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CRDM performance tests of PGSFR

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1. Introduction

The control rod drive system of PGSFR (Prototype Gen-IV SFR) consists of six primary and three secondary control rod drive mechanisms (CRDMs). Control rod assembly movement for the reactor reactivity control is achieved by a reactivity control motor of the primary CRDM, which has also a reactor emergency shutdown function [1,2]. The shutdown is performed by the electromagnet device of the CRDM, and confirmed by a follow insertion by a fast drive-in motor as shown in Figure 1.

This paper presents with the test results of the primary CRDM as follow items.

- Reactivity control performance
- Scram and fast insertion performance
- Rod stop system performance
- Planed simulation test for verifying an integral performance.

The test facility includes the motor drive system, the driveline and electromagnet parts, forced insertion resistance device, rod stop system, and sensor system of the primary CRDM.

2. Configuration of CRDM

The CRDM moves the control rod assembly (CRA) up and down in the reactor core. The driveline of CRDM penetrating the reactor head is connected to CRA at bottom part, and axially actuated by the drive motor mechanism above the reactor head. The control rod assembly gripper is assembled at the lower end of the driveline. The major components of CRDM are classified follows as shown in Fig. 2, Fig.3 and Fig. 4.

- Motor support and shield plug,
- Driveline,
- Motor,
- CRDM housing,
- Electromagnet & Gripper,
- Seals and sensors.

There are several functional and design requirements of CRDM performance as follow;

- The reactivity control motor is connected to the ball nut gear through the torque limiter clutch.
- The fast drive-in motor is only capable of insertion of one-way operation.
- The fast drive-in motor shall be capable of meeting the time requirements for fast insertion even though operated against a torque limiter.
- The fast drive-in motor should be capable of overcoming the pull-out force of the reactivity control motor (RCM) even if the torque limiter is not slipping due to sticking.
- An anti-rotation circuit brake is installed on the reactivity control motor to prevent the rotation of the screw ball-nut, which could lead to control rod movement when the motor power is disconnected.
- If the reactivity control motor fails, the manual or redundancy reactivity control motor shall be connected.

3. Configuration of Test Facility

Fig. 5 shows the test facility of the driving part of the CRDM. The test facility is fixed to the two-stair steel frame. The performance test facility was fabricated by the prototype size for both the upper and lower sections except for the shortened 7 m in the middle of the driveline. Two steel bellows are installed in the driveline at bottom of the reactor head. An electromagnet is located at the upper portion for providing the CRA latching force, and a motor system for driving the driveline up and down is located at the middle of the housing. A CRA gripper system is attached at the bottom, and the motor system is supported by a cylindrical support structure. A dummy cylinder of the same weight with a CRA is fabricated to simulate for the gripper device to grip and release it. A braking resistance device for the forced insertion test of the stuck CRA is located at the lower end.

Several features of the electromagnet, the motor driving, the ball-screw, the gripper device, the sensing equipment, rod stop system, and 800kg insertion resistance device are described below.

Electromagnet driving part

The electromagnet driving part of the test facility is shown in the upper part of Fig.2. The traction stroke distance of the electromagnet is adjustable from 10 mm to 20 mm and is now set at 15 mm. The electromagnet is equipped with dual coils that can be driven independently on the inside and outside. A current of 15A is supplied for gripper device operation, and then it is reduced to 0.8A ~ 2A for holding. A switch box for shutting off the power supply is used to enable the CRA scram test.

Motor driving part

AC servomotors are adopted in motor system of the test facility. The electric capacity of the fast drive-in motor is 400 W. The electric capacity of the reactivity control and RSS motors has of 50W, respectively.

Ball-screw drive part

The ball-screw device converts the rotational force of the motor into the axial force of the drive shaft. As shown in Fig. 2, the screw part made of a hollow cylinder with a groove outside for ball bearing-nut is a length of 1.7 m, an outer diameter of 63 mm, and a pitch of 10 mm. A penetration hole inside it is a maximum diameter of 37 mm which was machined with a gun drill so that the drive tube and the position indicator could pass through it. The driving stroke is about 110 cm, and the limit switches are attached to constrain the upper and lower strokes.

The drive shaft and the motor shafts are connected by the spur gear set in Fig.6. Spur gears have a limited gear reduction ratio due to the installation space of the ball bearing-nut and motors. 1/3 reduction ratio for the fast drive-in motor and 1/4 reduction ratio for the reactivity control motor are adopt.

Gripper device

The collet type gripper is adopted. It has nine or five fingers separated from each other in the form of branches, and the upper end of the fingers is connected to the drive tube. The driving tube is raised or fell by doing the connection and cutoff of the electromagnet power source. The latching actuation of the CRA head is performed through the pulling of the drive tube. The characteristics of the latching device are shown in Table 1.

Table 1 Gripper type of the primary CRDMs

<table>
<tr><th colspan="2">Parameters</th><th>Test facility</th></tr>
<tr><td colspan="2">Gripping stroke</td><td>10 ~ 15 mm</td></tr>
<tr><td colspan="2">CRA movement at gripping actuation</td><td>~ 5 mm</td></tr>
<tr><td colspan="2">Test CRA mass</td><td>~ 50 Kg (actual design, 56.8 kg)</td></tr>
<tr><td>Gripper types</td><td>Collet type</td><td> </td></tr>
</table>

Sensing equipment

The instruments in the CRDM consist of a laser distance sensor, a rotary encoder, and a thermocouple. They inform the CRA position during operation, the status of gripper whether the driveline holds the CRA or not, and the stopper position signal for adjusting the stopper position of the control rod stop system (RSS). It also monitors the operating environment temperature of the drive motor system. Details are given in Section 4.0.

Control rod stop system

Fig. 7 shows the stopper of the RSS, and the circular protrusion of the drive shaft is always positioned at the lower level of the RSS stopper for preventing the excessive unintentional withdrawal of the control rod drive shaft. The pull-out speed of the drive shaft was 5 mm/s at maximum, and the performance test was conducted by changing the setting value of the torque limiter of the reactivity control motor from 1.0 N-m to 3.0 N-m.

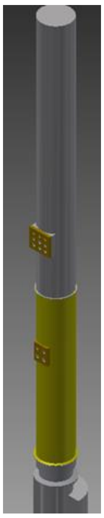
800kg insertion resistance device

An insertion resistance device for a forced insertion of a CRA by a fast drive-in motor was fabricated as shown in Fig. 8 using a brake system. The device has a joint device for adjusting the resistance force level and a load cell capable of measuring the resistance force.

4. Drive shaft position sensing system and control system

All sensors are installed inside the CRDM housing as shown in Figs. 4 and 5, and are connected to the outside of the housing through the sealed cable connector sockets. Table 2 shows the sensor type, number of installation, and sensing method to obtain the position of the CRA and latch state information. The position information of the CRA is provided by two rotary encoders installed on the spur gear connected to the drive shaft by a screw ball nut.

Table 2 Sensor type, cable number, and sensing method of the CRA location and latch state

<table>
<tr><th>Connector Position</th><th>Cable kind</th><th>Pin No.</th><th>Sensor to connector</th><th>Fixed or moving</th></tr>
<tr><td rowspan="10">
Upper connector</td><td>Rod latch laser sensor</td><td>3</td><td>Align electromagnet side wall and coil wire type</td><td>moving 1.1 m with drive shaft</td></tr>
<tr><td>Upper stroke limiter</td><td>2</td><td>Align electromagnet side wall and coil wire type</td><td>moving 1.1 m with drive shaft</td></tr>
<tr><td>Thermocouple</td><td>2</td><td>shorten line</td><td></td></tr>
<tr><td>Electromagnet power line</td><td>4</td><td>Align electromagnet side wall and coil wire type</td><td>moving 1.1 m with drive shaft</td></tr>
<tr><td>Reactivity motor & encoder</td><td>10</td><td>shorten line</td><td>fixed</td></tr>
<tr><td>Fast drive-in motor and encoder</td><td>10</td><td>shorten line</td><td>fixed</td></tr>
<tr><td>Rotary encoder 1</td><td>8</td><td>shorten line</td><td>fixed</td></tr>
<tr><td>Rotary encoder 2</td><td>8</td><td>shorten line</td><td>fixed</td></tr>
<tr><td>Lower stroke limiter 1 & 2</td><td>4</td><td>shorten line</td><td>fixed loc., mechanical analog type</td></tr>
<tr><td>Thermocouples</td><td>2</td><td>shorten line</td><td>fixed</td></tr>
<tr><td rowspan="4">Lower connector</td><td>RSS motor & encoder</td><td>10</td><td>shorten line</td><td>fixed</td></tr>
<tr><td>Rotary encoder</td><td>8</td><td>shorten line</td><td>fixed</td></tr>
<tr><td>Stopper distance laser sensor</td><td>3</td><td>shorten line</td><td>fixed</td></tr>
<tr><td>Stopper upper limiter</td><td>2</td><td>shorten line</td><td>fixed loc., mechanical analog type</td></tr>
<tr><td>Total pin number</td><td></td><td>76</td><td></td><td></td></tr>
</table>

Limiter switches to check whether the CRA is fully inserted or withdrawn are located near the middle and top of the housing. They generate direct signals from the fixed positions of the drive shaft. Also, the position data are acquired by the dual rotary encoder sensors mechanically connected to the drive shaft.

In the test facility, the three laser sensors are provided for measuring the position of the drive shaft, the stopper of control rod stop system (RSS) and the position indicator rod (PIR). The laser sensor for the drive shaft position is only used in the test facility for checking the overall behavior, this sensor is not adopted in actual design due to its low accuracy. Cables and I/O devices for transmitting sensor signals to the control computer were implemented.

The three rotary encoders are provided, two of which are connected to a spur gear mechanically connected to the drive shaft and one of which is connected to a helical gear mechanically connected to the motor and screw shaft of the RSS.

A computer is equipped with developed control software and the motion control board (NI PCI-7354, 4 axis stepper/servo motion controller) as shown in Fig. 5. The power supply to the electromagnet is done through EDP-3020. The test parameters were controlled on the computer screen in Fig.5. Data communication has been performed by an interface device between the drive motors, the electromagnet, the sensors, the motion control board, and the computer software.

5. CRDM performance tests

5.1 Performance test kinds

The performance test items of the CRDM driving parts are presented in Table 3. The performance tests are carried out to determine the influencing variables affecting the motor driving characteristics, such as up and down direction change and controllable speed range of the drive motor, the torque generated by the axial force of the drive shaft, and the operability when the motor reverse rotation acts as a slave load. The following is performance test items of the motor driving part.

○ Reactivity control motor (RCM) drive mechanism test
- Preliminary test for motor driving force and mechanical operation
- RCM operation for withdrawal / insertion of drive shaft
- RCM stop stability
- RCM torque test
- RCM shaft position accuracy test

○ Gripper operation and drop test
- Preliminary test for setting the gripper position for CRA latching
- Electromagnet power on / off test
- CRA latching and release

○ Fast drive-in and forced insertion test by fast drive-in motor
- Fast drive-in motor driving force test
- Insertion test during the RCM on stop
- Insertion test during the RCM on withdrawal
- Forced insertion test

○ Performance test of RSS
- Motor driving force test
- Withdrawal resistance test of stopper

○ Integrated performance test
- Planned test such as motor operation of start and stop, CRA drop, insertion, etc.

The test number in Table 3 is arbitrarily suggested to check the performance repeatability of the CRDM unit. These are different from the values that should be achieved in the reactor operating environment in [3] during reactor life or the life of the CRDM.

Table 3 Test kind of CRDM driving performance

	Test items	Test variable	Measuring parameter	Test number
Reactivity control motor (RCM) mechanism test	- RCM withdrawal / insertion	Driving velocity	Operability	50
	- RCM stop	Stop stability	Operability	50
	- RCM torque	Rotating force	Slip force	50
	- RCM drive shaft movement	movability	Position	50
Gripper operation and drop test	Electromagnet on/off	Gripping distance	Gripper ability	50
	CRA withdrawal, up and down, drop	Drop and insertion	Drop or fail	30
Fast drive-in and forced insertion test	Motor forced drive-in force	Max. driving velocity	Operability	5
	Insert-ability on stopped RCM	RCM stop force	Insertion time	5
	Insert-ability on withdrawal action	RCM withdrawal force	Insert-ability	5
	Forced insertion test	Resistance force ~8,000 N	Insertion time	20
Performance test of RSS	Motor driving force	Driving velocity 1~5 (mm/sec)	Operability	3
	Withdrawal resistance force of stopper		Stopper operability & integrity	30
Integrated performance test	Planned tests of motor action, CRA drop, etc.	Action scenario	Fulfill of the scenario	30

5.2 Reactivity control motor drive mechanism test

The CRDM driveline of PGSFR is about 13 m long and the stroke is designed to be about 1,150 mm. However, in the test facility, the length of the driveline located inside the reactor vessel was shortened, and the stroke of the driveline was slightly different to the actual design. 0 mm indicates the fully withdrawal state of the driveline, and 1,050 mm indicates the fully inserted state. Since several rubber pads for absorbing the drop impact of the CRA in test facility are installed on the bottom, so the full insertion position can be changed from 967 mm to 1030 mm.

The functional test of the motor driving part was performed by 50 times as shown in Table 3. Based on the tests, the motor torque was sufficient for moving the drive shaft in CRA holding state, and the position of the drive shaft was accurately controlled.

5.3 Gripper operation and drop test

The gripper operation does work only when the CRA head is inserted into the gripper fingers. In this operation, the axial deformations of the gripper and PIR bellows can be predicted as shown in Fig.9.

The gripper operation tests were performed by 50 times while changing the position of the drive shaft from 965 to 973 mm with increment steps of 1 mm to 2 mm to adjust the insertion amount of the drive shaft for making an optimal overlap distance with CRA head. As shown in Fig.10, the CRA was pulled by about 4 mm to 9 mm by the latching action on when the gripper device actuates in normal condition. Based on the PIR level change value by a latching action, it can be confirmed whether or not the gripper operation is successful.

5.4 Fast drive-in and forced insertion test

Prior to this test, a test was conducted to find the characteristic curve for the CRA insertion resistance generated by tightening or loosing the braking device with a torque limiter. The forced insertion resistance force data according to the squeeze pressure loads were obtained [4].

Insertion resistance required in test was set by the braking device. It is confirmed that the forced insertions are possible in all cases that the maximum required insertion resistance was within 8,000N. The 8,000 N is a suggest force that could pull out a stuck CRA caused by a trouble like as a core deformation, etc.

In tests, the recording data on the load cell were observed. The insertion resistance at the initial stage is temporarily increased and then is decreased during insertion, but increased again when the insertion was stopped. The instability due to the resistance force change of the braking device was not occurred when the motor speed was above 2,000 rpm. Insertion instability was observed at low speeds of less than 1,500 rpm in test. This is not a problem because the actual insertion speed is 3,000 rpm (42 mm/sec) by the fast drive-in motor.

5.5 Performance test of RSS

Three test variables are considered in the RSS performance test, one is the withdrawal speed change of the drive shaft in the range of 1 mm/s to 5 mm/s, and the second is the set value change of the torque limiter installed in RCM in range of 1.0 N/m to 3.0 N/m. The third is the RSS stopper position change from 50 mm to 400 mm.

The CRA withdrawal prevention tests were performed by changing above three parameters, and the test results are recorded. The withdrawal prevention function, which physically blocks the excessive withdrawal of the drive shaft by the reactivity control motor, was operated well at all predictable operation conditions (withdrawal speed, position of the RSS stopper, torque limiter setting value of the reactivity control motor).

5.6 Integrated Performance Test

The control system of the CRDM tests facility consists of a control board, a computer, control software, an interface device, and a visualization monitor.

The control board, the computer software and interface devices control the servo drive motor system consisted of the RCM(M1), fast drive-in motor(M2), RSS motor(M3) made by Mitsubishi. EDP-3020 DC power supply is used for driving the electromagnets. The control software communicates with the interface device to collect signals from various sensors, and makes commands to the driving devices.

The most drivers are controlled interactively by the computer screen. The control software is written in MS C-language. The speed and the moving target position of the drive motors can be operated manually and automatically.

<u>Performance test scenario</u>

A reference scenario generated artificially just for confirming the CRDM key performance is represented in Table 4. Various scenarios modified from the reference scenario were generated and tested to confirm that the individual performance tests can be continuously operated for accommodating various situations to be occurred in the reactor operation. The test scenario is controlled on the computer screen as shown in Fig. 5, and the several parameters such as a drive shaft position and the gripper operation state are displayed in monitor with a real time. If the test is completed successfully without any abnormality, a success message is displayed, and all sensor data measured in tests are stored in the computer hard disk. Those include the operation of the gripper, the position control, the drop of the control rod, and the fast drive-in action, etc.

<u>Performance test results</u>

The one sample of test records obtained by the laser sensor and rotary encoders during the performance tests is represented in Figs. 11 and 12. The position histories of the drive shaft and RSS stopper are showed that all the operation performance were satisfied.

While the drive shaft moves continuously the scenario path, the RSS stopper has well followed the moving path in keeping a limited distance in the gap range of 10 to 40 mm with the drive shaft for preventing an unintentional excessive withdrawal of the drive shaft.

The gap range between the RSS stopper and the drive shaft protrusion stopper can be controlled by parameters in computer control screen.

Table 4 Scenario test of CRDM driving performance

Step	Planned action	Device	Coil current (A)	CRA (mm)	Duration (sec)
1	Drive shaft insertion	Reactivity control motor (M1)	0	1,050	0
2	Gripper latching	electromagnet	15	1,050	120
3	Drive shaft withdrawal	Reactivity control motor (M1)	1.2	1,045	2
4	Drive shaft insertion and withdrawal (3 times)	Reactivity control motor (M1)	1.2	500	60
5				600	60
6				500	60
7				600	60
8				500	60
9				600	60
10	Scram	SW box	Power line off	600	0.2
11	CRA drop	Gravity	0	1,050	1
12	Drive shaft forced insertion	Fast drive-in motor (M2)	0	1,050	< 24

6.0 Conclusions

The individual function test of the motor driving part was performed by the reactivity control motor torque and driving test at first step, and based on the tests the planned performance tests were successfully executed. The motor rotation force for moving the drive shaft holding the CRA was sufficient, and the target moving position of the drive shaft was also accurately controlled. The error of the driving distance was negligible. Stable operation of the CRA gripper device was confirmed through repeated actuation of the CRA latching and releasing operation.

Forced insertion test of a CRA by a fast drive-in motor was performed assuming that the CRA was stuck by some foreign matters or core deformation in the event of a gravity drop into the core. Various insertion resistances were set by using the brake system, and the forced insertion tests by the fast drive-in motor showed that the insertion resistance of 8,000 N required by the design was sufficiently overcome. In addition, the performance of the rod stop system which prevents unintentional drive shaft withdrawal has been confirmed to work well. The integrated performance test of the CRDM system was performed according to the planned scenario, all the results have been satisfied the requirements.

ACKNOWLEDGEMENT

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REFERENCES

[1] Status of fast reactor research and technology development, IAEA-TECDOC-1691, 2012.
[2] Lee, Jae-Han and Kim, Sung-Kyun, "A Study on Diversity and Independent Features of Shutdown System of the PGSFR," 2017 KNS Spring meeting, 2017.05.
[3] CRDM repair and replacement strategy, SFR-190-DM-185-001, 2017.06.
[4] CRDM functional test of driving part for forced insertion, SFR-730-DM-458-002, 2016.09.

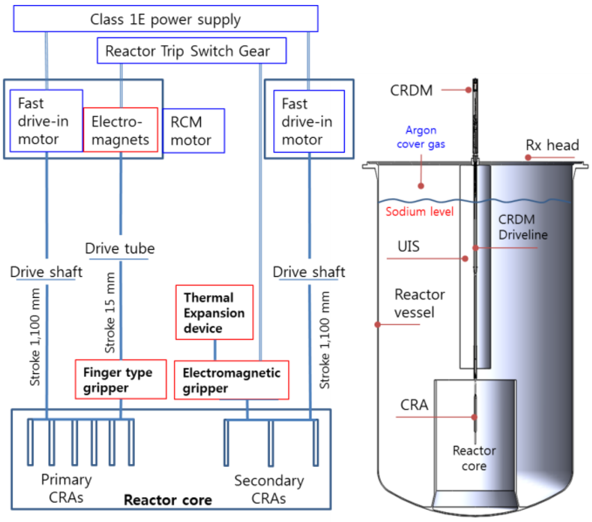

Figure 1 PGSFR Shutdown Ways

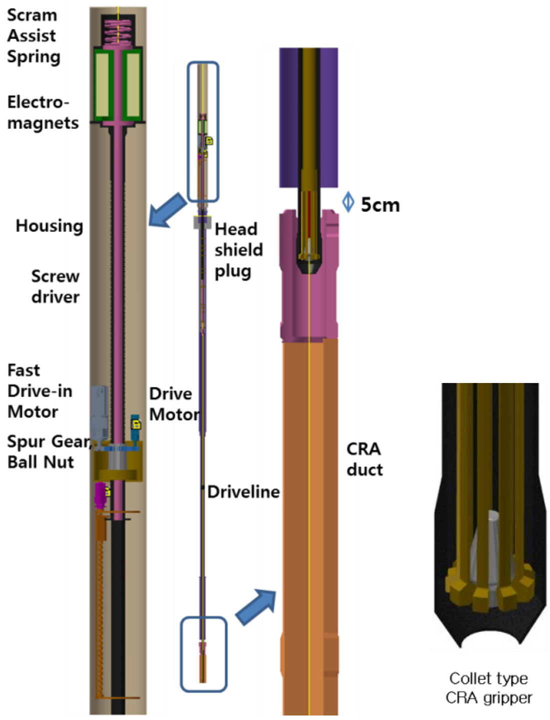

Figure 2 Overview of CRA gripper system of the primary CRDMs

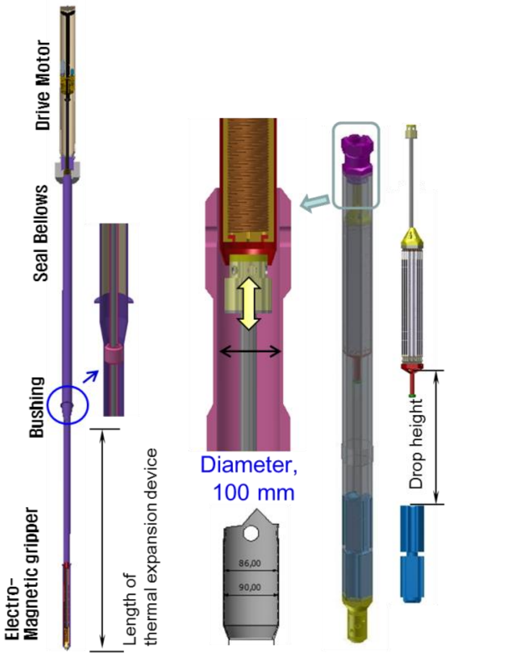

Figure 3 Secondary control rod drive system with passive shutdown device

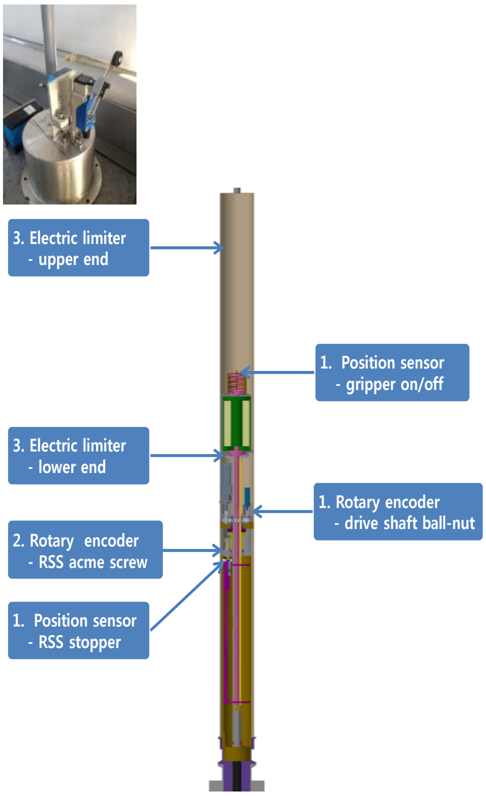

Figure 4 CRDM sensor system

Figure 5 Overall test facility configurations of the primary CRDMs

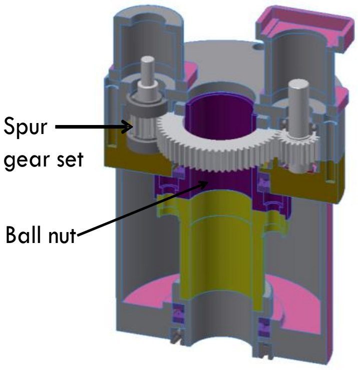

Figure 6 Drive motor spur gear set

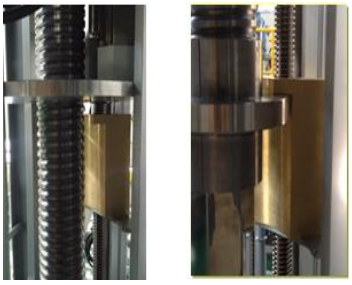

Figure 7 Control rod stop system

Figure 8 Forced insertion apparatus

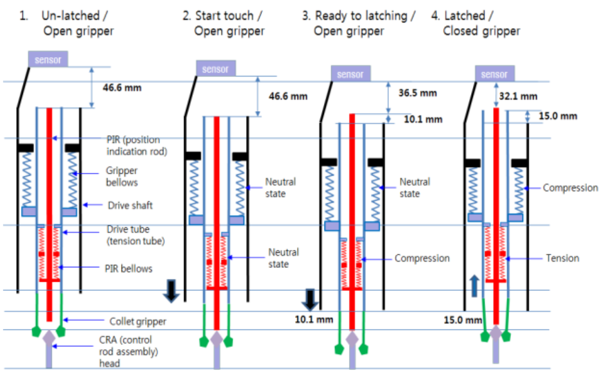

Figure 9 Bellows movement status during CRA gripper operation

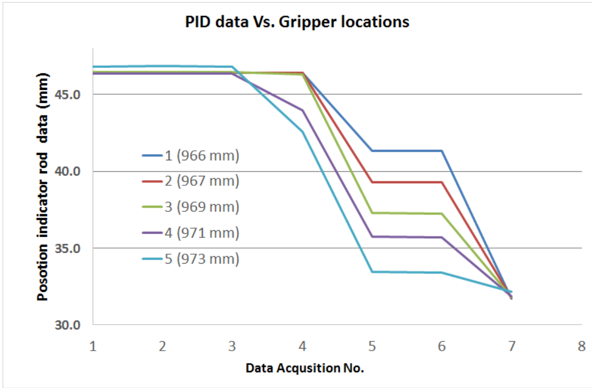

Figure 10 CRA gripper tests according to overlap distances between gripper and CRA head

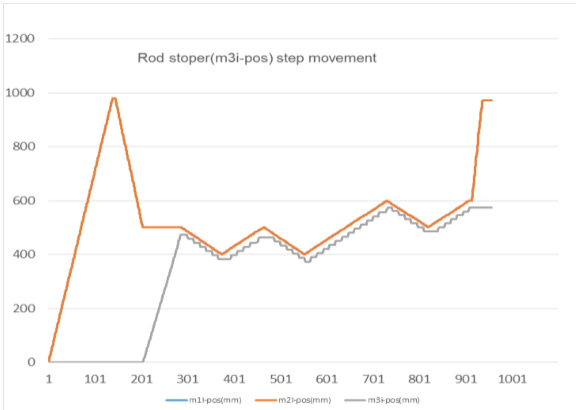

Figure 11 Step movements of rod stop system stopper for following the drive shaft

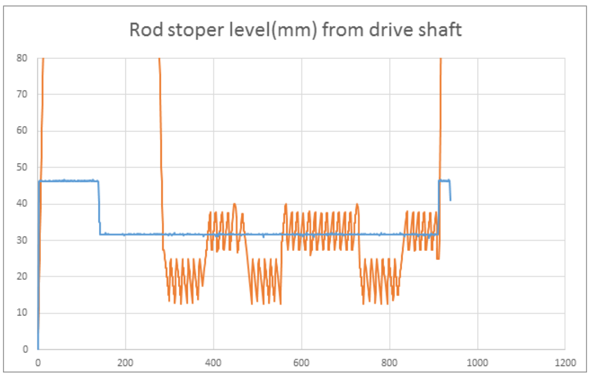

Figure 12 Step movement details of rod stop system stopper for following the drive shaft