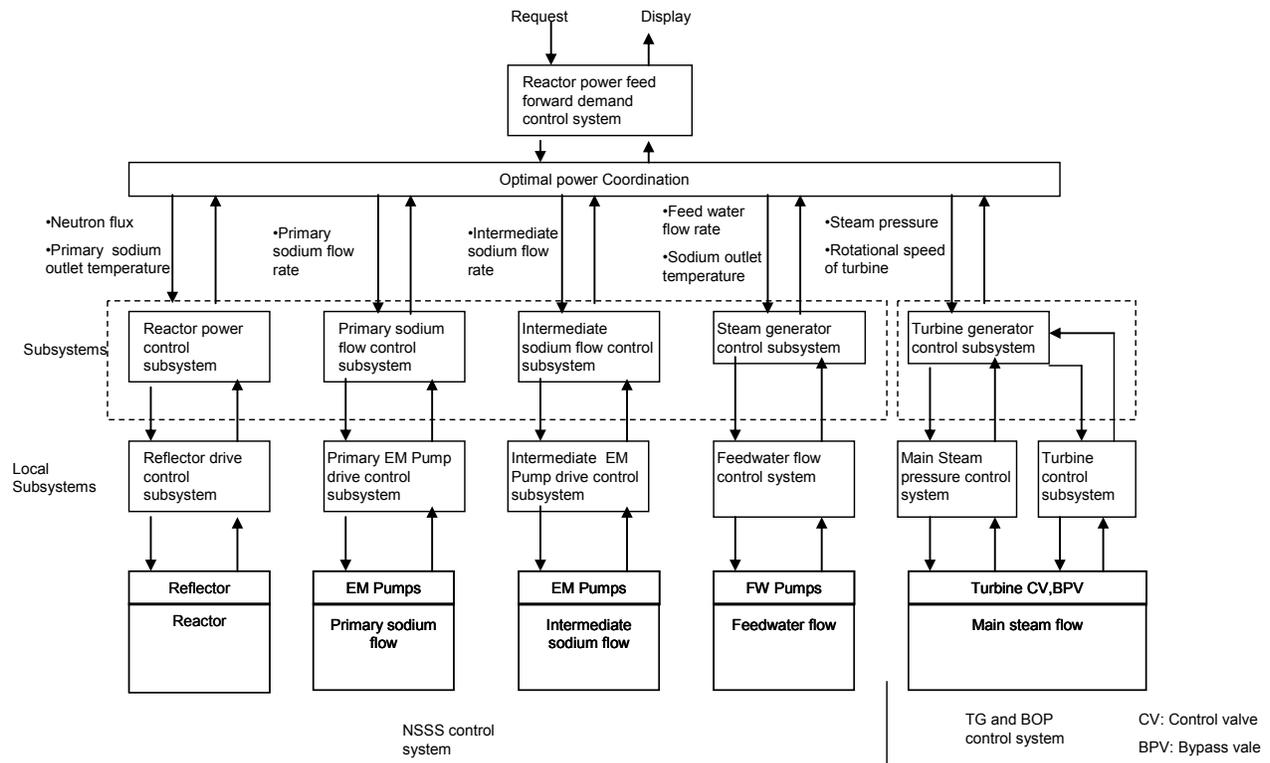


Figure 5-2 4S Plant Control System (PCS)

## **6 CONCLUSION**

The instrumentation and control system is composed of system related to safety and the system related to non-safety. The system related to safety includes reactor protection system (RPS), engineering safety feature actuation system (ESFAS), remote shutdown system (RSS) and other instrumentation system required for safety (OISRS). The RPS adopts the two out of three voter logic to have redundancy. So sensor, cable and actuator switching breaker associated with RPS are grouped into three groups and they are electrically and physically separated.

Systems related to non-safety consist of plant control system (PCS) and interfacing reactor system (IRS). The IRS has the function of diagnostic and monitoring various reactor subsystems such as radiation monitoring system, fire protection system, impurity monitoring system and leak detecting system of intermediate piping. The principles of specific sensors of sodium cooled reactor are described.

4S plant is operated by using these instrumentation and control systems.

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