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A Study on Diversity and Independent Features of Shutdown System of the PGSFR

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1. Introduction

There are several design types of the reactor control and shutdown systems in SFRs[1].

Motor driving system with a screw-drive gear is typically used for an accurate axial movement of CRAs to control the core reactivity of SFR. An electro-mechanical type mechanism is typically adopted for the CRA release as the primary shutdown system. Some SFRs adopt a passive shutdown system (self-actuated shutdown system, SASS) implemented in a group of CRDMs to mitigate a severe accident without any operator's action.

This paper describes the design concepts of control rod drive mechanism, and the diversity and independent features of shutdown system of PGSFR.

2. Functional requirement of active shutdown system of Gen-IV[2]

Fundamental functions

- Two independent reactor shutdown systems should be provided.
- The insertion time and reactivity worth should be ensured not to exceed the specified design limits taking the transient characteristics such as a flow coast-down into account.

Design margin

- At least one of the two reactor shutdown systems should be able to maintain the safe shutdown state with an one rod stuck margin under the largest excess reactivity condition during the reactor operation cycle.
- The reactor shutdown systems should keep the reactor sub-critical considering handling of core elements including control rods subassemblies and their misloading during the reactor shutdown.
- The reactor shutdown systems should keep the reactor sub-critical considering possible jumping-up of core elements including control rods subassemblies against earthquakes during the reactor shutdown.

Ensuring insertion

- Control rods insertion should be assured even in case of deformation of core components due to, for instance, irradiation or design basis earthquakes. The reactor shutdown system, which functions as reactor controller under normal operation, e.g., reactor start-up, and power regulation, should also be designed so that any failure of the control function, such as control rod position change by motor drive mechanism, shouldn't affect the reactor shutdown function.

Limitation of power increase

- In order to limit power increase in case of erroneous withdrawal of control rod (malfunction, operation mistake), rod stop system of withdrawal prevention should be provided, and rate of reactivity insertion by erroneous withdrawal of control rod should be limited.
- Individual operation of control rods should be applied in order to prevent excessive reactivity insertion due to unexpected withdrawal of control rods.
- Power reactivity coefficient of reactor core should be negative in all the operation conditions.

Reliability (diversity and independency)

- Two shutdown systems should be designed to have independence and diversity to the extent practicable to prevent common cause failures. Examples of diversities are:
  - Activation : mechanical latch, electromagnet
  - Driving force : fast drive-in motor, gravity drop
  - Insertion : control rod with drive shaft or control rod only
- Detection parameters for the reactor shutdown systems should be diverse to the extent practicable. Typical detection parameters are neutron flux, reactor outlet coolant temperature, off site electric power voltage.
- The reactor shutdown systems should be designed to ensure reactor shutdown considering failure of any elements of entire system including detectors and electric circuits, activation and insertion mechanisms, and control rods, and influence of any abnormal events which may happen in the reactor power plant.
- Reactor shutdown systems should be a fail-safe design.
  - The control rods should be inserted when electric power supply of holding control rod is lost.
  - When one reactor shutdown system is activated, withdrawal of control rod of the other reactor shutdown system should be prevented.

Environmental condition

- Two shutdown systems should be designed to withstand, throughout the reactor's lifetime, environmental conditions, such as irradiation, temperature, chemical effects, geometrical change, and DBAs.

Testability and inspection

- During reactor shutdown, insertion time of control rods and their reactivity worth should be confirmed by tests such as scram simulation and control rods operation.
- The control rod position and status of latch / de-latch should be monitored during the reactor operation.

3. Design concept of CRDM and shutdown systems

The PGSFR has six primary control rod assemblies (CRAs) and three secondary shutdown assemblies. The primary and secondary control rod drive mechanisms (CRDMs) are used to drive the CRAs. The drive mechanism is mounted on top of the rotatable plug and controls the axial motion of the CRAs. The failure frequency of the system is less than 10^{-6}/ry, which also meets the safety criteria. PGSFR has independent and diversified reactor shutdown functions.

3.1 Shutdown system

The primary system is used for reactivity control, burn-up compensation and reactor shutdown in response to demands from the plant control and protection systems. The primary system consists of the drive motor assembly, the driveline, and its housing. The driveline consists of three concentric members of a drive shaft, a drive tube, and a position indicator rod, and the driveline connects the drive motor assembly motion to the CRA.

Each CRDM has two means of rod insertion for reactor shutdown. The first is by releasing the CRA from the driveline allowing it to drop into the core by gravity. The reactor trip sequence using the primary CRAs is as follows; the electric current to the electromagnet in CRDM housing is cut off, then the electromagnetic holding force of the drive tube is weaken, then the drive tube moves down about 15mm, the gripper holding a CRA head is open, finally the CRA drops down by gravity. The second is the forced insertion of the CRA with the driveline by the drive-in motor power. The general design requirements of the CRDM are listed in Table 1.

The secondary system is only used to trip the reactor in response to the plant protection system, and each CRDM has two means of the rod insertion like as the primary system. The reactor trip sequence using the secondary CRAs is as follows; the electric current to the electromagnet immerged in sodium above the core is cut off, then the holding force of the CRA is weaken, then the CRA drops down by gravity. The second is the forced insertion of the CRA by the fast drive-in motor same as the primary system.

The third shutdown system is a passive concept, which is implemented in the secondary system for the mitigation of a severe accident. The system automatically releases the control rod assembly (CRA) at set temperature above the design value, and then the CRA is inserted by gravity into the core without any external control signal and any actuating power.

The primary and secondary systems are simultaneously actuated by RPS and DPS trip signals. The forced insertion function of CRAs by a fast drive-in motor is also used for ensuring CRA complete insertion.

The PGSFR shutdown system issued in this section is represented in Figure 1.

Table 1 Design requirements of CRDM

Parameters	Primary CRDM	Secondary CRDM
Maximum driveline drive-in force	3,500 N	8,000 N
Maximum driveline stroke	1,100 mm	1,100 mm
Maximum rod withdrawal speed	1 mm / sec.	5 mm/ sec.
Rod insertion speed	1~5 mm/ sec.	41.7 mm/ sec.
CRA mass	~ 58 kg	~ 58 kg
Gripper type	Collet fingers	Electromagnet
Electromagnetic coil type (number)	Solenoids (dual)	Solenoid
Mechanism protection sealing from sodium	Bellows	Bellows

3.2 Control rod gripper system

Primary control rod gripper system

The gripper of the primary CRDM consists of flexible multiple fingers branched from the bottom end of the drive tube, as shown in Figure 2. The fingers are mechanically opened and closed by the up-down movement of the drive tube inside the hollow drive shaft. The drive tube is operated by an electromagnet system.

Latching a CRA is accomplished by raising the gripper to its trigger position by the drive tube after that the gripper moves down to the bottom of its stroke with the drive shaft.

Secondary control rod gripper system

The gripper of the secondary CRDM is an electromagnet of solenoid coil type, which is located in a limited space and a hot environment. The design requirements and materials are represented in Tables 2 and 3.

The size of the electromagnet is determined to be 80 mm in outer diameter, and about 300mm in length, as shown in Figure 3. The electromagnet outer core encloses the coil and protects the sodium ingress into the coil. The inside diameter of the outer core is 64 mm. The outer diameter of the inner electromagnet core is 50 mm[3].

An electromagnet armature is attached to the CRA extension rod top. The extension rod plays a role of the armature of the electromagnet system. The size of the armature is 60mm in diameter and the thickness of 20 mm.

Table 2 Design requirements of secondary CRDM

Parameters	Requirements
Installation space	< 100 mm in diameter
Gripper off mechanism	Bimetal thermal expansion difference : ~ 5 mm (temp.: 600°C~650°C)
Secondary CRA mass	~ 58 kg
Gripper type	Electromagnet with solenoid coil

Table 3 Passive component material of secondary CRDM

Components	Materials
Electromagnet coil	Cu
Electromagnets & armature	SS410 & 2.25Cr-1Mo
Drive shaft corresponding to the thermal expansion region	Inconel 718 or Mod.9Cr-1Mo
Thermal expansion device	SS316

3.3 Passive shutdown device

Passive shutdown system is implemented in the secondary control rod drive mechanism. The passive shutdown system consists of a thermal expansion device, an electromagnet to hold and trigger off the CRA, and a flow guide structure. The redan diameter of the extension rod of the secondary CRA is determined to be 74 mm so that it is compatible with the bottom shape of the thermal expansion device, as shown in Figure 4. The thermal expansion device length will be determined within 2.86 m. The maximum expansion difference between SS316 and Inconel 718 is expected to be about 1.7 mm ~ 2.6 mm when the environment fluid temperature rises up about 100 °C - 150 °C more than the normal operation temperature. The calculation results are as follows[3]:

$$1.72\text{ mm} = \sim (6.0 \times 10^{-6}\ /^{o}C) \times (100^{o}C) \times (2.86\text{ m}).$$
$$2.57\text{ mm} = \sim (6.0 \times 10^{-6}\ /^{o}C) \times (150^{o}C) \times (2.86\text{ m})$$

The electromagnetic forces on the CRA with a 1 mm gap are in the range of ~ 300 N. Thus, the thermal expansion difference of the thermal expansion device to trigger off the CRA shall be controlled within 1 mm at the setting temperature.

3.4 CRA insertion information at shutdown

After a trip signal from RPS and DPS, the CRA insertion information both of the primary and secondary CRDM is obtained as follows;

Time (sec)	Action
0	Cut the power on the electromagnet from RPS trip signal
0.12	Gripper releases CRA, and CRA is dropped by gravity
1	Fast drive-in motor starts to insert the drive shaft
2	CRA insertion is finished by gravity. Neutron flux detector might be used to check the CRA drop status, but there is some uncertainty.
5 ~ 6	The core exit coolant temperature changes from the thermocouples around CRA can be used to detect the CRA insertion information.
20 ~ 25	Fast drive-in motor stops to insert the drive shaft when the drive shaft ledge touches the bottom limiter switch. The CRA complete insertion signal from the switch is informed to the operator.

4. Measures of shutdown system diversity and independency

There are several index for checking the shutdown diversity and independence issued in reference [4]. The independence measures between shutdown mechanisms are listed, and the availability is checked for the scram instrument and control system parameters in Table 4.

Table 4 Independent measures of shutdown systems

Independence measure	Sensors	Signal processing	SCRAM circuit	SCRAM logic	SCRAM switch	Power supply	Cable and connectors
Functional design	O	O				X	X
Physical separation	O	O	O	O	O	O	O
Electrical isolation	O	X	X	X	X	O	X
Component technology	O	O	O	O	O	O	X
Design concept	O	O	O	O	O	O	X
Manufacturing	X	X	X	X	X	O	X
EMI and EMC	O	O	O	O	O		X
Maintenance and testing	O	O	O	O	O	X	

O: the relevant measures to enhance independence/diversity is present,
X: not present,
Blank: not ascertained/not applicable.

The diversity parameters of shutdown mechanisms for the scram actuation system are suggested in Table 5. Main parameters are the designer, CRA insertion mechanism, insertion device, CRA shape, insertion type, etc.

Table 5 Diverse features between shutdown mechanisms

Diverse feature parameters	**PCRDM/ PCRA**	**SCRDM/ SCRA**	**Fast Drive-in Motor**
1. Designer	Different	Different	Different
2. Insertion initiation device	Electromagnet (DC) => Finger type gripper	Electromagnet (DC)	AC servo motor
3. CRA insertion mechanism	Gravity drop by cutting off DC power	Gravity drop by cutting off DC power	Motor driving force by AC power supply
4. Insertion initiation device temperature	60 °C / 500 °C (electromagnet /gripper)	500 °C (electromagnet)	60 °C (motors)
5. Insertion initiation device location	Above reactor head/ Top of the core	Top of the core	Above reactor head
6. Insertion initiation device environment	Inter seal argon / Sodium	Sodium	Inter seal argon
7. CRA axial position during operation	Partially inserted in active core	Withdrawn from active core, but within duct assembly	-
8. Weight of insertion part	~58 kg	~58 Kg	~310 Kg
9. CRA shape	Hexagonal	Hexagonal (option : circular)	-
10. Insertion part on SCRAM	CRA only	CRA only	CRA and driveline
11. Insertion time	< 2 seconds	< 2 seconds	< 24 seconds
12. Fail-safe condition for external power supply	Fail-safe design	Fail-safe design	Active (1E-class power)

PCRDM : primary control rod drive mechanism / PCRA : Primary control rod assembly

SCRDM : Secondary control rod drive mechanism / SCRA : Secondary control rod assembly

5. Summary

The design concepts of control rod drive mechanism of PGSFR are introduced. The shutdown system of PGSFR has diversity and independent features required in Gen-IV SFR design. In future, the physical shutdown reliability analysis will be performed based on probability values of the actuation components of the diversity and independency features.

ACKNOWLEDGEMENT

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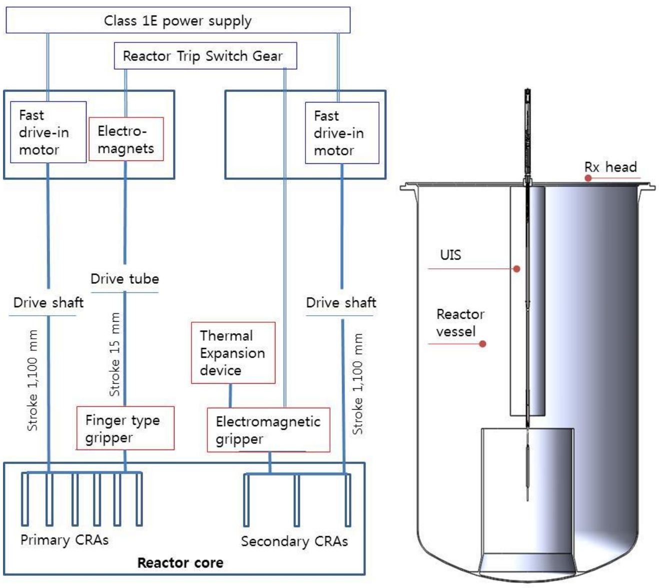

Figure 1 PGSFR Shutdown Ways

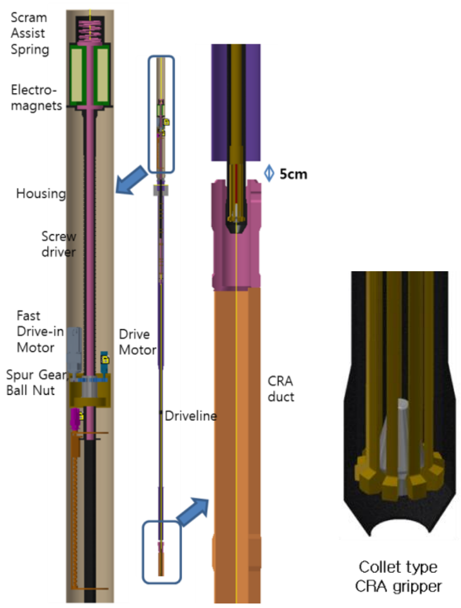

Figure 2 Overview of CRA gripper system of the primary CRDMs

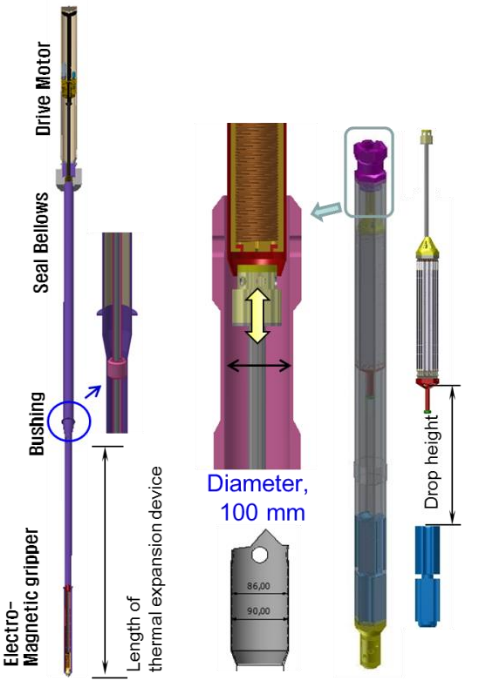

Figure 3 Design concepts of the passive shutdown system and secondary control rod drive system

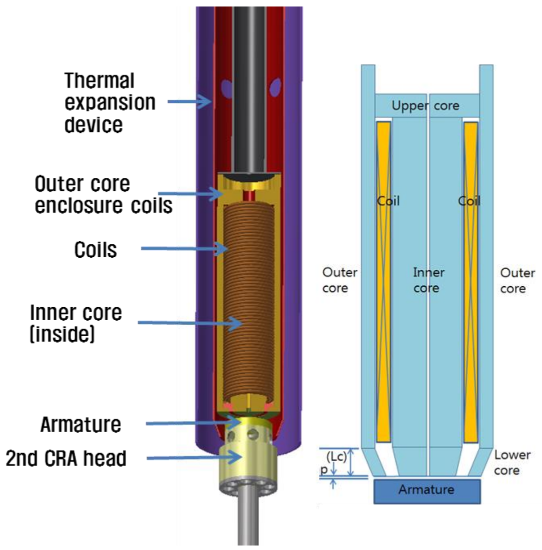

Figure 4 Design concept of electromagnet and thermal expansion device of the passive shutdown system