Subsidy Project of Decommissioning and Contaminated Water Management

Development of Technology for Investigation inside the Reactor Pressure Vessel (RPV)

Final Report

August 2022

International Research Institute for Nuclear Decommissioning (IRID)

Contents

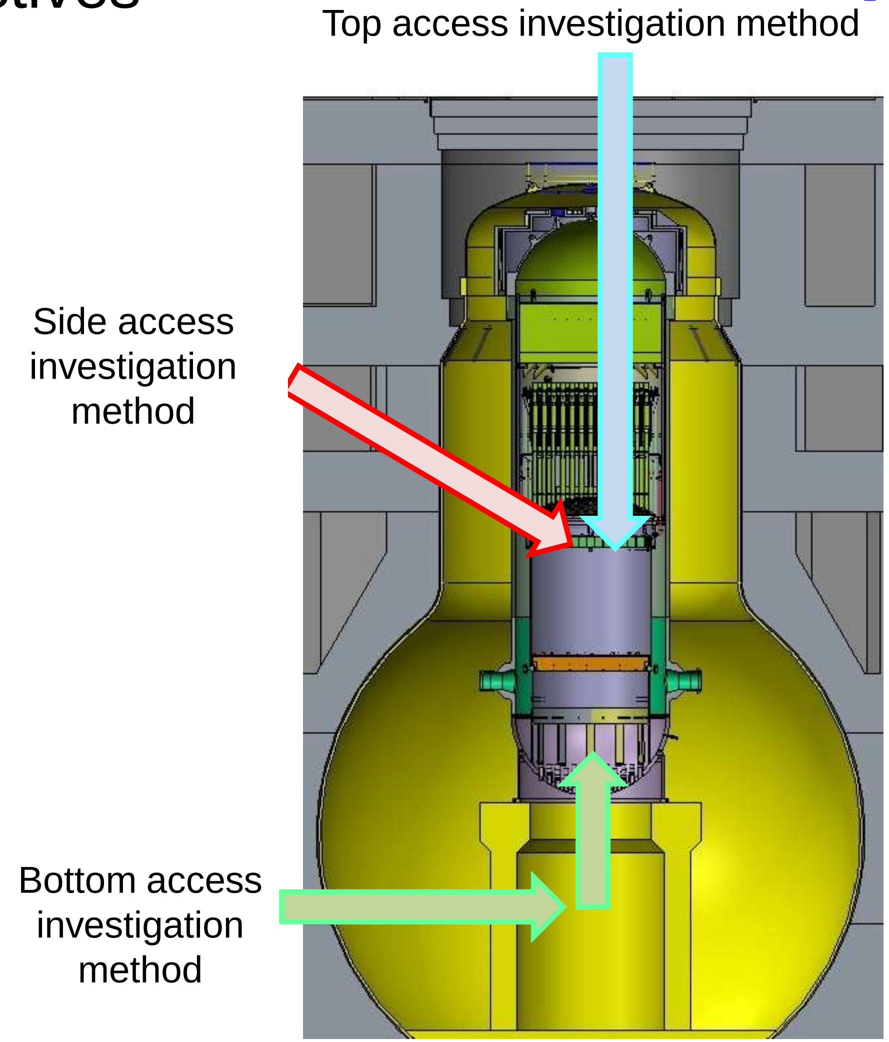
1. Research background and objectives

[Purpose of investigation inside the reactor pressure vessel (RPV)]

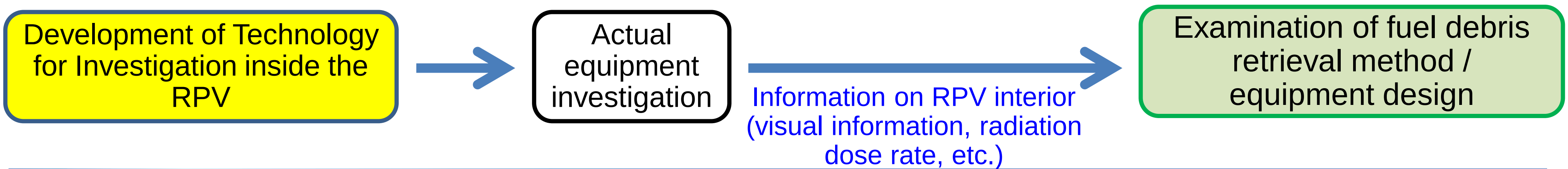
Acquisition of basic information about RPV interior (distribution of fuel debris, radiation dose, structure condition, etc.) to retrieve fuel debris.

[Implementation details up to FY2019]

Methods for accessing the reactor core by making an opening from the top and from the side were investigated (hereinafter referred to as “the top access investigation method” and “side access investigation method,” respectively). In the previous subsidy project “Development of Technology for Investigation inside the RPV” (FY2018/2019), the functions of both methods was verified through element tests of equipment for actual equipment applicability, the concepts of the investigation method were organized, and equipment specifications were developed by FY2019.



[Future applications of this project]



1. Research background and objectives

[Implementation details of this project]

For the top access investigation method, development of an abrasive water jet (AWJ) method to cut openings in the reactor internals (steam dryer, steam separator, shroud head, etc.) for establishment of an access route into the shroud was a priority, even though there is little certainty about the condition of the reactor internals. However, there are issues to be addressed in developing a method to reduce the volume of secondary waste (abrasives, etc.) generated from the access route establishment, and a method to suppress radioactive dust dispersion during the work. Due to the change in the spent fuel removal method for Unit 2, further engineering work will be needed to verify how the side access investigation method can actually be applied on-site.

Therefore, in order to improve the applicability of the top access investigation method with actual equipment, this project aims to develop a new method of opening the reactor internals (steam dryer, steam separator, shroud head, etc.) for establishment of an access route into the shroud, and aims to develop a processing technology that generates less secondary waste (abrasives, etc.) and radioactive dust dispersion by cutting inside the RPV, compared to the conventional abrasive water jet (AWJ) method.

⇒ (1) Upgrading of processing technology for the top access investigation method

It is also important to develop a method that may enable earlier investigation inside the RPV, since substantial time is needed before the top and side access investigation methods can be applied on-site. The access route establishment work for the detailed investigation inside the PCV is underway.

Therefore, in this project, investigation equipment will be installed in the pedestal interior using the access route that has already been established to proceed with the project of Development of Technology for Detailed Investigation inside the PCV and the project of Development of Technology for Gradually Increase of Retrieval Scale of Fuel Debris. Investigation equipment will be inserted into an opening at the bottom of the RPV; the conceptual study of the bottom access and suitable investigation equipment to investigate inside the RPV will be conducted.

⇒(2) Development of the bottom access investigation method

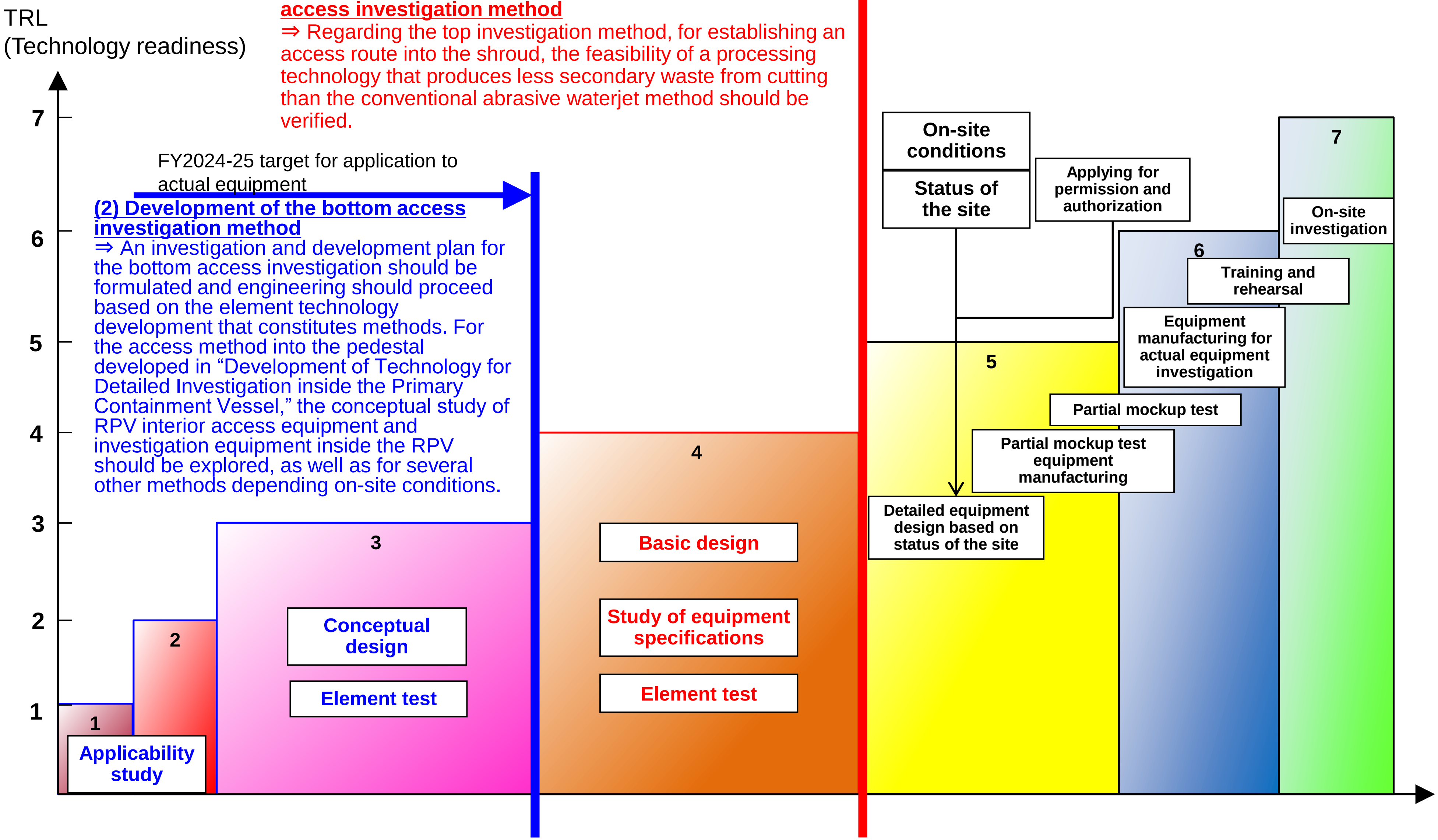
2. Goals

Achieving the technology readiness level (TRL) for investigation method by making openings developed by FY2019

(1) Upgrading of processing technology for the top access investigation method
⇒ Regarding the top investigation method, for establishing an access route into the shroud, the feasibility of a processing technology that produces less secondary waste from cutting than the conventional abrasive waterjet method should be verified.

FY2024-25 target for application to actual equipment

(2) Development of the bottom access investigation method
⇒ An investigation and development plan for the bottom access investigation should be formulated and engineering should proceed based on the element technology development that constitutes methods. For the access method into the pedestal developed in "Development of Technology for Detailed Investigation inside the Primary Containment Vessel," the conceptual study of RPV interior access equipment and investigation equipment inside the RPV should be explored, as well as for several other methods depending on-site conditions.



3. Implementation items, their co-relation and relation to other projects

Development of Technology for Detailed Investigation inside PCV

Development of Technology for Gradually Increasing Retrieval Scale of Fuel Debris

【input】
- Access equipment specifications
- Various constraints

Study of fuel debris retrieval method and equipment

Study of criticality control

【output】
- Information on the RPV interior and access route (visual information, radiation dose rate, etc.)

Development of Technology for Investigation inside the RPV

This project

Detailed design, equipment manufacturing, mockup, etc

Actual equipment investigation

- Top access investigation
- Bottom access investigation

【input】
- Investigation results of the upper part of the pedestal (RPV bottom) (location of openings, condition of structures, etc.)

Development of Technology for Detailed Investigation inside PCV

4. Implementation schedule

Implementation items	FY2020	FY2021
(1) Upgrading of processing technology for the top access investigation method ① Investigation and evaluation of potential alternative processing technologies	Organization of investigation items/parameters Simplified test Comparative evaluation	Selection of alternative processing technology candidates
② Planning of development for potential alternative processing technologies	Study of development plan	Basic design Planning of outline specifications for potential alternative processing technologies
③ Element tests of potential alternative processing technologies, feasibility verification		Element test Evaluation
(2) Development of the bottom access investigation method ① Planning of top access/investigation and development plan for access/investigation equipment	Drafting of investigation plan Results of study of candidate technologies Feasibility study (test) Feasibility evaluation	Investigation and Development Planning
② Conceptual study of bottom access/investigation equipment		Conceptual design Element test Evaluation Planning of method

5. Project organization

This project aims to develop technology for investigation inside the RPV. The interface with each development project team is of utmost importance. Therefore, IRID Head Office, Toshiba Energy Systems & Solutions Corporation (Toshiba ESS), and Hitachi-GE Nuclear Energy (Hitachi-GE) are working together to develop a safe, reliable, logical, rapid, and site-oriented fuel debris retrieval technology for the Fukushima Daiichi, through mutual technological cooperation among IRID Japanese plant component manufacturers, in order to analyze the on-site situation and to develop a series of measures that are consistent with the fuel debris retrieval plan, etc.

International Research Institute for Nuclear Decommissioning (IRID) (Head Office)
- ○ Overall planning and technological supervision
- ○ Technological management of technology development progress, etc.

Tokyo Electric Power Company Holdings, Inc.
- ○ Adjustments for on-site applicability

Toshiba Energy Systems & Solutions Corporation

(2) Development of the bottom access investigation method
① Planning of top access/investigation and development plan for access/investigation equipment
② Conceptual study of bottom access/investigation equipment

Hitachi-GE Nuclear Energy, Ltd.

(1) Upgrading of processing technology for the top access investigation method
① Investigation and evaluation of potential alternative processing technologies
② Planning of development for potential alternative processing technologies
③ Element tests of potential alternative processing technologies, feasibility verification
(2) Development of the bottom access investigation method
① Planning of top access/investigation and development plan for access/investigation equipment
② Conceptual study of bottom access/investigation equipment

Sugino Machine Limited
-(1) Structural design for upgrading of processing technology for the top access investigation method

Hitachi Plant Construction, Ltd.
-(1) Technological investigation for upgrading of processing technology for the top access investigation method

Partner development project teams
- Development of Technology for Gradually Increasing Retrieval Scale of Fuel Debris
- Development of Technology for Detailed Investigation inside PCV

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

<Summary of implementation in the second half of FY2021>

Using the nozzle designed in the first half of the fiscal year, element test plans for AWJ (Abrasive Water Jet) cutting and laser cutting were drafted, and the tests were conducted.

<Details of implementation in the second half of FY2021>

Processing technology	Details of implementation	
AWJ/ Laser	①	Element test plan
	②	Conducting of element tests
	③	Design of actual equipment

<Results>

AWJ

- Although the effect of increasing flow rate by approximately twice the conventional level were not verified, the abrasive feed rate with good cutting performance was verified (for purposes of reducing abrasive consumption), and the rate was revised from the conventional 500 g/min to 100 g/min.
- The operational conditions for each cutting site were verified at an abrasive feed rate of 100 g/min, **and the prospects of achieving the target abrasive consumption of 500 kg or less** (presented in the solicitation information) **were found.**

Laser

- In FY2020, the nozzle was only applied to vertical cutting of the steam separator, but a new nozzle for horizontal cutting was designed, and **prospects of applying the horizontal cutting were found.**
- Based on those results, **prospects for applying the laser cutting process to all of the reactor internals required for the top access were found**, and the operational conditions for each target cutting site were verified by testing.

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

1) Summary of results through the first half of FY2021 (1/4)

After investigating pressure and flow rate increases for AWJ (Abrasive Water Jet) cutting, it was determined that pressure increase is unacceptable. Flow rate increase is feasible, and the AWJ nozzle design that can handle a higher flow rate and the system design were devised. For laser cutting, a small nozzle was designed for horizontal cutting application.

Implementation details and results

1. Organization of implementation details for FY2021

- Implementation details were organized for AWJ and laser cutting. For AWJ cutting, the pressure and flow rate increase were studied and a nozzle was designed based on those results, and verification of cutting performance through element tests was conducted.

Table 1 Flow of FY2021 implementation items (AWJ)

Method	FY2020 test results		FY2021 implementation policy			
	Target sites	Test details/results	Step 1	Step 2	Step 3	Step 4
			Theoretical study (test portion available)	Test		Study of actual equipment applicability
AWJ	Other than the separator body	-	-	-	**Element test** ① Verification of cutting the partial mock-up ② Planning of optimal operational conditions when applying to actual equipment	**Design for equipment in the actual use** ① Design equipment in the actual use based on element test results
	Separator body	**Adoption of a small nozzle** (1) Downsizing of nozzle makes it possible to approach the cutting target. (Shorter standoff improves cutting efficiency) **Significant reduction in volume of abrasives (from 8 tons to 0.33 tons)** (2) Pressure, flow rate - Pressure: 343 MPa - Flow rate: 3.7 liter/min (3) Abrasive feed rate - Feed rate: 500 g/min	**Study of pressure and flow rate increase** ① Study of feasibility of pressure and flow rate increase **Nozzle design** ① Nozzle design for increased flow rate	**Basic test of flow rate increase** ① Verification of cutting performance under the condition of Increasing the flow rate ② Verification of the appropriate value of the abrasive under the condition of increased flow rate ③ Comparison of performance with the nozzle used in FY2020 ④ Measurement of the processing reaction force under the condition of increased flow rate	**Element test** ① Verification of cutting the partial mock-up ② Planning of optimal operational conditions when applying to actual equipment	**Nozzle durability test** ① Evaluation of the nozzle lifetime by durability testing under the operational conditions verified by the element test

Implementation details for the first half of the fiscal year

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

1) Summary of results through the first half of FY2021 (2/4)

Implementation details and results

1. Organization of implementation details for FY2021

For laser cutting, a nozzle suitable for horizontal cutting was designed, and the cutting performance was verified through element tests.

Table 2 Flow of FY2021 implementation items (laser)

Method	FY2020 test results		FY2021 implementation policy			
	Target sites	Test details/results	Step 1	Step 2	Step 3	Step 4
			Theoretical study (test portion available)	Test		Study of actual equipment applicability
Laser	Other than the separator body	-	-	-	**Element test** ① Verification of cutting the partial mock-up ② Planning of optimal operational conditions when applying to actual equipment	**Design for equipment in the actual use** ① Design equipment in the actual use based on element test results ② Planning of investigation into countermeasures to project issues (implementation details of next phase)
	Separator body	**Adoption of laser cutting** (1) Vertical cutting is available. (2) The nozzle was too large to be inserted between the three separator tubes, so it was not adopted for horizontal cutting.	**Nozzle design** ① The downsized nozzle design that is suitable for horizontal cutting (including sampling test)	**Basic test of a small nozzle** ①Test of small nozzle cutting performance	**Element test** ① Verification of cutting the partial mock-up ② Planning of optimal operational conditions when applying to actual equipment	
		-	**Identification of issues in application to actual equipment** ① Identification of issues in application to actual equipment and study of countermeasures			

Implementation details for the first half of the fiscal year

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

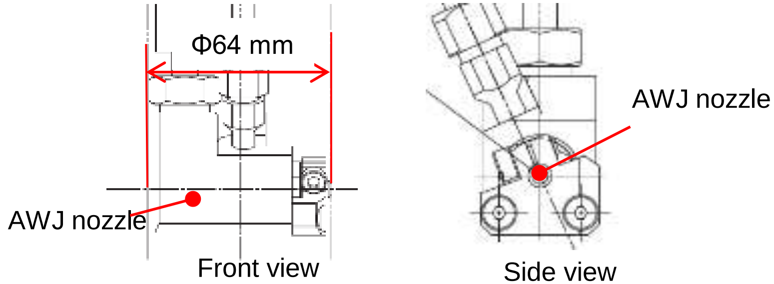
1) Summary of results through the first half of FY2021 (3/4)

Implementation details and results

2. AWJ (Abrasive Water Jet) nozzle (angle nozzle) design

- Nozzle design considerations were identified, and the results of the study were applied to the nozzle design.

No.	Study details	Study results
1	**Pressure increase** - In FY2020, a simplified test at a pressure of 343 Mpa was conducted, so the pressure will be increased (to about twice the target) to improve the cutting efficiency and reduce the amount of abrasive consumption.	**Deemed not applicable** -When increasing the pressure to 400 MPa or higher, it is necessary to switch from a high-pressure hose to a steel pipe. Since it is difficult to incorporate a steel pipe into the equipment, additional pressure increase was deemed not feasible.
2	**Flow rate increase** - In FY2020, a simplified test was conducted at a flow rate of 3.7 liter/min, so the flow rate will be increased (to about twice the target) to improve the cutting efficiency and reduce the amount of abrasive consumption.	**Deemed applicable and the flow path design implemented** -Since it was possible to increase the flow rate without changing the hose diameter, a nozzle and system were designed to handle about twice the FY2020 flow rate.
3	**Downsizing of nozzle** - In FY2020, a test was conducted by using a nozzle of nominal dimensions such that can be inserted into the space between the three steam separator tubes. - It is necessary to consider accessibility to the steam separator.	**Downsizing of nozzle is possible** - The nozzle size (Φ64 mm) was chosen for ease of access to the steam separator.



AWJ Nozzle (angle nozzle)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

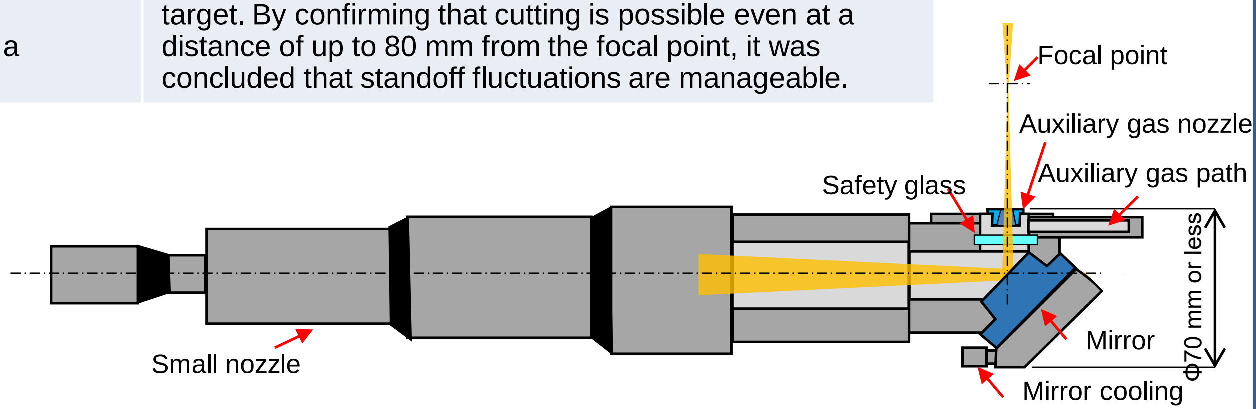
1) Summary of results through the first half of FY2021 (4/4)

Implementation details and results

3. Laser nozzle (angled nozzle) design

- Issues pertaining to horizontal cutting were identified and appropriate countermeasures were applied to the nozzle design.

No.	Issues of horizontal cutting	Countermeasures
1	**Damage to mirror section** -Since cutting is performed in the space between the three steam separator tubes, there is only a short distance to the cutting target. Therefore the focal point and the mirror are close to each other, so the energy density of the laser beam on the mirror is high, resulting in a risk of mirror damage.	**Additional mirror cooling** - In order to suppress mirror temperature increase, a water cooling structure was added.
2	**Decreased cutting capacity** -Since horizontal cutting has a large standoff fluctuation range, cutting may not be possible if the distance from the focal point to the cutting target is too great. (Distance from focal point to cutting target: a maximum of 30 mm)	**Preliminary confirmation test** -In designing the nozzle, a preliminary confirmation test was conducted to confirm whether cutting was possible at a greater distance from the focal point to the cutting target. By confirming that cutting is possible even at a distance of up to 80 mm from the focal point, it was concluded that standoff fluctuations are manageable.



Laser nozzle (angled nozzle)

6. Implementation details

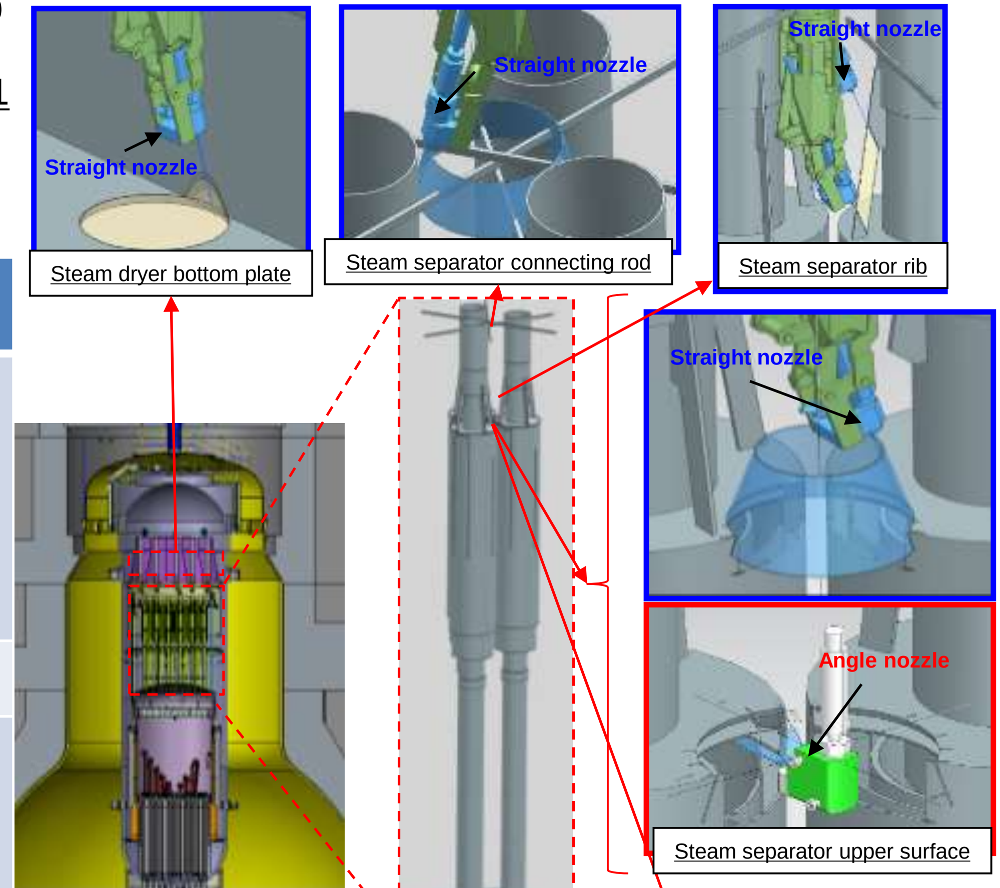
(1) Upgrading of processing technology for the top access investigation method

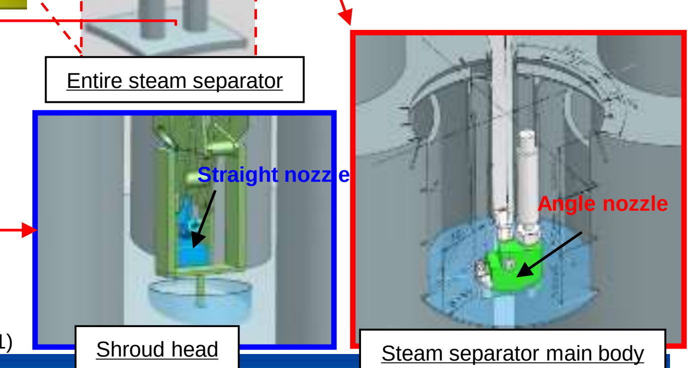
2) Implementation details for the second half of FY2021

① Test plan (AWJ: Abrasive Water Jet)

The flat plate cutting test and the mockup cutting test shown in the table below are conducted to confirm cutting performance.

Test Category	Test item	Purpose
Flat plate cutting test	Test to verify the effect of flow rate increase (including processing reaction force measurement)	- Verification of cutting performance (Performance comparison between the FY2020 and the improved FY2021 angle nozzles included) - Verification of processing reaction force under the condition of increased flow rate
	Test to verify the suitable value for abrasive feed rate	- Verification of the suitable abrasive feed rate
Mockup cutting test	Cutting test on steam dryer bottom plate	- Verification of conditions under which operation is possible - Identification of operation-related issues
	Cutting test on steam separator connecting rod	
	Cutting test on steam separator rib	
	Cutting test on steam separator upper surface	
	Cutting test on steam separator main body	
	Cutting test on the shroud head	





*:
- **Straight nozzle**: A nozzle that emits a straight stream without bending the flow of high-pressure water (conventional nozzle prior to FY2019)
- **Angle nozzle**: A nozzle that bends the flow of high-pressure water and emits at a right angle (first applied in FY2020, design improved in FY2021)

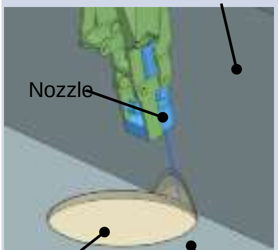
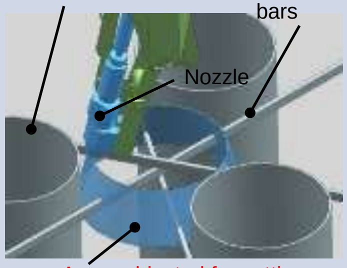
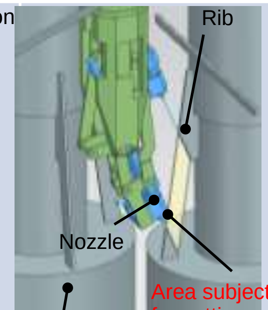
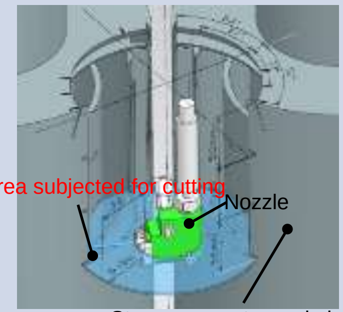
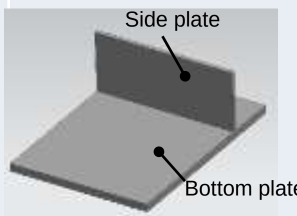
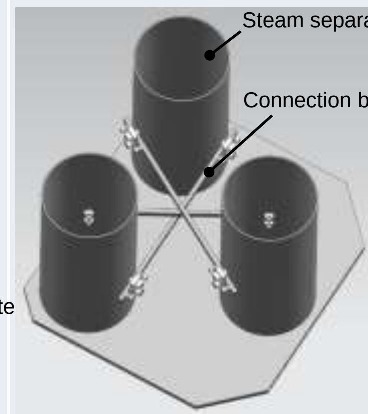
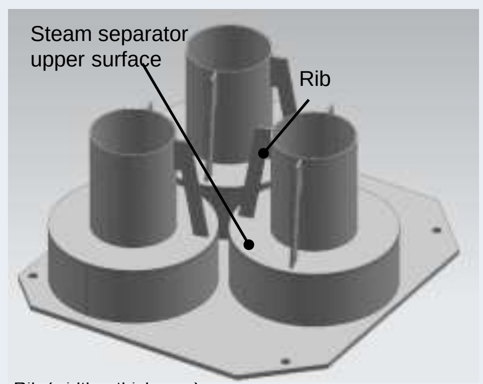
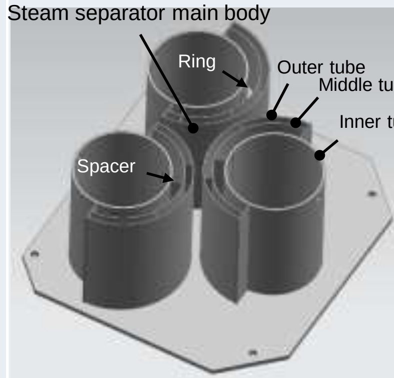
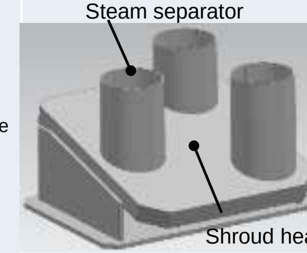
6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

① Test plan (AWJ (Abrasive Water Jet))

The test pieces for each treatment target were used for simulations of cutting range and the area that would be obstructed during cutting. Each simulated range is shown in the table below.

	Processing objects					
	Steam dryer	Steam separator				Shroud head
	Bottom plate	Connection bars	Rib	Upper surface	Main body	-
AWJ cutting conditions						
Shape of test pieces (simulation range)	 - Bottom plate (thickness): Actual equipment 12.7 mm Test piece 13 mm - Side plate (thickness): Actual equipment 6.4 mm Test piece 8 mm	 - Connecting rod (width x height): Actual equipment 6.4 mm × 12.7 mm Test piece 8 mm × 12.7 mm	 - Rib (width x thickness): Actual equipment 5 mm x 28.1 mm (1F-4 information) Test piece 5 mm × 28.1 mm - Upper surface (thickness): Actual equipment 6.4 mm → Test piece 8 mm		 - Outer tube (thickness): Actual equipment 3.2 mm → Test piece 3 mm - Middle tube (thickness): Actual equipment 3.2 mm → Test piece 3 mm - Inner tube (thickness): Actual equipment 6.35 mm → Test piece 6 mm - Spacer (thickness): Actual equipment 3.2 mm → Test piece 3 mm - Ring (thickness): Actual equipment 12 mm → Test piece 12 mm	 - Shroud head (thickness): Actual equipment 50.8 mm → Test piece 50 mm The actual shroud head is spherical, but in this case, a flat plate was used to simulate a spherical shape. It was concluded that there was no problem using a flat plate in the simulation due to the lack of a significant difference in standoff and emission angle. - Stand-off: Actual equipment < Test piece (0.33 mm) - Emission angle: Actual equipment > Test piece (0.97°)

6. Implementation details

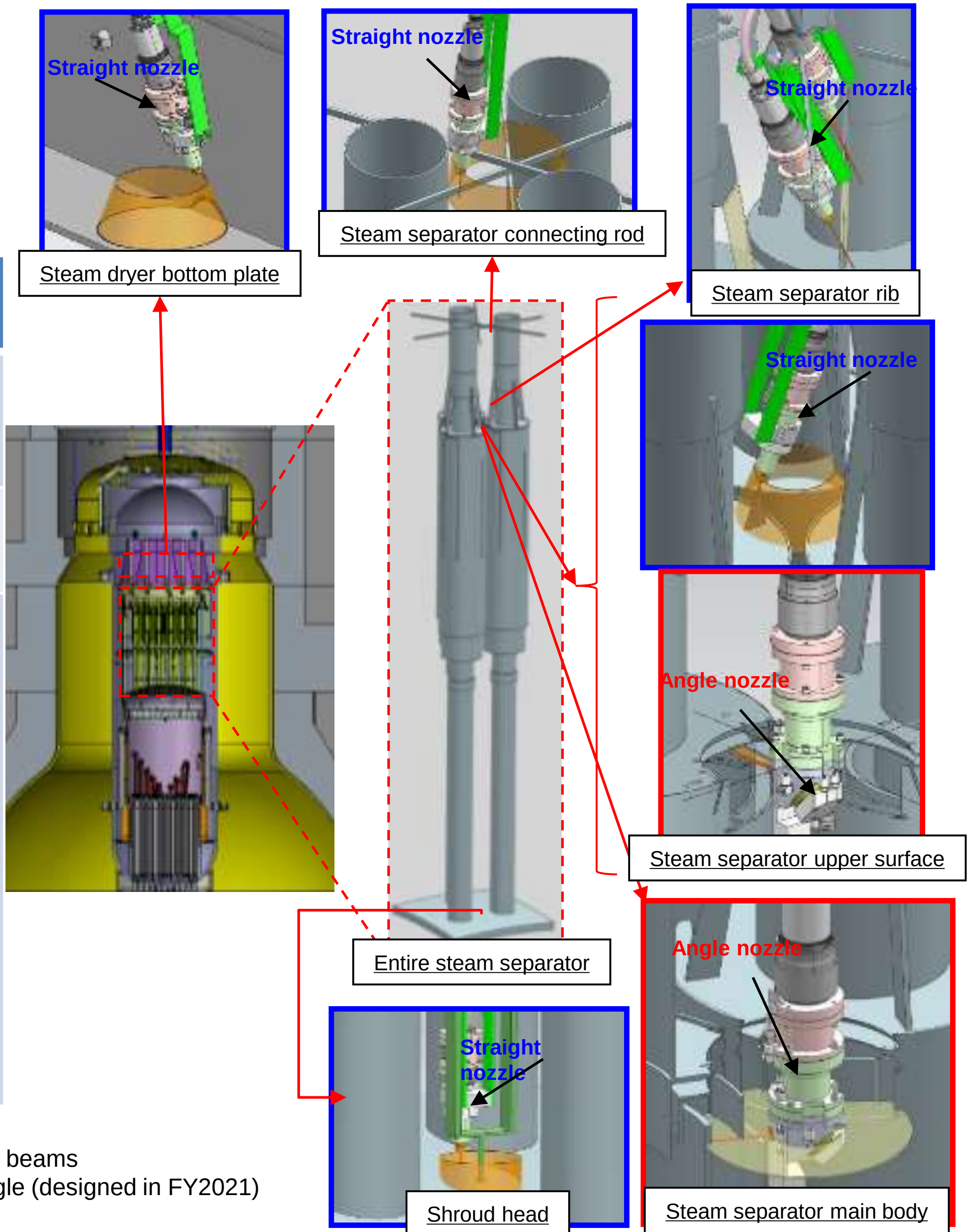
(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

② Test plan (laser)

The flat plate cutting test and the mockup cutting test shown in the table below areconducted to confirm cutting performance.

Test Category	Test item	Goal
Flat plate cutting test	Small nozzle cutting test	- Performance verification of a small nozzle
	Cutting test with low laser power output	- Verification of cutting performance for each laser power output
Mockup Cutting test	Cutting test on steam dryer bottom plate	- Verification of conditions under which operation is possible - Identification of operation-related issues
	Cutting test on steam separator connecting rod	
	Cutting test on steam separator rib	
	Cutting test on steam separator upper surface	
	Cutting test on steam separator main body	
	Cutting test on the shroud head	



*:
- **Straight nozzle**: A nozzle that irradiates a straight stream without bending laser beams
- **Angle nozzle**: A nozzle that bends the laser beam and irradiates it at a right angle (designed in FY2021)

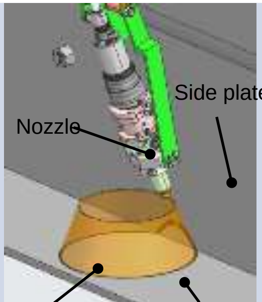
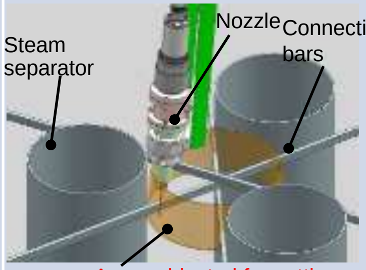
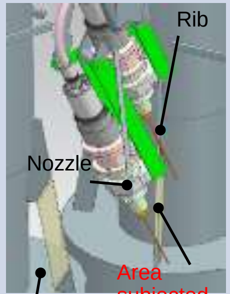
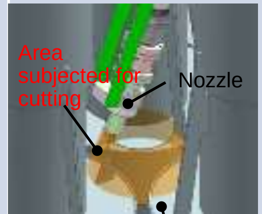
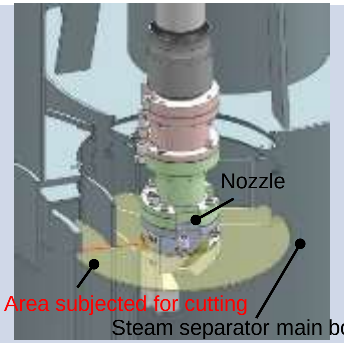
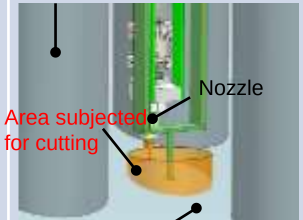
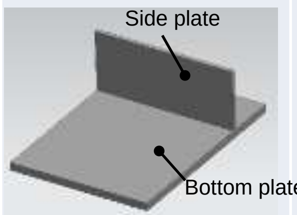
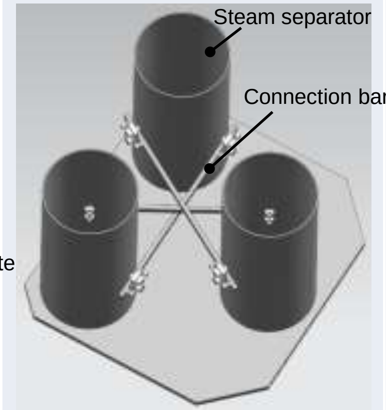
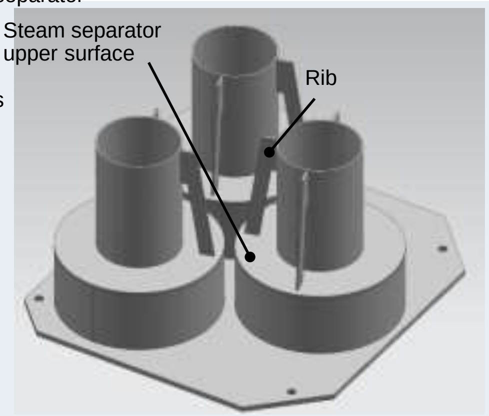
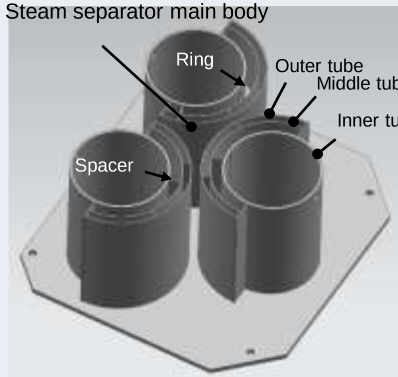
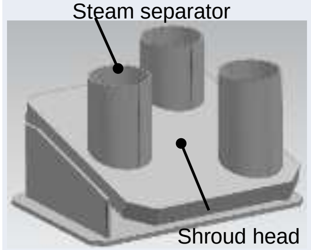
6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

② Test plan (laser)

The test pieces for each treatment target were used for simulations of cutting range and the area that would be obstructed during cutting. Each simulated range is shown in the table below.

	Processing objects					
	Steam dryer	Steam separator				Shroud head
	Bottom plate	Connection bars	Rib	Upper surface	Main body	-
Laser cutting conditions						
Shape of test pieces (simulation range)	 - Bottom plate (thickness): Actual equipment 12.7 mm Test piece 13 mm - Side plate (thickness): Actual equipment 6.4 mm Test piece 8 mm	 - Connecting rod (width x height): Actual equipment 6.4 mm × 12.7 mm Test piece 8 mm × 12.7 mm	 - Rib (width x thickness): Actual equipment 5 mm x 28.1 mm (1F-4 information) Test piece 5 mm × 28.1 mm - Upper surface (thickness): Actual equipment 6.4 mm → Test piece 8 mm		 - Outer tube (thickness): Actual equipment 3.2 mm → Test piece 3 mm - Middle tube (thickness): Actual equipment 3.2 mm → Test piece 3 mm - Inner tube (thickness): Actual equipment 6.35 mm → Test piece 6 mm - Spacer (thickness): Actual equipment 3.2 mm → Test piece 3 mm - Ring (thickness): Actual equipment 12 mm → Test piece 12 mm	 - Shroud head (thickness): Actual equipment 50.8 mm → Test piece 50 mm The actual shroud head is spherical, but in this case, a flat plate was used to simulate a spherical shape. It was concluded that there was no problem using a flat plate in the simulation due to the lack of a significant difference in standoff and emission angle. - Stand-off: Actual equipment < Test piece (0.33 mm) - Emission angle: Actual equipment > Test piece (0.97°)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

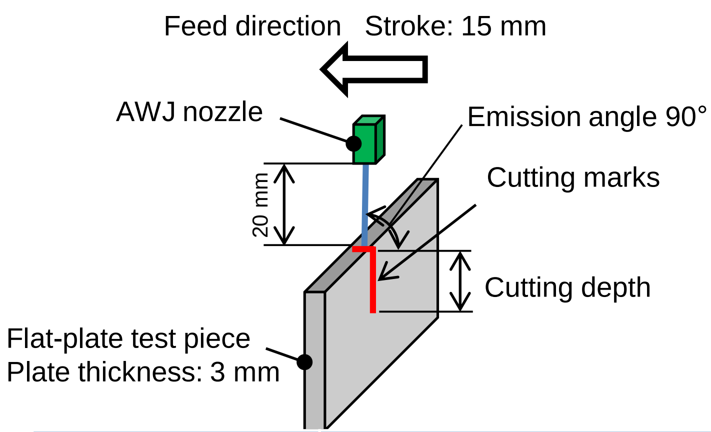
③ Test results (AWJ: Abrasive Water Jet) [flat plate cutting test (1/4)]

- Test to verify the effect of flow rate increase (without supply of abrasives)

<Test details>

The flat plate was cut by moving the nozzle in the direction of the flat plate edge in the condition that the AWJ flow rate is increased to 8.4 liter/min. The effect of the increased flow rate was verified from the cutting length.

<Test conditions>



Items	Conditions
AWJ nozzle	Angle nozzle
Injection pressure	343 MPa
Injection flow rate	8.4 liter/min
Abrasive feed rate	**0 (water jet (WJ) cutting)**

<Test results>

Abrasive feed rate (g/min)	Nozzle speed (mm/min)	Standoff: 20 mm			
		Flow rate: 8.4 liter/min		Flow rate: 3.7 liter/min*	
		No.	Cutting depth (mm)	No.	Cutting depth (mm)
0	0.5	1	**3**	3	**2**
	0.2	2	**4**	4	**2**

*: The flow rate result of 3.7 liter/min is from the FY2020 test results.

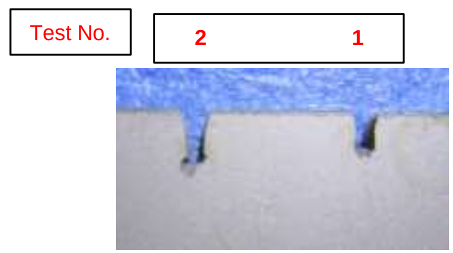


Photo of test piece (flow rate 8.4 liter/min)

Photo of test piece (flow rate 3.7 liter/min)

<Conclusion>

- Compared to the result of 3.7 liter/min from the FY2020 test, the **maximum cutting depth was doubled**.
  Therefore, **water jet (WJ) cutting verified the effect of high flow rate.**
- Although cutting effect was obtained, cutting performance was low, and as in FY2020, the **WJ cutting is not applicable to actual equipment.**

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [flat plate cutting test (2/4)]

- Test to verify the effect of flow rate increase (AWJ)

<Test details>

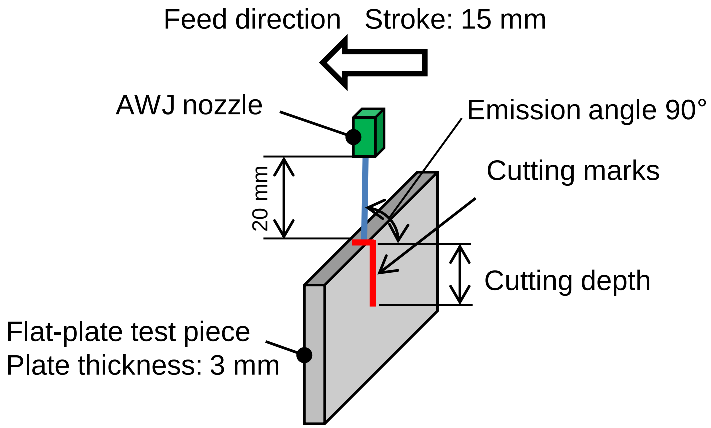
The flat plate was cut by moving the nozzle in the direction of the flat plate edge in the condition that the AWJ flow rate is increased to 8.4 liter/min. The effect of the increased flow rate was verified from the cutting depth.

<Test results>

Cutting speed (mm/min)	Abrasive feed rate: 500 g/min Standoff: 20 mm Flow rate: 8.4 liter/min		Abrasive feed rate: 500 g/min Standoff: 20 mm Flow rate: 3.7 liter/min*	
	No.	Cutting depth (mm)	No.	Cutting depth (mm)
100	1	**11**	5	**12**
80	2	**12**	6	**14**
60	3	**16**	7	**16**
40	4	**26**	8	**27**

*: The flow rate result of 3.7 liter/min is referred from the FY2020 test results.

<Test conditions>



Items	Conditions
AWJ nozzle	Angle nozzle
Injection pressure	343 MPa
Injection flow rate	8.4 liter/min
Abrasive feed rate	500 g/min

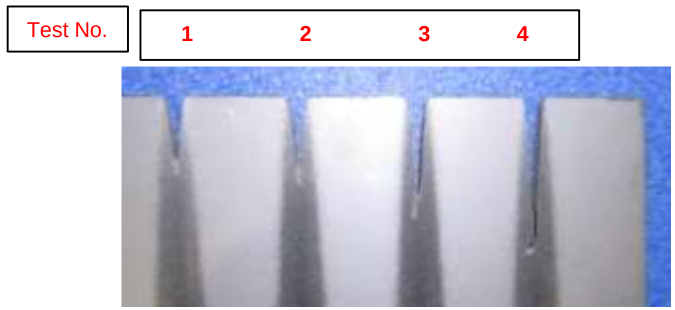


Photo of test piece (flow rate 8.4 liter/min)

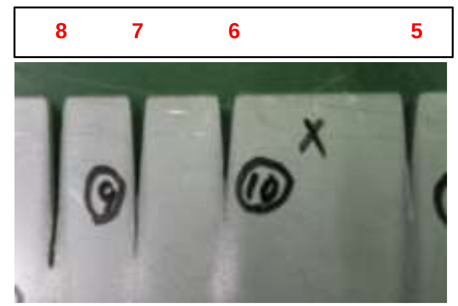


Photo of test piece (flow rate 3.7 liter/min)

<Conclusion>

- Compared to the result of 3.7 liter/min from the FY2020 test, **the effect of an improvement in cutting efficiency through increasing the flow rate was not verified** with an abrasive feed rate of 500 g/min.
- However, depending on the abrasive feed rate, it may be possible to verify the effect of increasing the flow rate, so a test was conducted to verify the suitable abrasive feed rate.

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

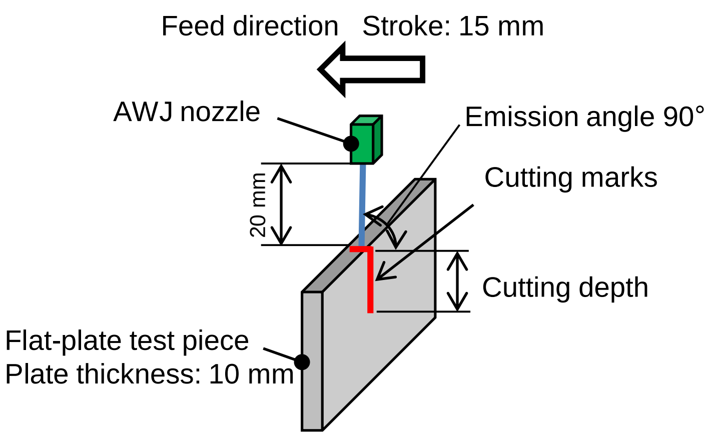
③ Test results (AWJ: Abrasive Water Jet) [flat plate cutting test (3/4)]

- Test to verify the effect of flow rate and abrasive feed rate (1/2)

<Test details>

The abrasive feed rate was varied under conditions of AWJ flow rates of either 8.4 liter/min or the conventional 3.3 liter/min. The flat plate was cut by moving the nozzle in the direction of the flat plate edge and the relationship between flow rate and abrasive feed rate were verified from the cutting depth.

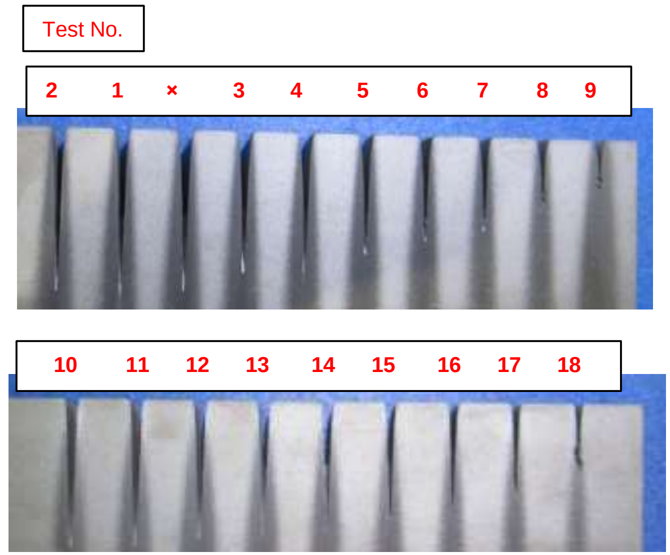
<Test conditions>



Items	Conditions
AWJ nozzle	Angle nozzle
Injection pressure	343 MPa
Injection flow rate	8.4, 3.3 liter/min
Abrasive feed rate	100 to 900 g/min

<Test results>

A table of the test results is provided on the next page.



Phot of test piece (standoff: 20 mm)

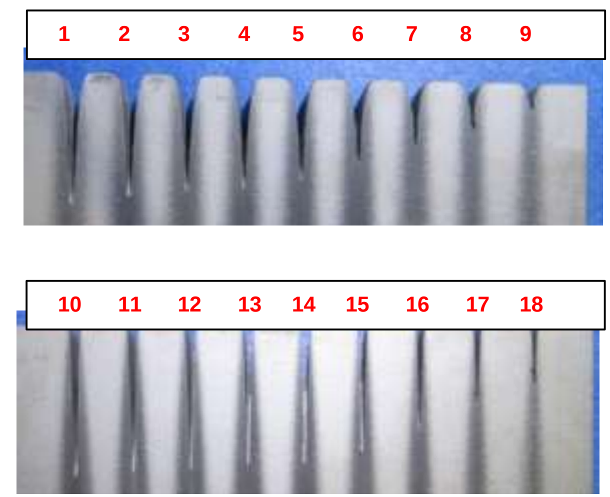


Photo of test piece (standoff: 50 mm)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [flat plate cutting test (4/4)]

- **Test to verify the effect of flow rate and abrasive feed rate (2/2)**

<Test results>

Abrasive feed rate (g/min)	Speed (mm/min)	Abrasive supply rate (g/mm) *1	Standoff: 20 mm						Standoff: 50 mm					
			Flow rate: 8.4 liter/min			Flow rate: 3.3 liter/min			Flow rate: 8.4 liter/min			Flow rate: 3.3 liter/min		
			No.	Cutting depth (mm)	Cutting efficiency (mm^2/g) *2	No.	Cutting depth (mm)	Cutting efficiency (mm^2/g) *2	No.	Cutting depth (mm)	Cutting efficiency (mm^2/g) *2	No.	Cutting depth (mm)	Cutting efficiency (mm^2/g) *2
900		15.0	1	23	1.53	10	19	1.27	1	19	1.27	10	19	1.27
800		13.3	2	27	2.03	11	18	1.35	2	18	1.35	11	18	1.35
700		11.7	3	20	1.71	12	17	1.46	3	17	1.46	12	17	1.46
600		10.0	4	19	1.90	13	16	1.60	4	15	1.50	13	17	1.70
500	60	8.3	5	16	1.92	14	15	1.80	5	14	1.68	14	16	1.92
400		6.7	6	14	2.10	15	14	2.10	6	10	1.50	15	13	1.95
300		5.0	7	12	2.40	16	11	2.20	7	8	1.60	16	11	2.20
200		3.3	8	8	2.40	17	9	2.70	8	5	1.50	17	8	***2.40***
100		1.7	9	6	***3.60***	18	7	***4.20***	9	4	***2.40***	18	4	***2.40***

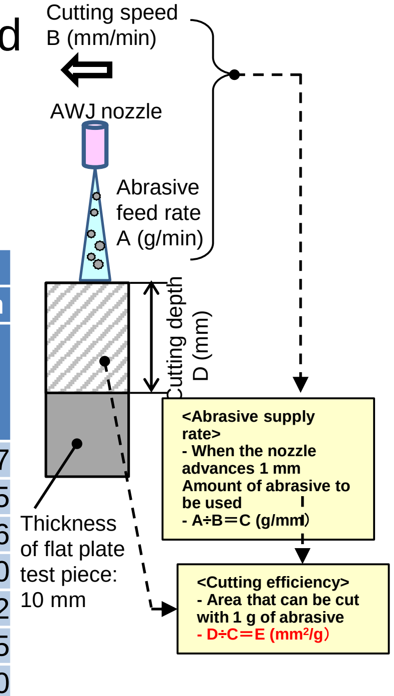


Fig. 1 Regarding cutting efficiency

*1: Abrasive supply rate (g/mm) is the value obtained by dividing the abrasive feed rate (g/min) by the cutting speed (mm/min).
*2: Cutting efficiency is the value (mm^2/g) obtained by dividing the cutting depth (mm) by the abrasive supply rate (g/mm) (refers to the area that can be cut per 1 g of abrasive when moving 1 mm in the feed direction (See Fig. 1)).

<Conclusion>

- It was verified that the **cutting efficiency is satisfactory with an abrasive feed rate of 100 g/min** under both conditions of flow rate 8.4 liter/min and 3.3 liter/min (red frame in the table).
- In comparing flow rates of 8.4 liter/min and 3.3 liter/min at 20 mm standoff, 500 g/min or higher abrasive feed rate, the flow rate of 8.4 liter/min resulted in higher cutting efficiency (blue frame in the table). There were no other differences between the two flow rates but 3.3 liter/min gave better results.

- It was verified that increasing the flow rate was effective under some conditions but had only a small effect in other cases.
- Focused on reducing the amount of abrasive consumption, the cutting efficiency of 3.3 liter/min and 100 g/min was satisfactory, and these parameters were adopted in the mockup cutting test.

6. Implementation details

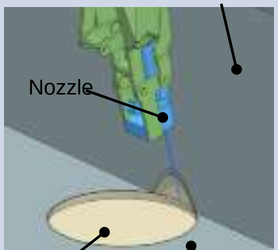
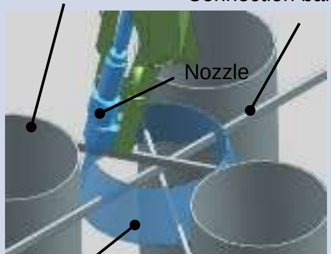
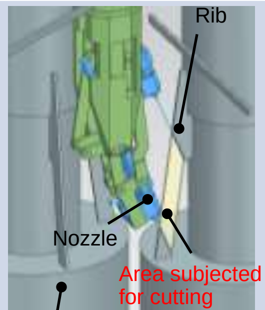
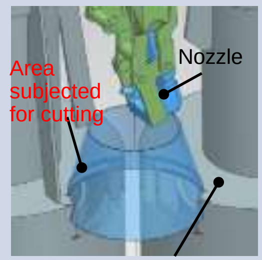
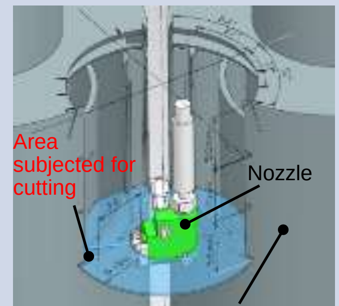
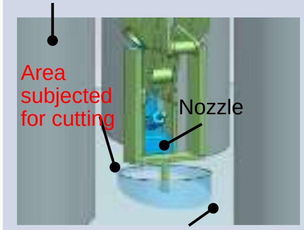
(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [Mockup cutting test (1/9)]

- Summary of operational conditions for each treatment target

The table below shows the operational conditions for each treatment target verified in the mockup cutting test.

	Processing objects					
	Steam dryer	Steam separator				Shroud head
	Bottom plate	Connection bars	Rib	Upper surface	Main body	-
AWJ cutting conditions						
Cutting speed	- Small diameter machining : 50° /min - Large diameter machining : 3 to 10° /min	- Connecting rod cutting : 10°/min	- Upper rib cutting : 5°/min - Lower rib cutting : 10°/min	- Upper flat plate cutting : 30°/min - Vertical cutting : 10 to 15 mm/min - Horizontal cutting : 12°/min	- Vertical cutting : 10 to 30 mm/min - Horizontal cutting : 12°/min	- Drilling of central hole : 60°/min - Circumferential cutting : 6°/min
Nozzle type	**- Straight nozzle**	**- Straight nozzle**	**- Straight nozzle**	**- Straight nozzle** + **- Angle nozzle**	**- Angle nozzle**	**- Straight nozzle**
Common conditions	Injection pressure: 343 MPa, Abrasive feed rate: 100 g/min Injection flow rate: 3.45 liter/min (straight nozzle) / 3.3 liter/min (angle nozzle)					

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

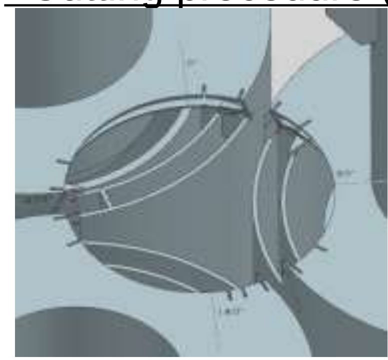
③ Test results (AWJ: Abrasive Water Jet) [mockup cutting test (2/9)]

- Steam separator: cutting of main body (1/7)

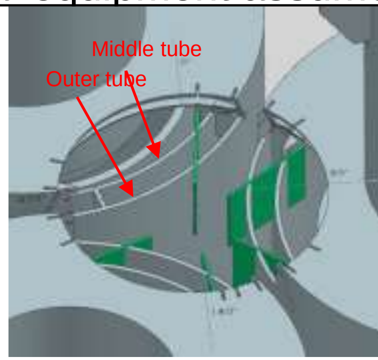
<Test details>

The conditions for cutting the main structure of the steam separator with an abrasive feed rate of 100 g/min were verified.

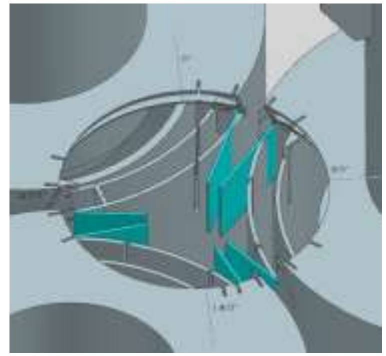
<Cutting procedure (actual equipment assumed)>



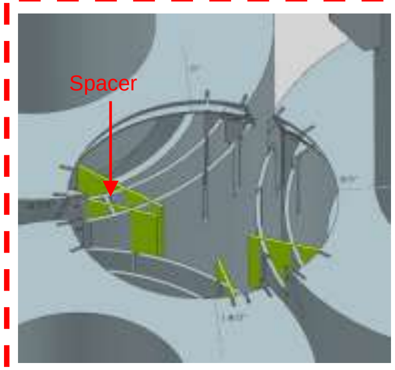
Shape before treatment



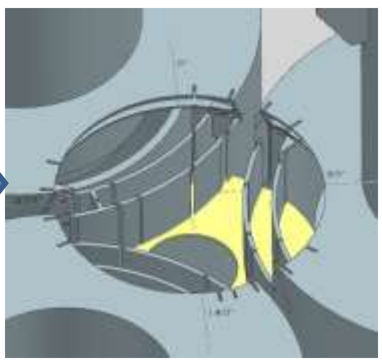
① Vertical cutting (interior)



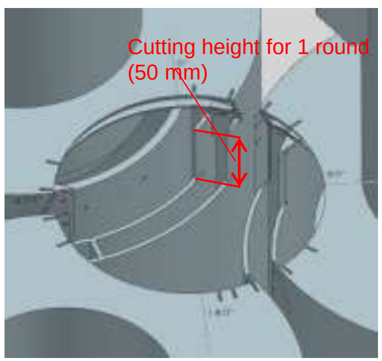
② Vertical cutting (exterior)



③ Vertical cutting (spacer)

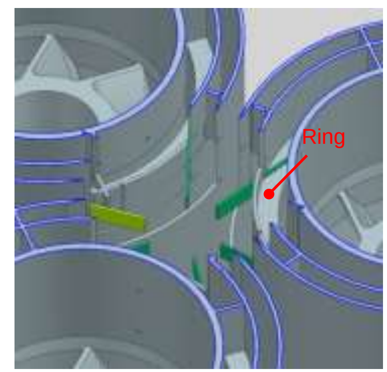


④ Horizontal cutting



Shape after treatment (1 round)

Repeat steps 1 to 4 until the specified number of rounds



⑤ Vertical cutting (ring)

: Range added in FY2021, not simulated until FY2020.

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

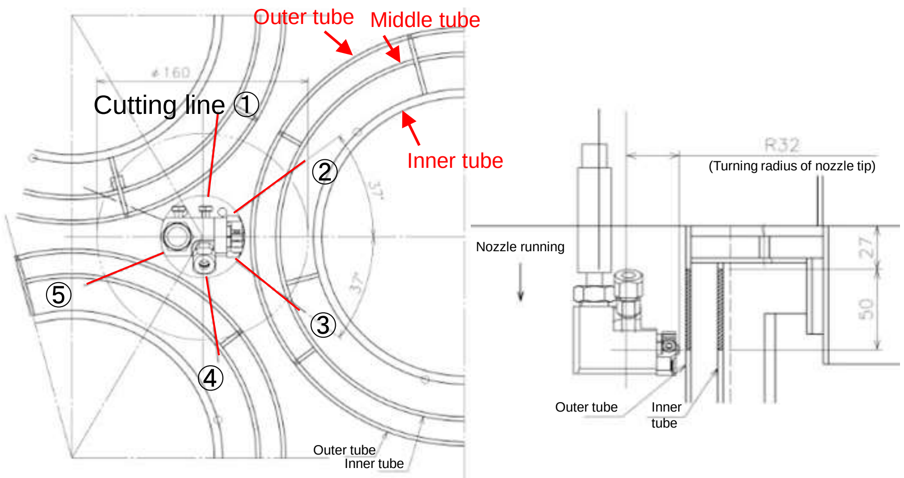
2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [mockup cutting test (3/9)]

- Steam separator: cutting of main body (2/7)

<Test conditions>

① Vertical cutting (interior)



Drawing of cutting conditions

Items	Conditions
AWJ nozzle	Angle nozzle
Injection pressure	343 MPa
Injection flow rate	3.3 liter/min
Abrasive feed rate	100 g/min
Standoff	16.3 mm (until the outer tube) 47.5 mm (until the middle tube)
Cutting speed	**20 mm/min**

<Test results>

- Vertical cutting (interior) was possible for cutting the outer and middle tubes at 20 mm/min.

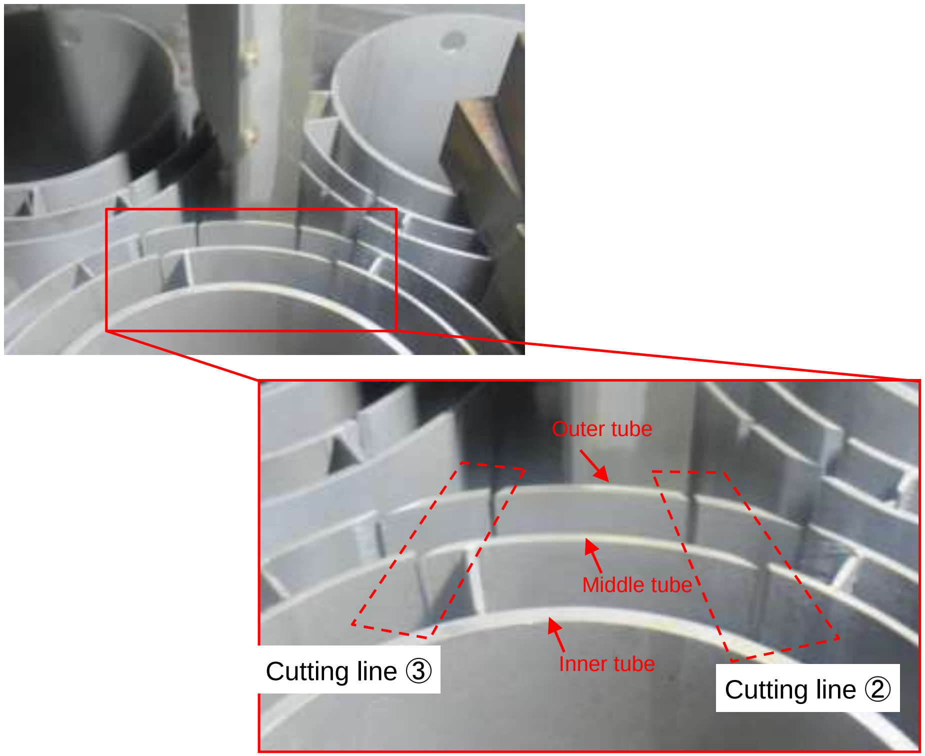


Photo of test piece: vertical cutting (interior)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

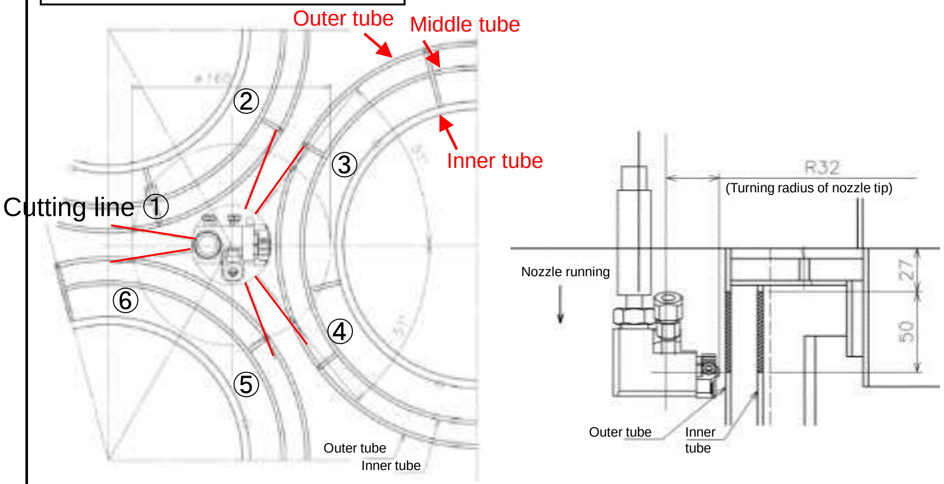
2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [mockup cutting test (4/9)]

- Steam separator: cutting of main body (3/7)

<Test conditions>

② Vertical cutting (exterior)



Drawing of cutting conditions

Items	Conditions
AWJ nozzle	Angle nozzle
Injection pressure	343 MPa
Injection flow rate	3.3 liter/min
Abrasive feed rate	100 g/min
Standoff	41.9 mm
Cutting speed	**10 mm/min**

<Test results>

- Vertical cutting (exterior) was possible for cutting the outer tube at 10 mm/min.

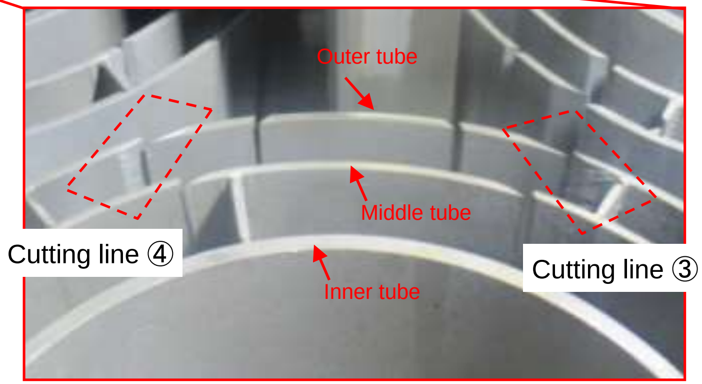


Photo of test piece: vertical cutting (exterior)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

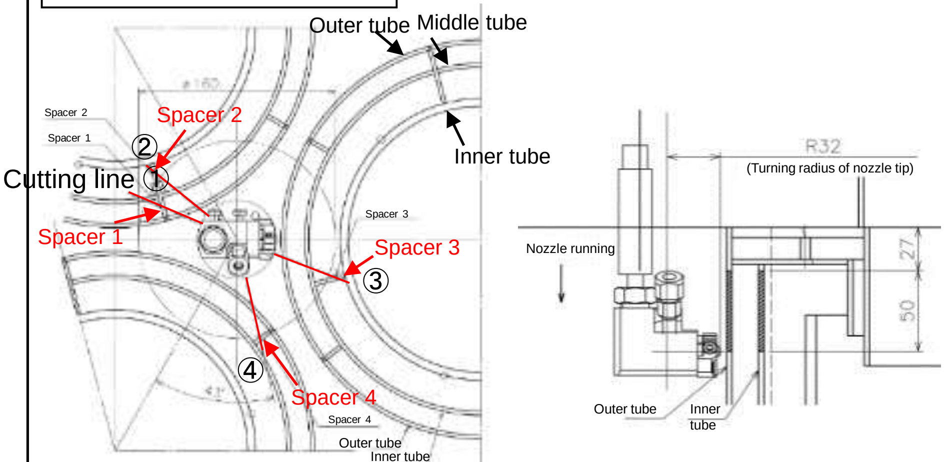
2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [mockup cutting test (5/9)]

- Steam separator: cutting of main body (4/7)

<Test conditions>

③ Vertical cutting (spacer)



Drawing of cutting conditions

Items	Conditions
AWJ nozzle	Angle nozzle
Injection pressure	343 MPa
Injection flow rate	3.3 liter/min
Abrasive feed rate	100 g/min
Standoff	①: 31.1 mm (until the spacer) ②③: 52.6 mm (until the spacer) ④: 49.5 mm (until the spacer)
Cutting speed	**①: 30 mm/min (one round trip)** **②③④: 20 mm/min**

<Test results>

- For vertical cutting (spacers), the cutting of each spacer was possible at the following cutting speeds.
  [Cutting speed] Spacer 1: 30 mm/min (one round trip), spacer 2: 20 mm/min
  Spacer 3: 20 mm/min, spacer 4: 20 mm/min

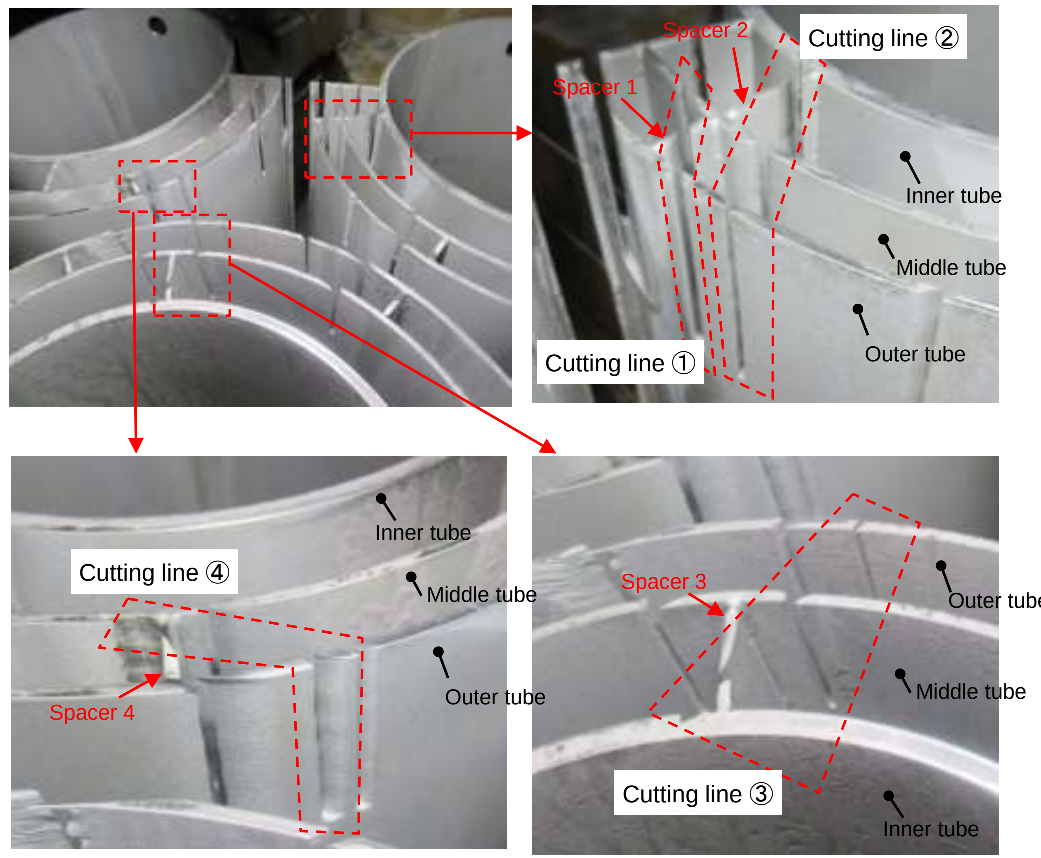


Photo of test piece: vertical cutting (spacer)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

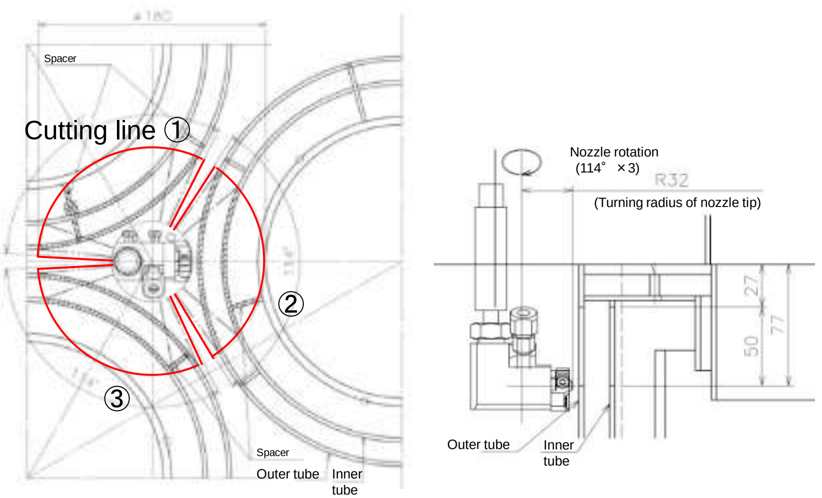
2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [mockup cutting test (6/9)]

- Steam separator: cutting of main body (5/7)

<Test conditions>

④ Horizontal cutting



Drawing of cutting conditions

Items	Conditions
AWJ nozzle	Angle nozzle
Injection pressure	343 MPa
Injection flow rate	3.3 liter/min
Abrasive feed rate	100 g/min
Standoff	4 mm to 58 mm
Cutting speed	**12°/min**

<Test results>

- Horizontal cutting was possible for cutting the outer and middle tubes and spacers at 12° /min.

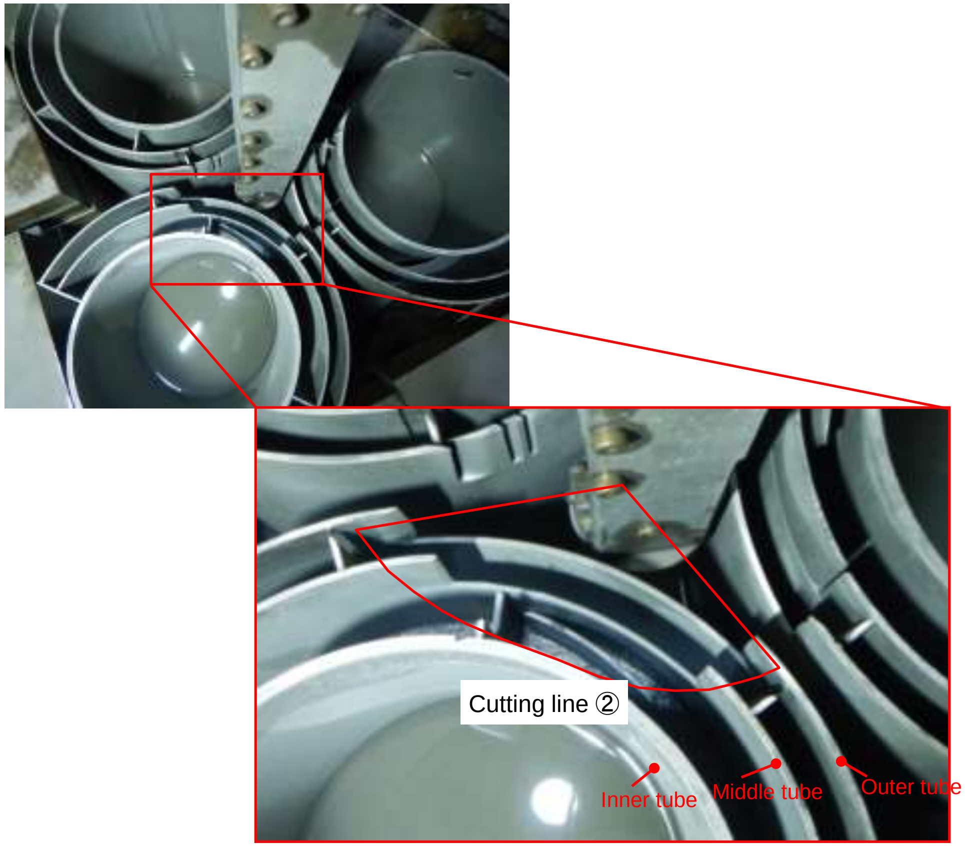


Photo of test piece: horizontal cutting

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

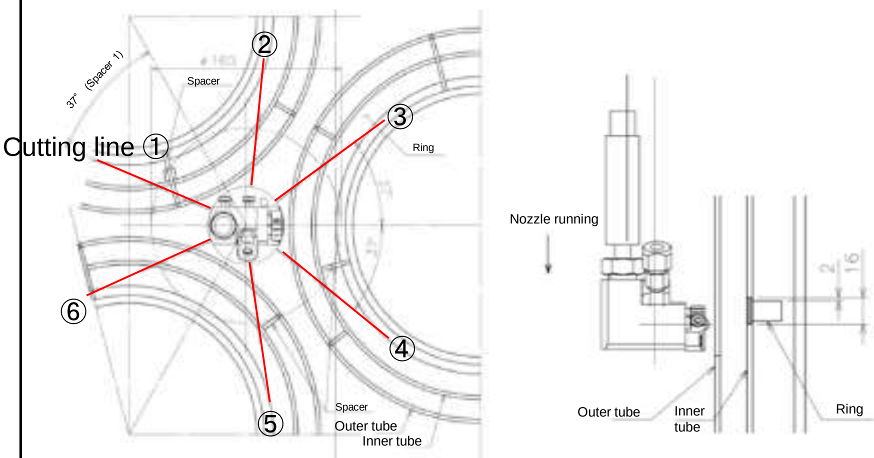
2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [mockup cutting test (7/9)]

- Steam separator: cutting of main body (6/7)

<Test conditions>

⑤ Vertical cutting (ring)



Drawing of cutting conditions

Items	Conditions
AWJ nozzle	Angle nozzle
Injection pressure	343 MPa
Injection flow rate	3.3 liter/min
Abrasive feed rate	100 g/min
Standoff	53.5 mm (until ring)
Cutting speed	**30 mm/min (9 round trips)**

<Test results>

- Vertical cutting (ring) was possible for cutting the ring at 30 mm/min (9 round trips).

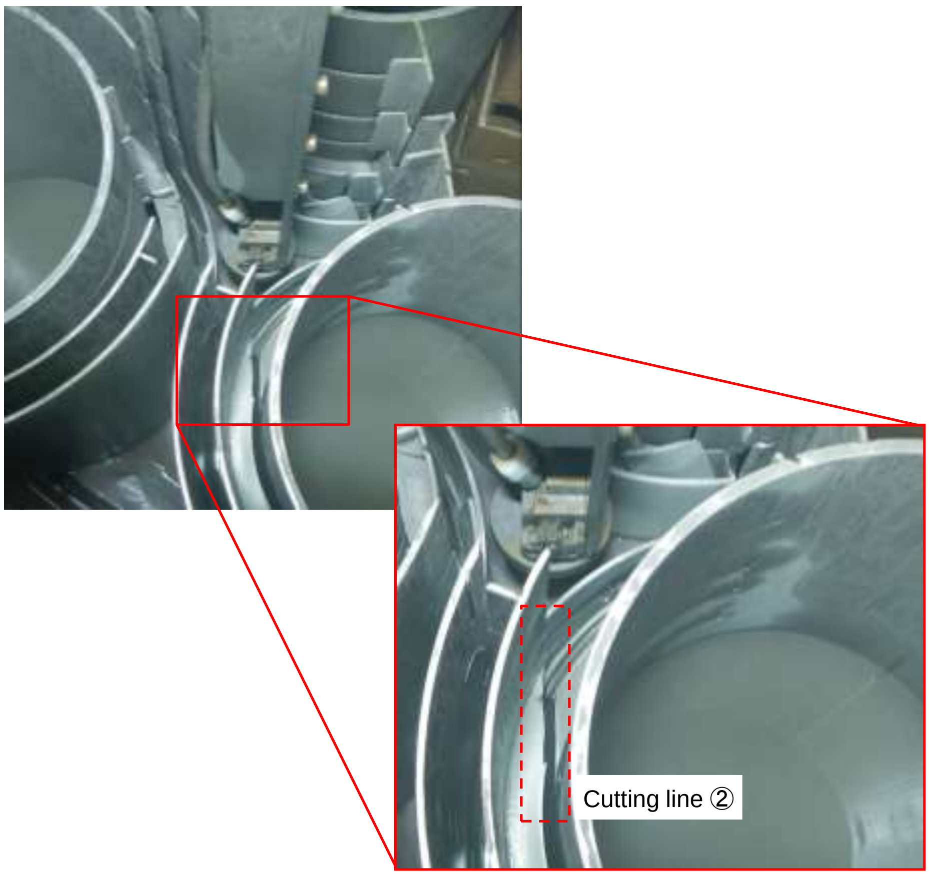


Photo of test piece: vertical cutting (ring)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [mockup cutting test (8/9)]

- Steam separator: cutting of main body (7/7)

<Test results>

Photo ① of test pieces before cutting

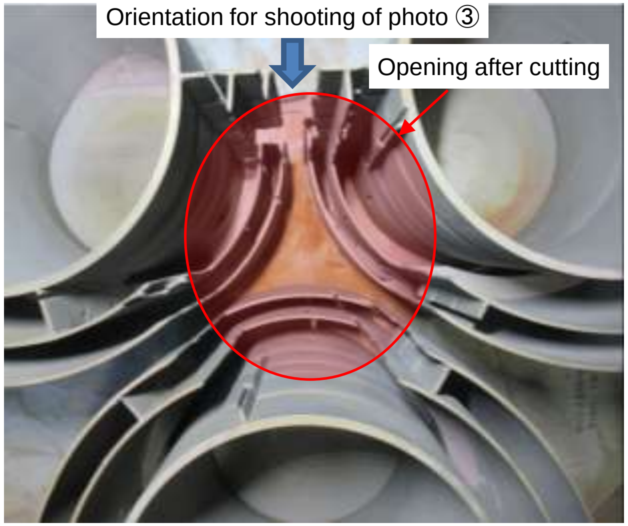


Photo ② of test pieces after cutting into 4 pieces

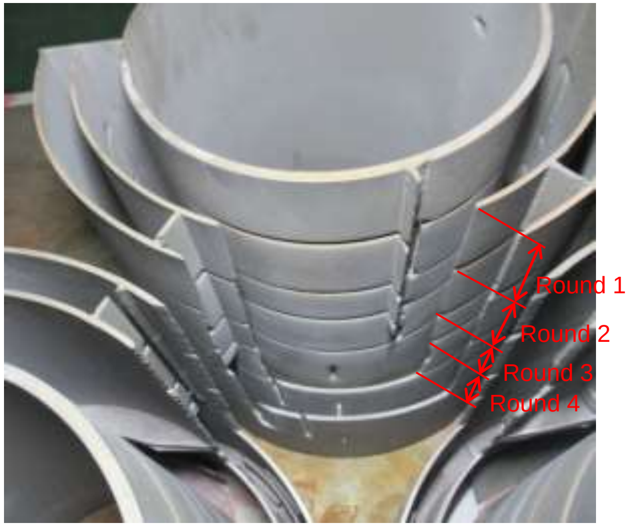


Photo ③ of test pieces after cutting inro 4 pieces

According to the cutting procedure described in the previous pages, the main body of the steam separator was cut into four pieces by using the angle nozzle designed in FY2021.

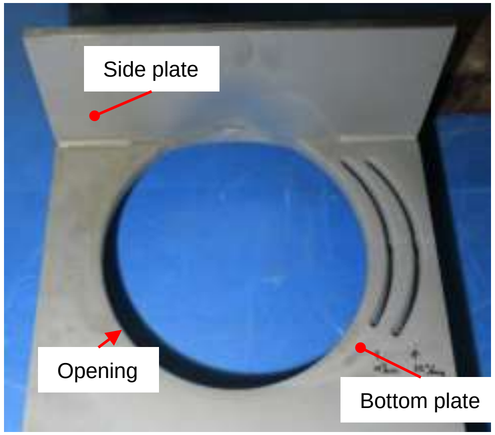
6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

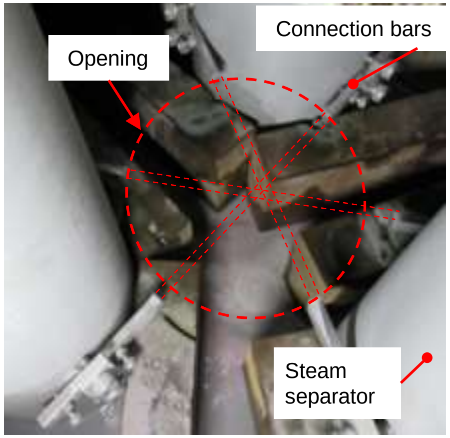
2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [mockup cutting test (9/9)]

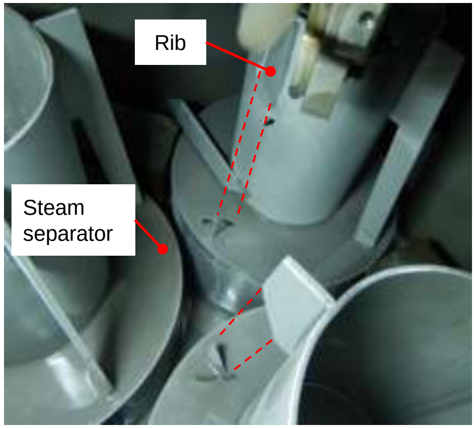
- Other treatment targets



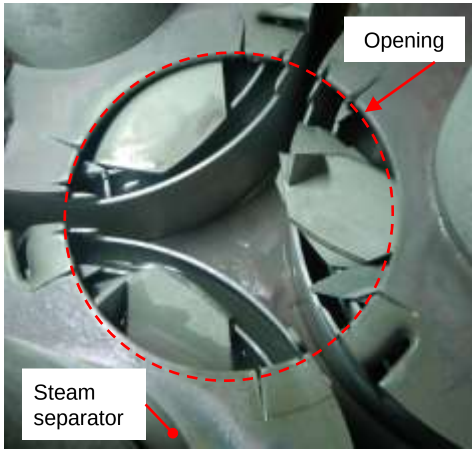
Steam dryer bottom plate



Steam separator connecting rods



Steam separator ribs



Steam separator upper surface

Shroud head

Cutting tests for objects to be processed other than the main body of the steam separator were carried out by using every nozzle. It was verified that all reactor internal structures to be processed can be cut.

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet)

[Estimation of abrasive consumption]

(*1): An abrasive feed rate of 100 g/min was used for the element test, but due to variations in the feed rate, 120 g/min was used in the Estimations.
(*2): The evaluations were made conservatively due to instability in the abrasive feed rate in past tests.
(*3): Targets where operational conditions were verified by new FY2021 simulations.

Processing objects			Abrasive consumption up to FY2019	FY2020 abrasive consumption	FY2021		
					Abrasive consumption (*1)	Changes in abrasive feed rate (yes: ○, no: x)	Changes other than abrasive feed rate
Steam dryer	Bottom plate	Small diameter treatment	2.74 kg	Same as that on the left	**0.88 kg**	○	No change
		Large diameter treatment	12.64 kg	Same as that on the left	**7.35 kg**	○	No change
Steam separator	Connection bars	—	60.00 kg (*2)	Same as that on the left	**1.08 kg**	○	- Limited emission range (364°→ 90°) - Reduced standoff
	Rib	—	8.59 kg	Same as that on the left	**1.56 kg**	○	- Change in emission range (17° → upper 20°, lower 25°) - Increase in cutting points (2 points → 4 points)
	Upper surface	- Upper flat plate cutting - Vertical cutting (interior) - Vertical cutting (exterior)	829.06 kg	Same as that on the left	**17.16 kg**	○	- Change in cutting combination (Combination of conical cuts → combination of conical cutting + vertical/horizontal cutting) - Change in emission range (364° → 342°)
		- Vertical cutting (spacer) (*3)	—	—	**0.17 kg**	○	No change (New consideration)
	Main body	- Vertical cutting (interior) - Vertical cutting (exterior) - Horizontal cutting	7840.21 kg	323.75 kg	**269.82 kg**	○	No change
		- Vertical cutting (spacer) - Vertical cutting (ring) (*3)	—	—	**20.12 kg**	○	No change (New consideration)
Shroud head	-	Drilling of central hole	4.5 kg	Same as that on the left	**0.97 kg**	○	No change
	-	Circumferential cutting	51.57 kg	Same as that on the left	**8.28 kg**	○	No change
Total (Rounded up to the nearest whole number)			**8810 kg**	**1293 kg**	**328 kg (Compared to previous FY: approx. 75% decrease)**	—	—
Total operation time (Rounded up to the nearest whole number)			**228 hr**	**37 hr**	**46 hr (Compared to previous FY: approx. 25% increase)**		

Although operation time will increase, the prospect of abrasive consumption of 500 kg or less can be achieved.

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

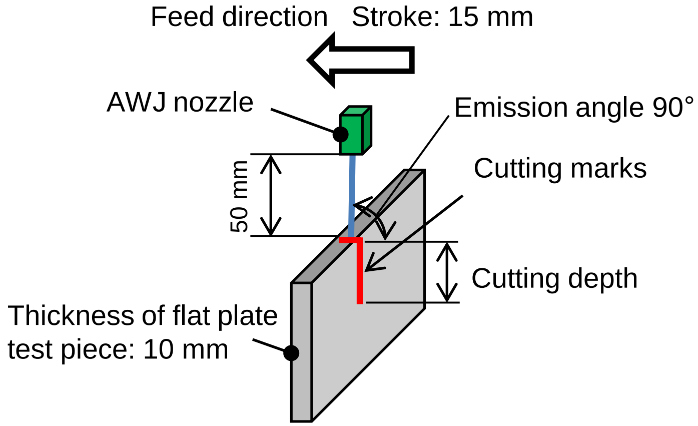
2) Implementation details for the second half of FY2021

③ Test results (AWJ: Abrasive Water Jet) [Results of nozzle durability test]

<Test details>

Flat plate was cut for every hour of emission, and the cutting depth is verified. Nozzle lifetime was evaluated from changes in cutting depth.

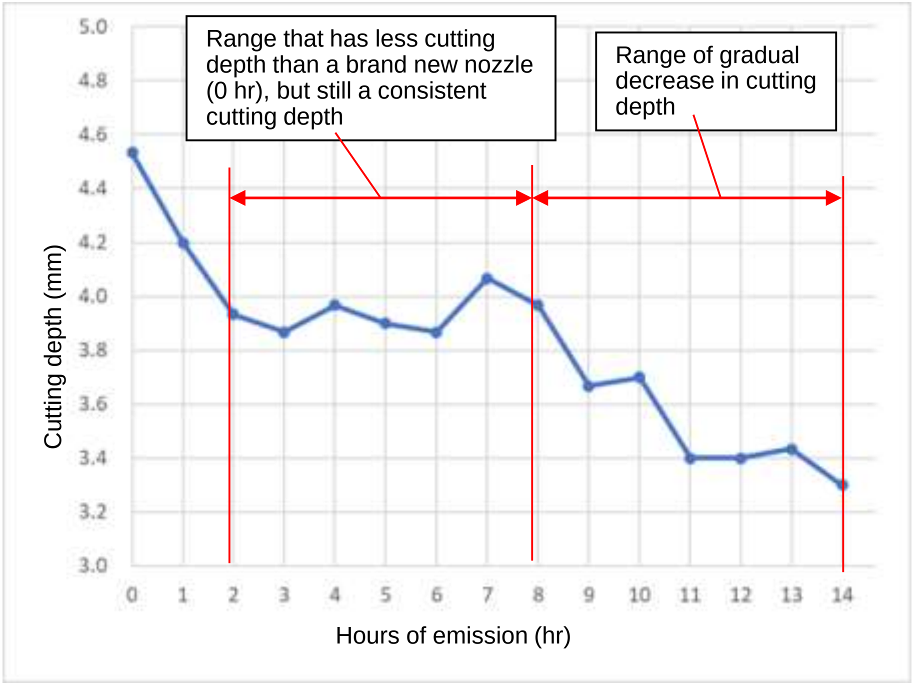
<Test conditions>



Items	Conditions
AWJ nozzle	Angle nozzle
Injection pressure	343 MPa
Injection flow rate	3.3 liter/min
Abrasive feed rate	100 g/min
Cutting speed	60 mm/min

<Test results>

- The cutting depth decreased slightly after 2 hours, remained stable after that until the 8th hour, and then gradually decreased after the 9th hour.



Nozzle durability test results

<Conclusion>

- Based on the above results, it was concluded that **the nozzle lifetime is 8 hours.**

It takes about 42 hours to install the angle nozzle, therefore, the method for replacing the nozzle needs to be considered in the future.

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

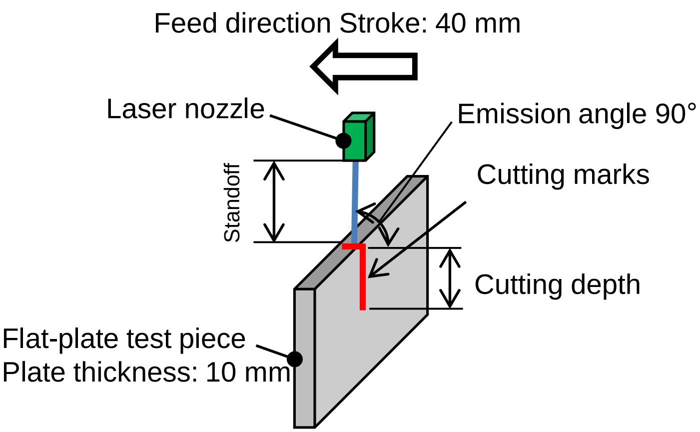
④ Test results (laser) [flat plate cutting test (1/2)]

- Angle nozzle performance test

<Test details>

Flat plates were cut in the direction of the flat plate thickness by using either angle or straight nozzles to verify the performance of the angle nozzle based on cutting depth.

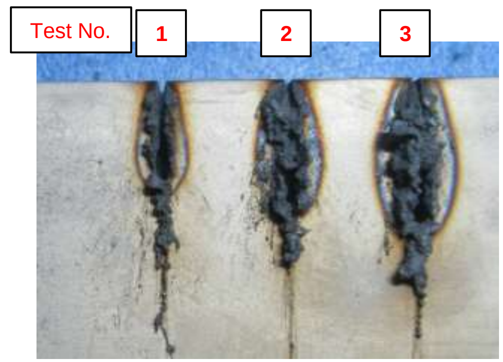
<Test conditions>



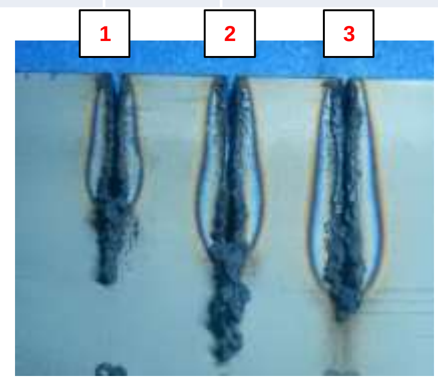
Items	Conditions
Laser nozzle	- Angle nozzle (Focal point: 35 mm from nozzle tip) - Straight nozzle (Focal point: 30 mm from nozzle tip)
Laser output	8 kW
Auxiliary air pressure	0.68 MPa
Auxiliary air flow rate	- Angle nozzle: approx. 680 liter/min - Straight nozzle: approx. 750 liter/min

<Test results>

Nozzle speed (mm/min)	Angle nozzle		Straight nozzle	
	Standoff: 55 mm (Nozzle tip to focal point: 35 mm + focal point to test piece: 20 mm)		Standoff: 50 mm (Nozzle tip to focal point: 30 mm + focal point to test piece: 20 mm)	
	No.	Cutting depth (mm)	No.	Cutting depth (mm)
300	1	**20**	1	**22**
180	2	**24**	2	**31.5**
120	3	**28**	3	**38.5**



Test pieces (angle nozzle)



Test pieces (straight nozzle)

<Conclusion>

- The angle nozzle of cutting performance was about 20 to 30% inferior to that of the straight nozzle.
- Although angle nozzles are inferior in performance to straight nozzles, **angle nozzles were deemed to have sufficient ability to cut the reactor internals.**
  (Even at a nozzle speed of 300 mm/min, a cutting depth of 20 mm was achieved, and it is possible to cut the steam separator main body of up to 3.2 mm in thickness)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

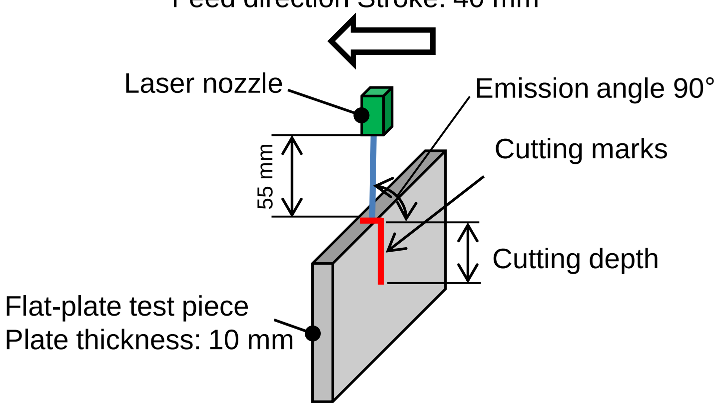
④ Test results (laser) [flat plate cutting test (2/2)]

- Performance test of laser output (actual equipment assumed)

<Test details>

The flat plate was cut by moving the nozzle in the direction of the flat plate thickness at 7.2 kW, which takes into account the loss of laser output in the actual equipment. The performance of the laser was verified from cutting depth.

<Test conditions>

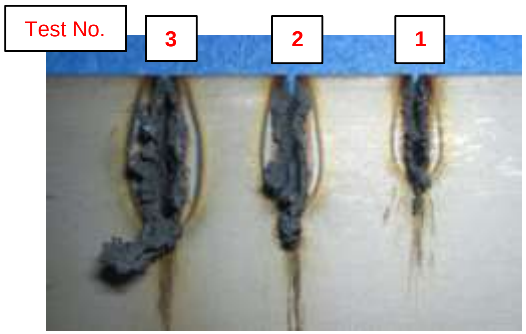


Items	Conditions
Laser nozzle	Angle nozzle (Focal point: 35 mm from nozzle tip)
Laser output	7.2 kW
Auxiliary air pressure	0.68 MPa
Auxiliary air flow rate	Approx. 680 liter/min

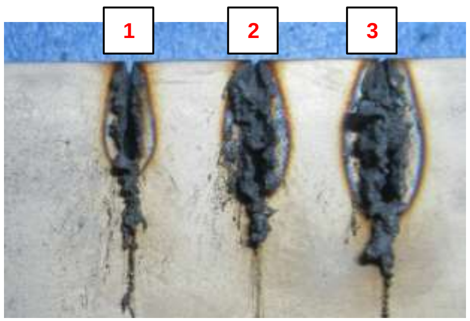
<Test results>

Nozzle speed (mm/min)	Laser output: 7.2 kW		Laser output: 8 kW (*1)	
	Standoff: 55 mm (Nozzle tip to focal point: 35 mm + focal point to test piece: 20 mm)			
	No.	Cutting depth (mm)	No.	Cutting depth (mm)
300	1	**19**	1	**20**
180	2	**23**	2	**24**
120	3	**28**	3	**28**

(*1): The laser output result of 8 kW is shown for comparison with the results of the angle nozzle performance test on the previous page.



Test pieces (laser output 7.2 kW)



Test pieces (laser output 8 kW)

<Conclusion>

- **There was no significant difference in cutting depth between laser outputs 7.2 kW and 8 kW;** the mockup cutting test was conducted with 7.2 kW laser output to verify operational conditions.

6. Implementation details

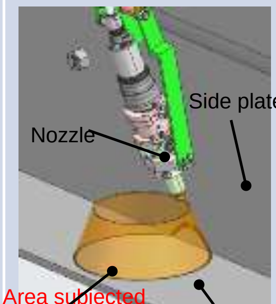
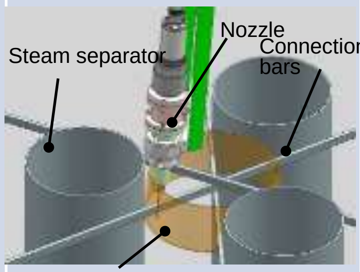
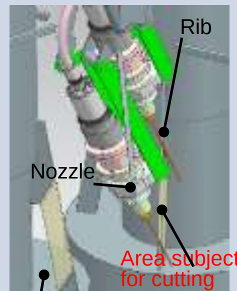
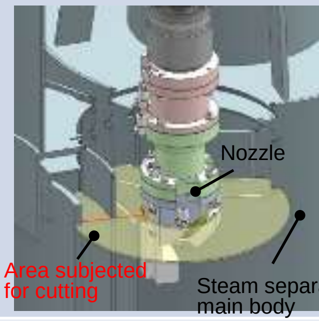
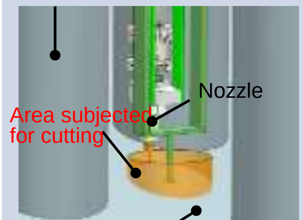
(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

④ Test results (laser) [Mockup cutting test (1/10)]

- Summary of operational conditions for each treatment target

The table below shows the operational conditions for each treatment target verified in the mockup cutting test.

	Processing objects					
	Steam dryer	Steam separator				Shroud head
	Bottom plate	Connection bars	Rib	Upper surface	Main body	-
Laser cutting conditions						
Cutting speed	- Small diameter machining : 516° /min - Large diameter machining : 46° /min	- Connecting rod cutting : 354°/min	- Upper rib cutting : 94°/min - Lower rib cutting : 118°/min	- Upper flat plate cutting : 92°/min - Vertical cutting : 60 to 120 mm/min - Horizontal cutting : 190°/min	- Vertical cutting : 60 to 300 mm/min - Horizontal cutting : 190°/min	- Drilling of central hole : 286°/min - Circumferential cutting : 20°/min
Nozzle type	**- Straight nozzle**	**- Straight nozzle**	**- Straight nozzle**	**- Straight nozzle** + **- Angle nozzle**	**- Angle nozzle**	**- Straight nozzle**
Common conditions	Laser output: 7.2 kW, auxiliary air pressure: 0.68 MPa Auxiliary air flow rate: approx. 750 liter/min (straight nozzle)/approx. 680 liter/min (angle nozzle)					

Total actual operation duration: approx. 4 hours

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6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

④ Test results (laser) [mockup cutting test (2/10)]

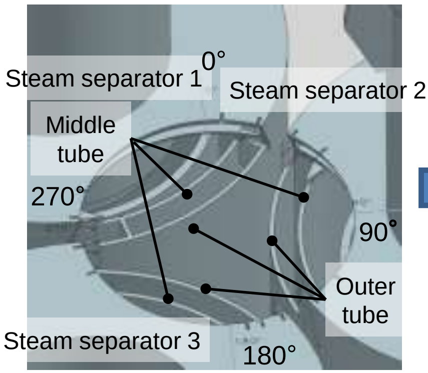
- Steam separator: cutting of main body (1/8)

<Test details>

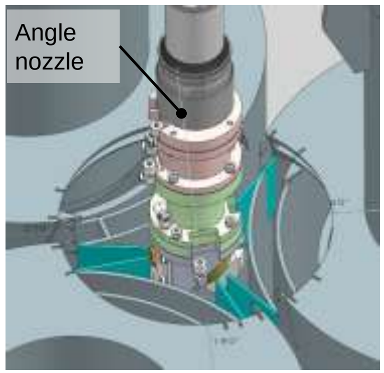
The conditions for cutting the main body of the steam separator were confirmed.

<Cutting procedure (actual equipment assumed)>

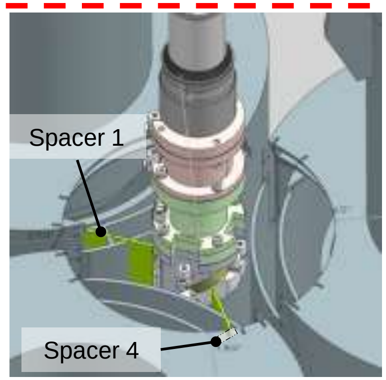
*: Cut the main body of the steam separator by combining steps ① through ⑥.



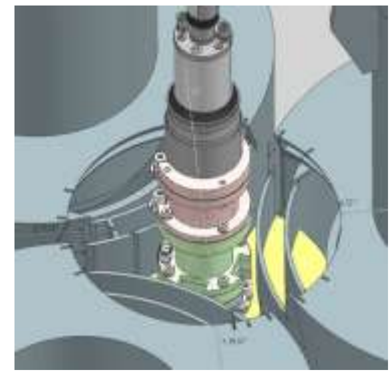
Shape before treatment

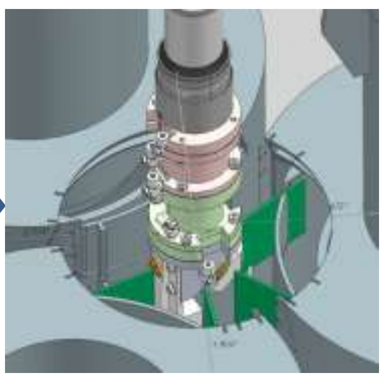


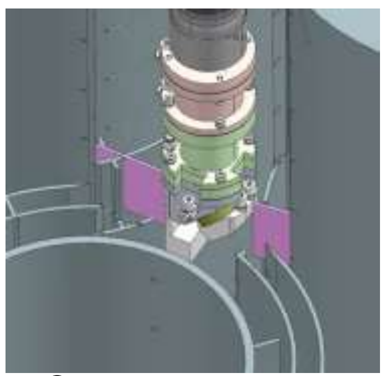
① Vertical cutting (exterior)

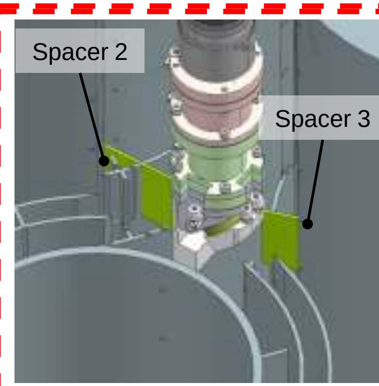


② Vertical cutting (spacers 1, 4)

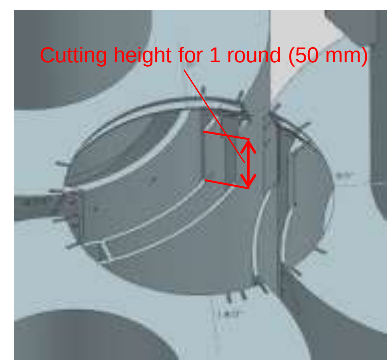

③ Horizontal cutting


④ Vertical cutting (interior)


⑤ Vertical cutting (before reaching spacer)



⑥ Vertical cutting (spacers 2, 3)



Shape after treatment (1 round)

: Range added in FY2021, not simulated in AWJ cutting until FY2020.

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

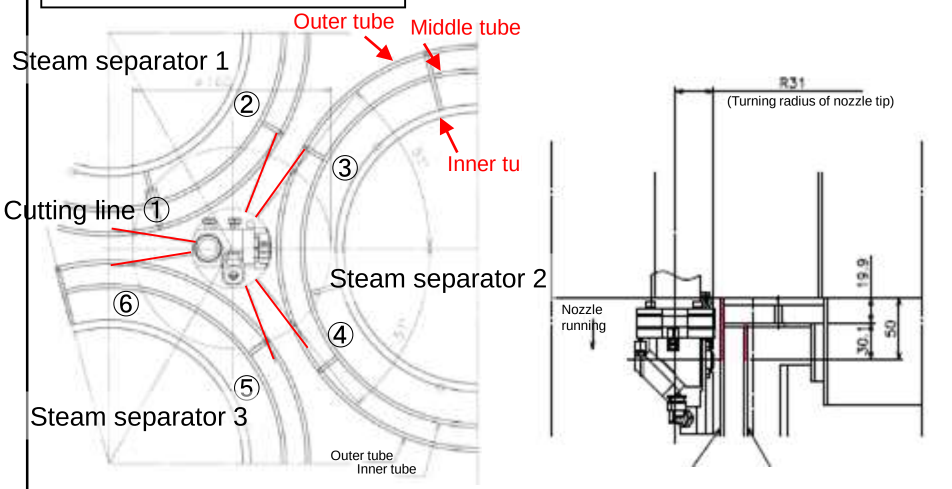
2) Implementation details for the second half of FY2021

④ Test results (laser) [mockup cutting test (3/10)]

- Steam separator: cutting of main body (2/8)

<Test conditions>

① Vertical cutting (exterior)



Drawing of cutting conditions

Items	Conditions
Laser nozzle	Angle nozzle
Laser output	7.2 kW
Auxiliary gas	Air
Auxiliary gas pressure / flow rate	0.68 MPa / approx. 680 liter/min
Standoff	47.2 mm
Cutting speed	**300 mm/min**

<Test results>

- Vertical cutting (exterior) for the outer tube at 300 mm/min was possible.

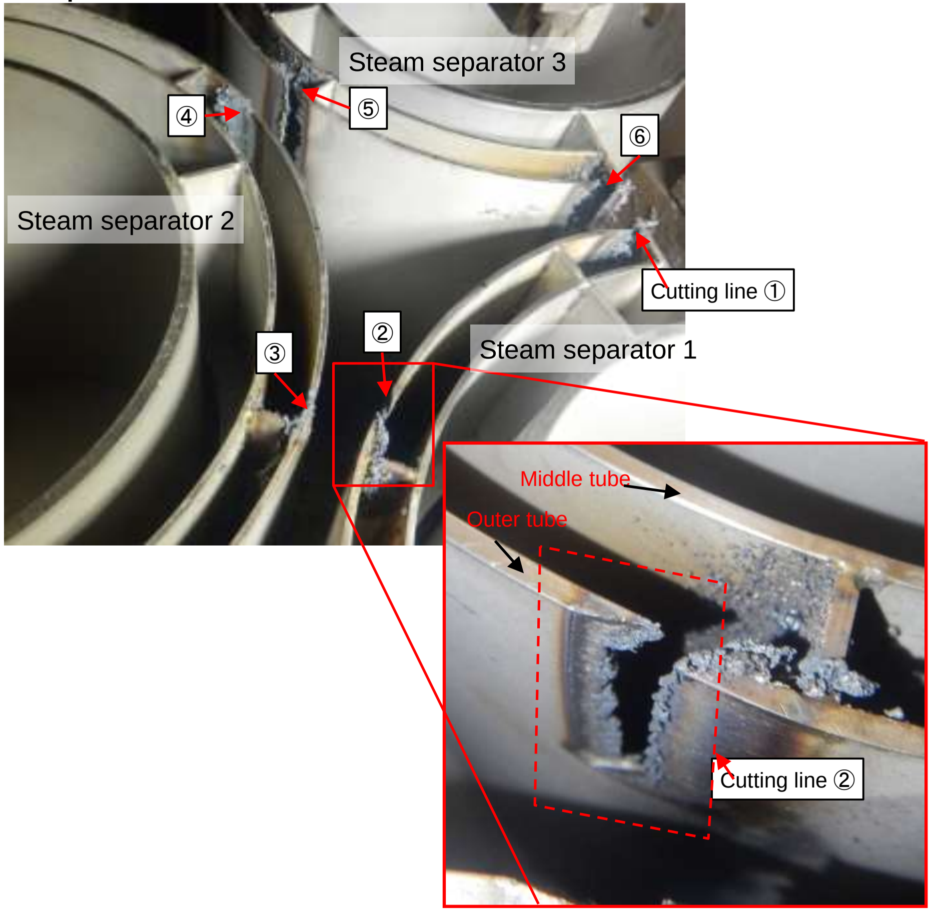


Photo of test piece: vertical cutting (exterior)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

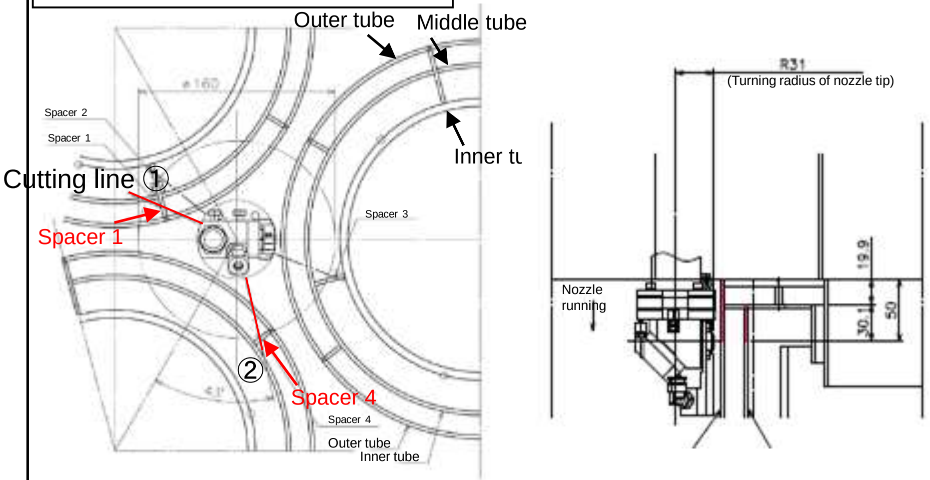
2) Implementation details for the second half of FY2021

④ Test results (laser) [mockup cutting test (4/10)]

- Steam separator: cutting of main body (3/8)

<Test conditions>

② Vertical cutting (spacers 1, 4)

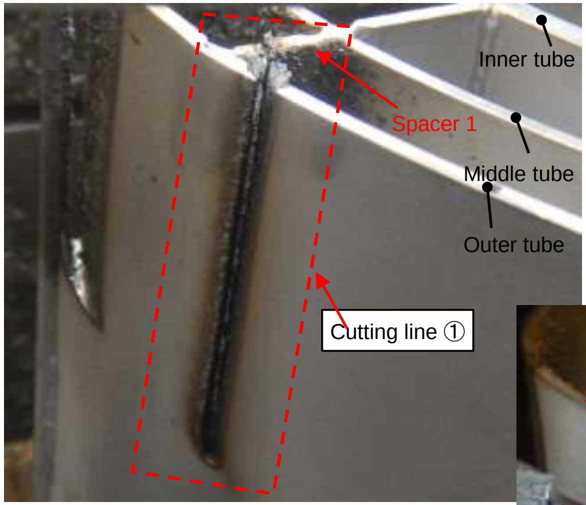


Drawing of cutting conditions

Items	Conditions
Laser nozzle	Angle nozzle
Laser output	7.2 kW
Auxiliary gas	Air
Auxiliary gas pressure / flow rate	0.68 MPa / approx. 680 liter/min
Standoff	①: 32.2 mm (until spacer) ②: 50.5 mm (until spacer)
Cutting speed	**①: 300 mm/min** **②: 300 mm/min**

<Test results>

- Vertical cutting (spacers 1, 4) for each spacer at 300 mm/min was possible.



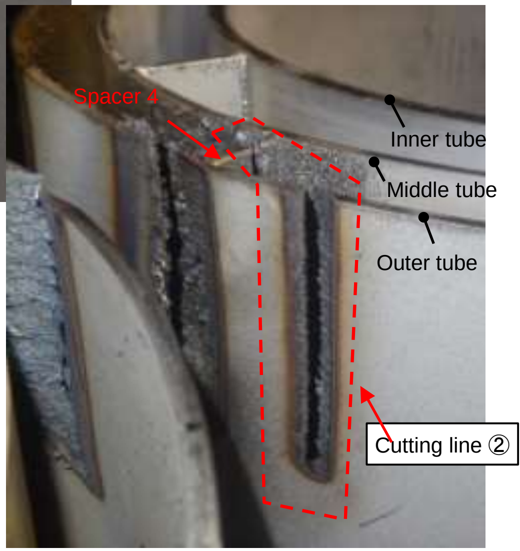


Photo of a test piece: vertical cutting (spacers 1, 4)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

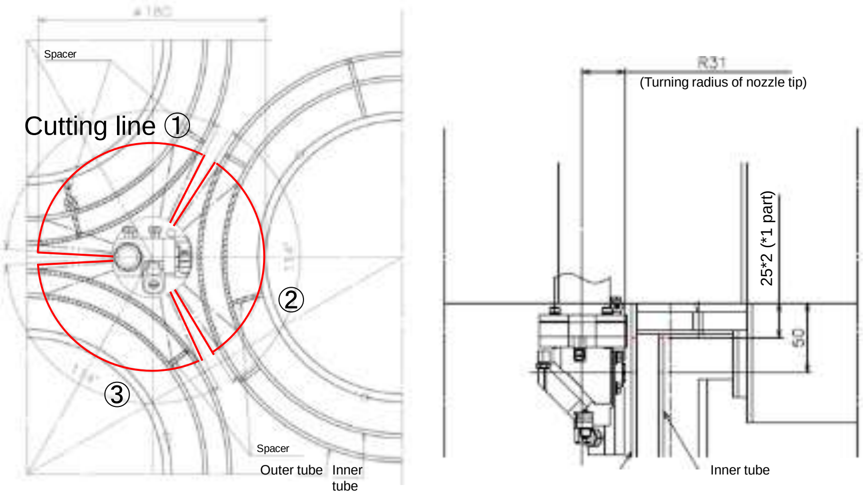
2) Implementation details for the second half of FY2021

④ Test results (laser) [mockup cutting test (5/10)]

- Steam separator: cutting of main body (4/8)

<Test conditions>

③ Horizontal cutting



Drawing of cutting conditions

Items	Conditions
Laser nozzle	Angle nozzle
Laser output	7.2 kW
Auxiliary gas	Air
Auxiliary gas pressure / flow rate	0.68 MPa / approx. 680 liter/min
Standoff	5 to 59 mm
Cutting speed	**190°/min**

<Test results>

- Horizontal cutting was possible for cutting the outer and middle tubes and spacer at 190° /min.

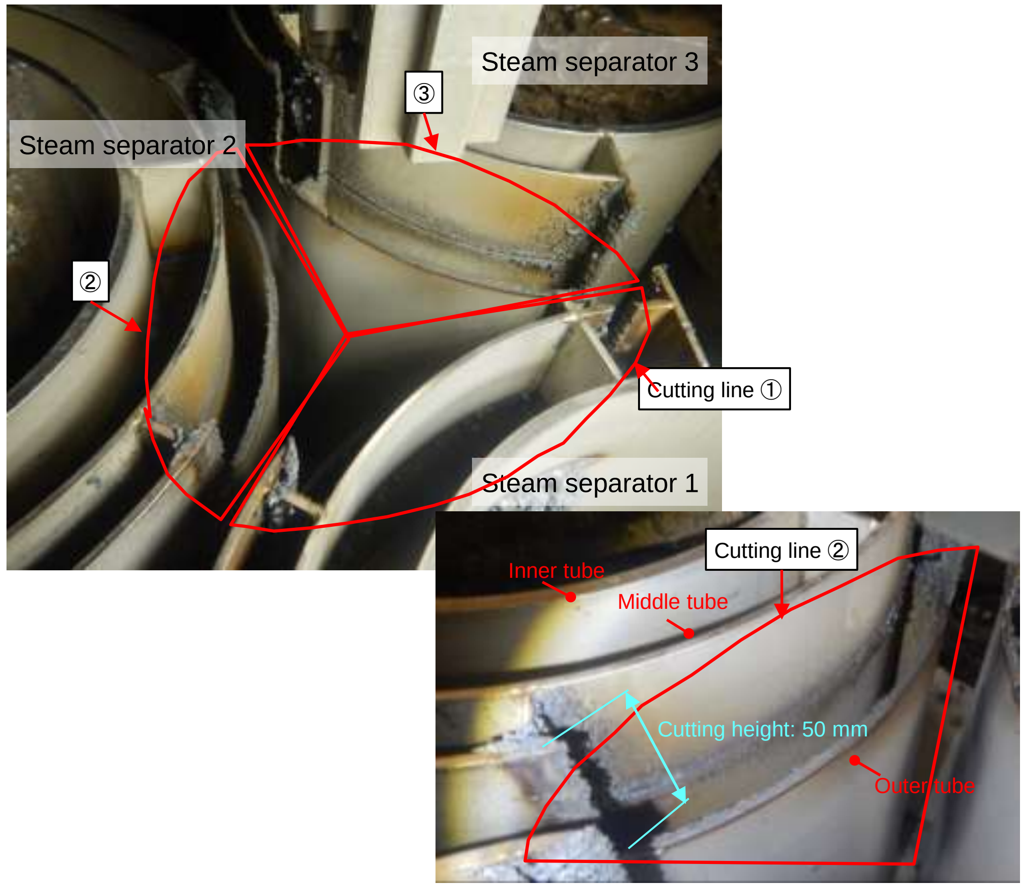


Photo of a test piece: horizontal cutting

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

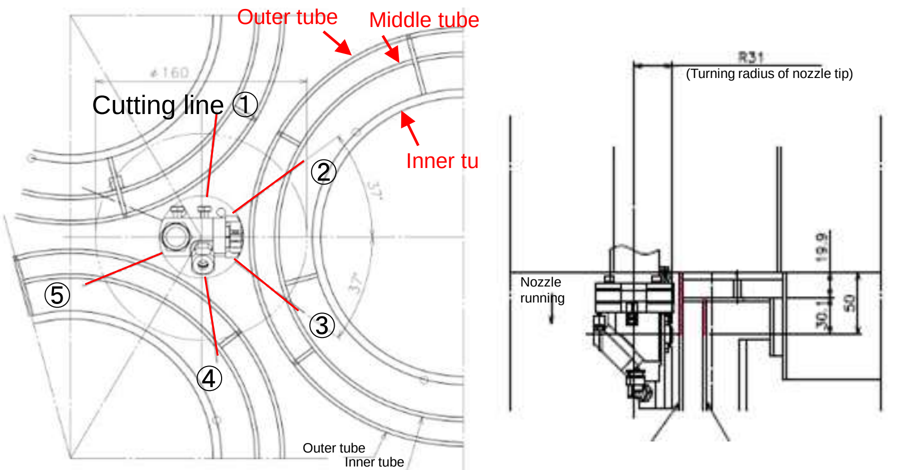
2) Implementation details for the second half of FY2021

④ Test results (laser) [mockup cutting test (6/10)]

- Steam separator: cutting of main body (5/8)

<Test conditions>

④ Vertical cutting (interior)



Drawing of cutting conditions

Items	Conditions
Laser nozzle	Angle nozzle
Laser output	7.2 kW
Auxiliary gas	Air
Auxiliary gas pressure / flow rate	0.68 MPa / approx. 680 liter/min
Standoff	8.3 to 30 mm
Cutting speed	**300 mm/min**

<Test results>

- Vertical cutting (interior) for the middle tube at 300 mm/min was possible.

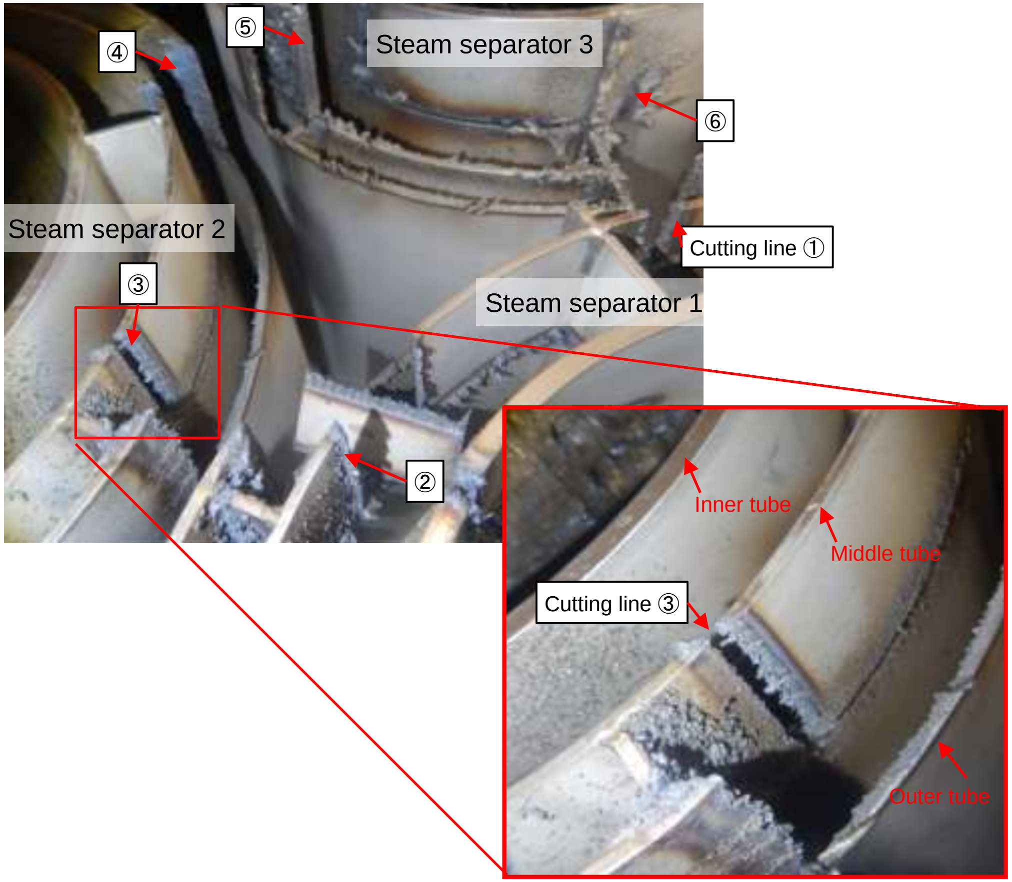


Photo of a test piece: vertical cutting (interior)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

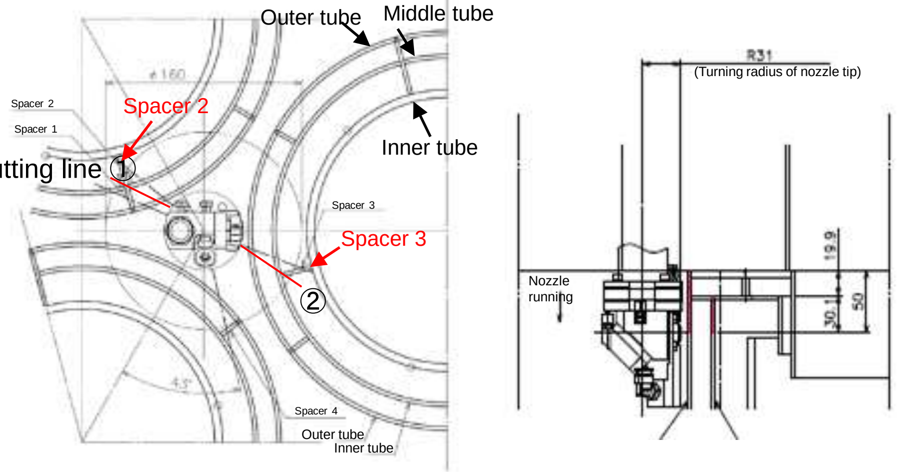
2) Implementation details for the second half of FY2021

④ Test results (laser) [mockup cutting test (7/10)]

- Steam separator: cutting of main body (6/8)

<Test conditions>

⑤ Vertical cutting (before reaching spacer)



Drawing of cutting conditions

Items	Conditions
Laser nozzle	Angle nozzle
Laser output	7.2 kW
Auxiliary gas	Air
Auxiliary gas pressure / flow rate	0.68 MPa / approx. 680 liter/min
Standoff	①: 44.9 mm (until spacer) ②: 44.9 mm (until spacer)
Cutting speed	**①: 300 mm/min** **②: 300 mm/min**

<Test results>

- Vertical cutting (before reaching spacer) at 300 mm/min was possible.

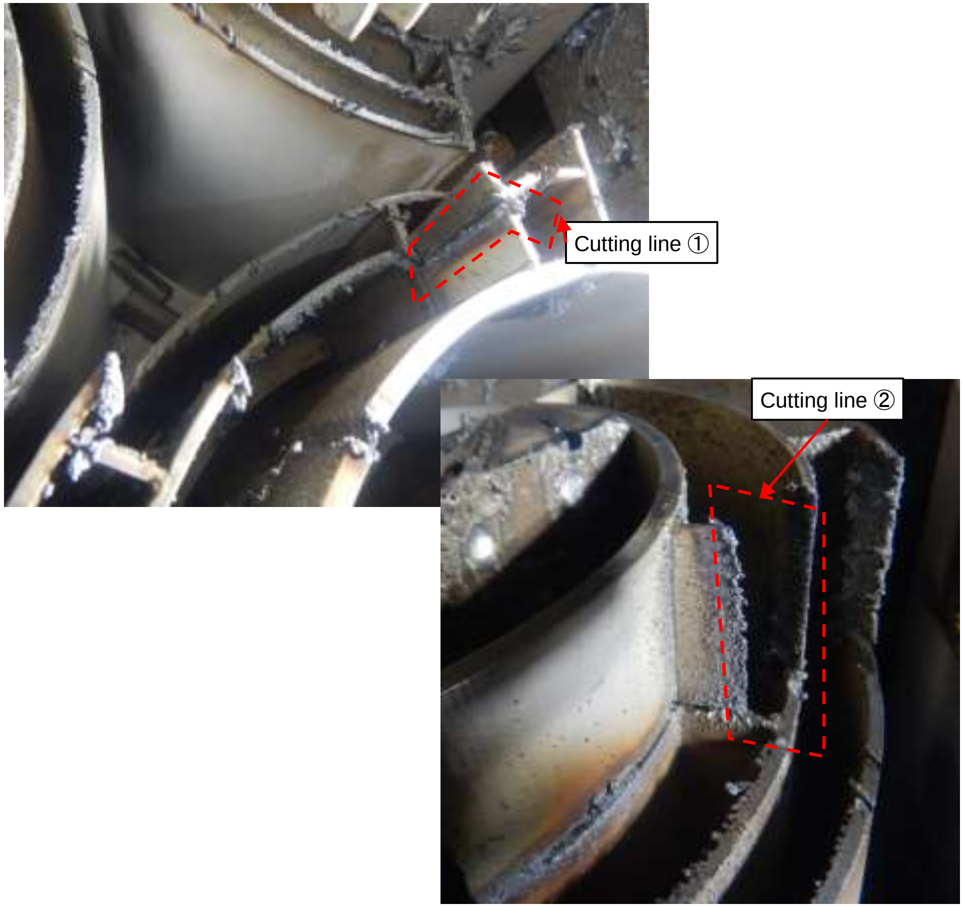


Photo of a test piece: vertical cutting (before reaching spacer)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

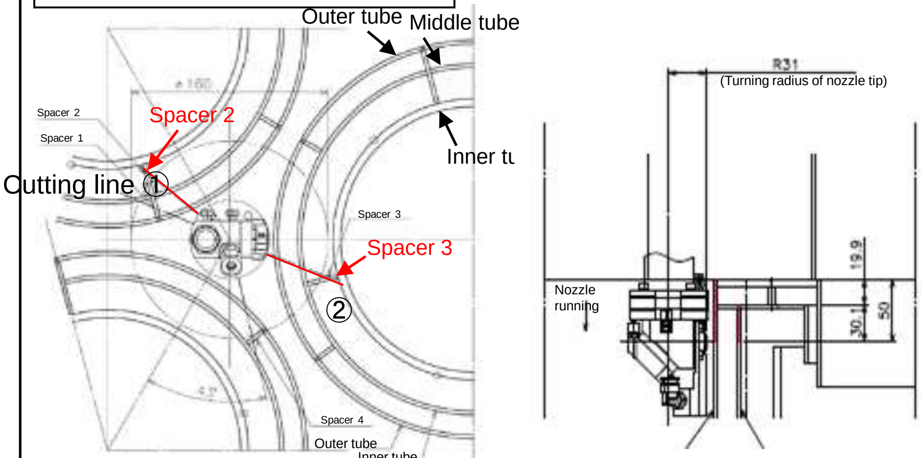
2) Implementation details for the second half of FY2021

④ Test results (laser) [mockup cutting test (8/10)]

- Steam separator: cutting of main body (7/8)

<Test conditions>

⑥ Vertical cutting (spacers 2, 3)



Drawing of cutting conditions

Items	Conditions
Laser nozzle	Angle nozzle
Laser output	7.2 kW
Auxiliary gas	Air
Auxiliary gas pressure / flow rate	0.68 MPa / approx. 680 liter/min
Standoff	①: 53.7 mm (until spacer) ②: 53.7 mm (until spacer)
Cutting speed	**①: 300 mm/min** **②: 300 mm/min**

<Test results>

- Vertical cutting (spacers 2, 3) at a cutting speed of 300 mm/min was possible.

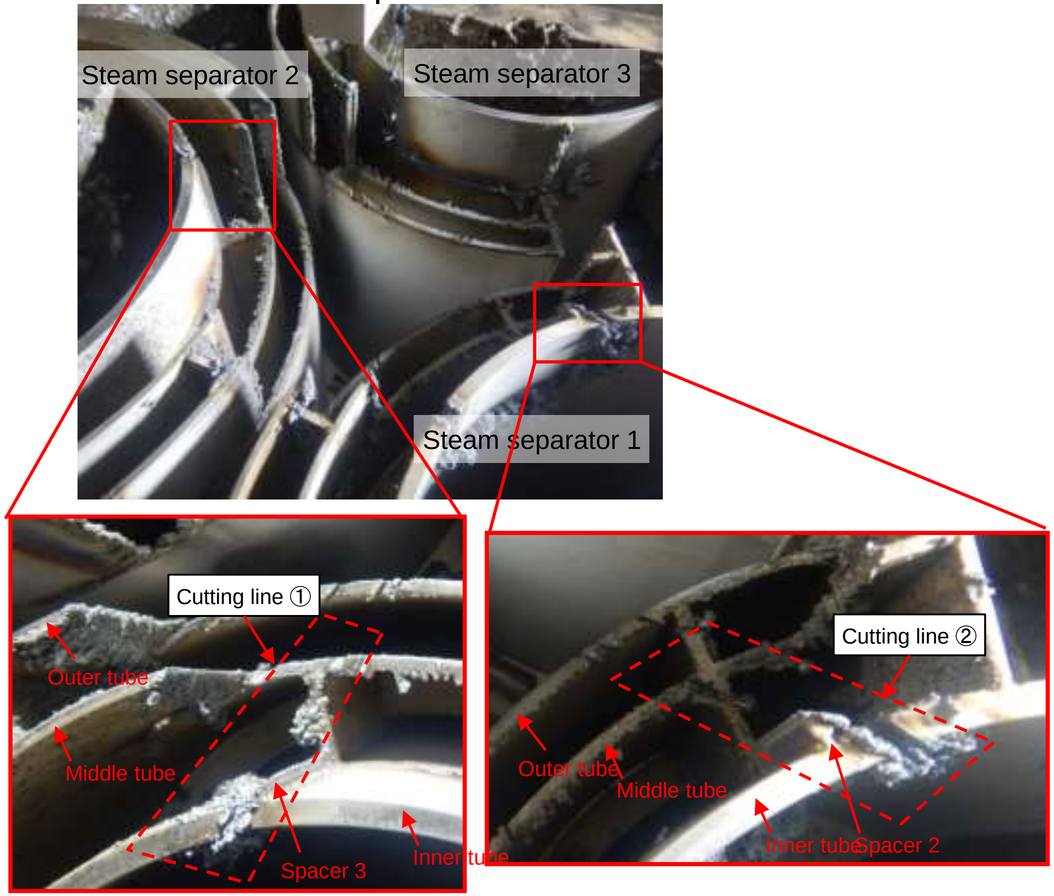


Photo of test piece: vertical cutting (spacer 2, 3)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

④ Test results (laser) [mockup cutting test (9/10)]

- Steam separator: cutting of main body (8/8)

<Test results>

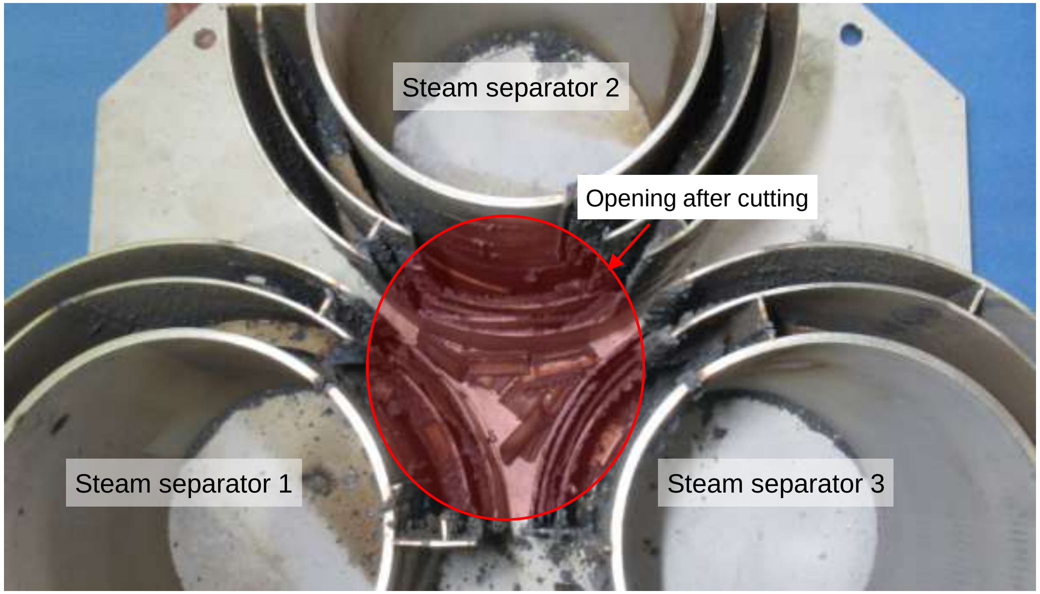


Photo ① of test pieces : after 4 rounds of cutting

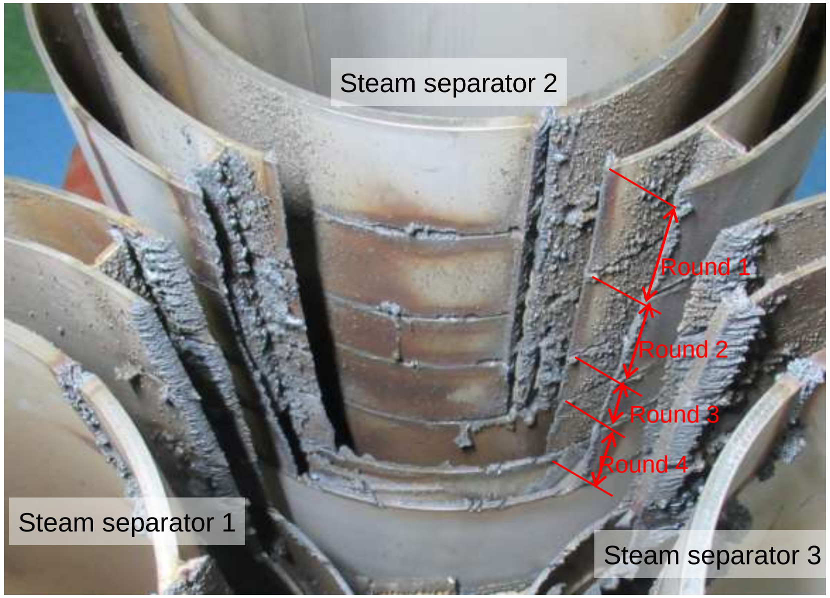


Photo ② of test pieces after 4 rounds of cutting

- The main body of the steam separator was cut into four pieces by using the angle nozzle in accordance with the cutting procedures described in the previous pages.
- To cut the steam separator body, **the angle nozzle can be applicable to vertical and horizontal cutting.**

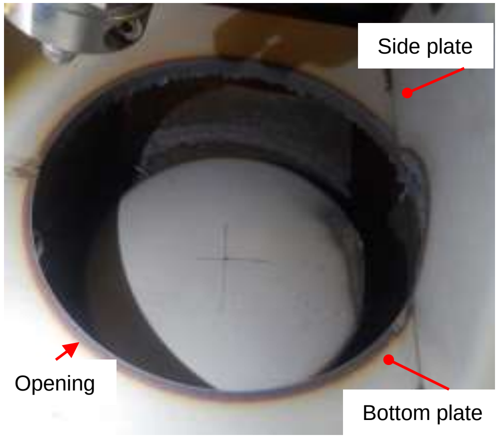
6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

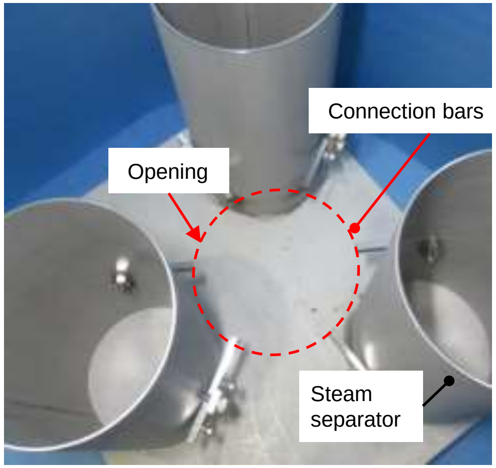
2) Implementation details for the second half of FY2021

④ Test results (laser) [mockup cutting test (10/10)]

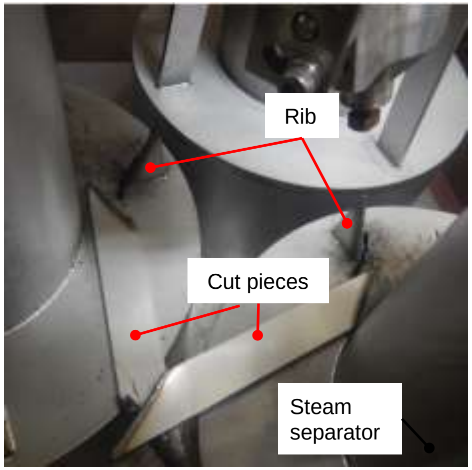
- Other treatment targets



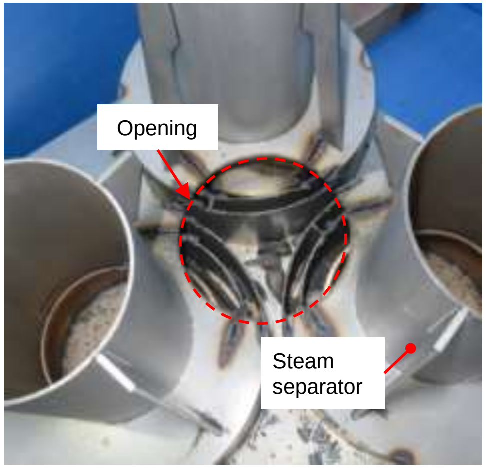
Steam dryer bottom plate



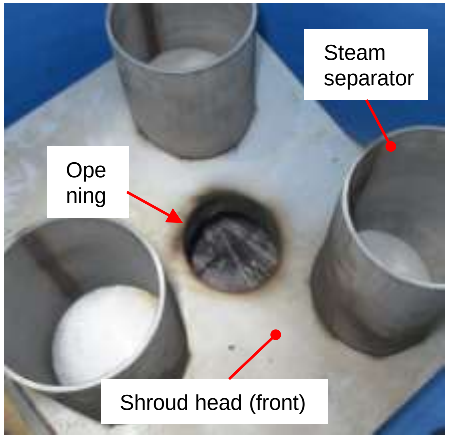
Steam separator connecting rods



Steam separator ribs



Steam separator upper surface



Shroud head

A cutting test for each nozzle was also carried out for objects to be processed other than the main body of the steam separator. It was verified that all reactor internal structures to be processed can be cut.
In addition, both the angle and straight nozzles were used for 1.5 times longer than the actual operational duration, **thus it was concluded that there are no issues concerning durability.**

6. Implementation details

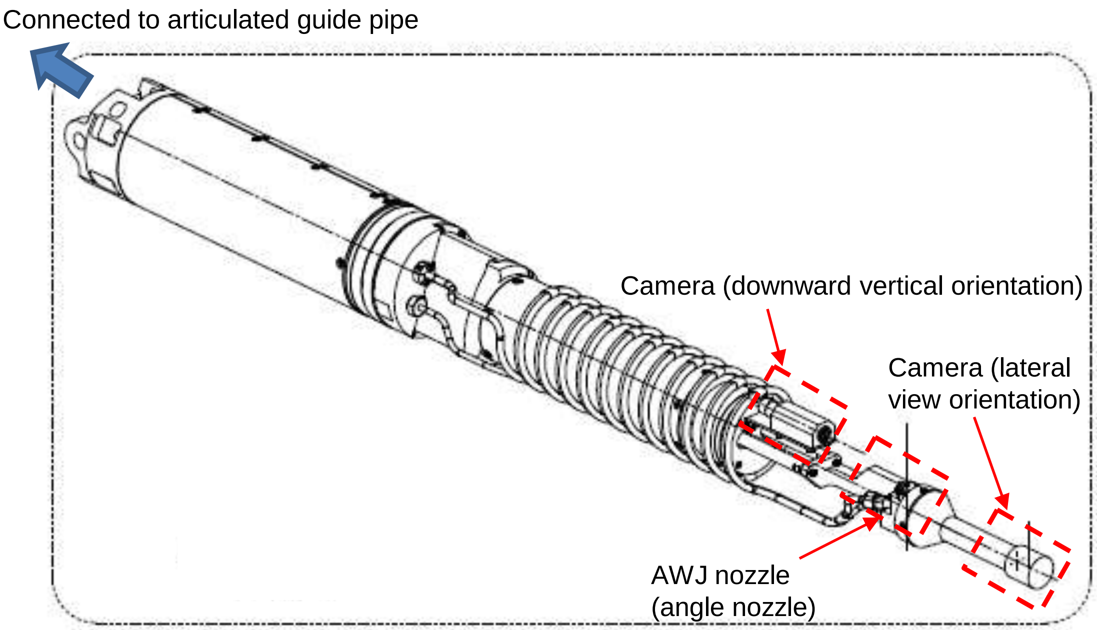
(1) Upgrading of processing technology for the top access investigation method

2) Implementation details for the second half of FY2021

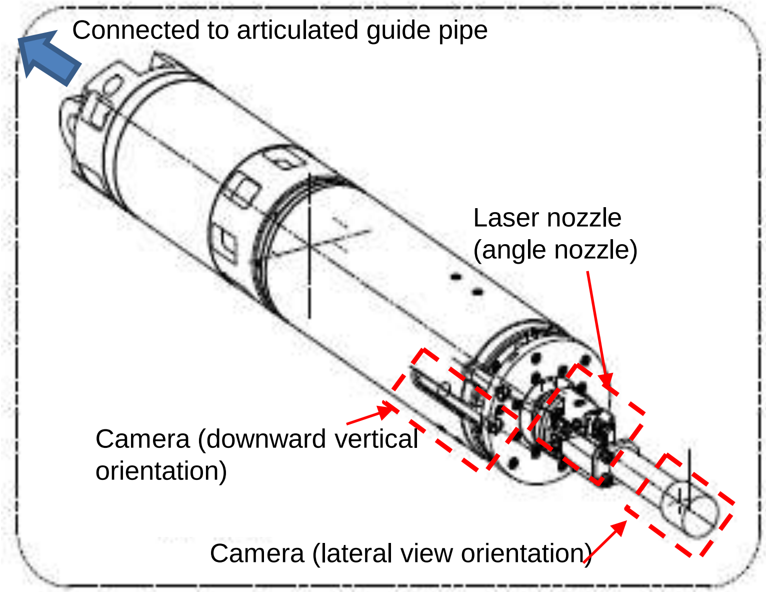
⑤ Design of actual equipment

- An element test was conducted to verify that there is no problem in cutting performance of the AWJ nozzle (angle nozzle) and laser nozzle (angle nozzle) that were designed in FY2021.

- **Designing for incorporation into actual equipment** was performed.
- Assuming actual equipment operations, **the addition of cameras to each nozzle** was examined and reflected in the design.



AWJ head (built-in angle nozzle)



Laser head (built-in angle nozzle)

6. Implementation details

(1) Upgrading of processing technology for the top access investigation method

3) Summary and future issues

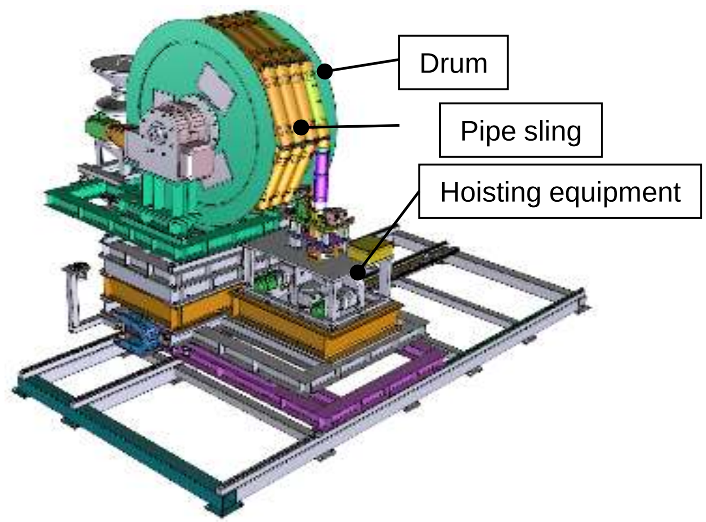
Summary

- Nozzle downsizing in FY2020 enabled a significant reduction in abrasive consumption when cutting the main body of the steam separator by AWJ (Abrasive Water Jet). In this fiscal year, study of further reduction of abrasive consumption including for cutting targets other than the main body of the steam separator was conducted. Due to reduction and optimization of the abrasive feed rate and use of the smaller FY2020 nozzles on cutting targets other than the main body of the steam separator, **the prospect of achieving the target abrasive consumption of 500 kg or less was verified through element tests.**

- Laser cutting was not applicable in FY2020 and a nozzle applicable for horizontal cutting of the steam separator main body was examined. By combining the nozzle studied in FY2020, **the operational conditions were verified to allow cutting of all targeted reactor internals.**

Issues to be addressed

No.	Major items	Intermediate items	Issues to be addressed
1	Cutting machine	AWJ cutting	- Nozzle lifetime
		Laser cutting	- Feasibility of the remote equipment, taking into account actual operational conditions
			- Incorporation into the fiber drum (*) (*):In reference to the drum, see diagram on the right.
			- Investigation or examination of slip rings for high power lasers
		Common	- Remote insertion of a cutting nozzle into narrow spaces - Verification method for the treatment target status before and after cutting
2	Ancillary operations	Common	- Treatment of cut pieces (moving)



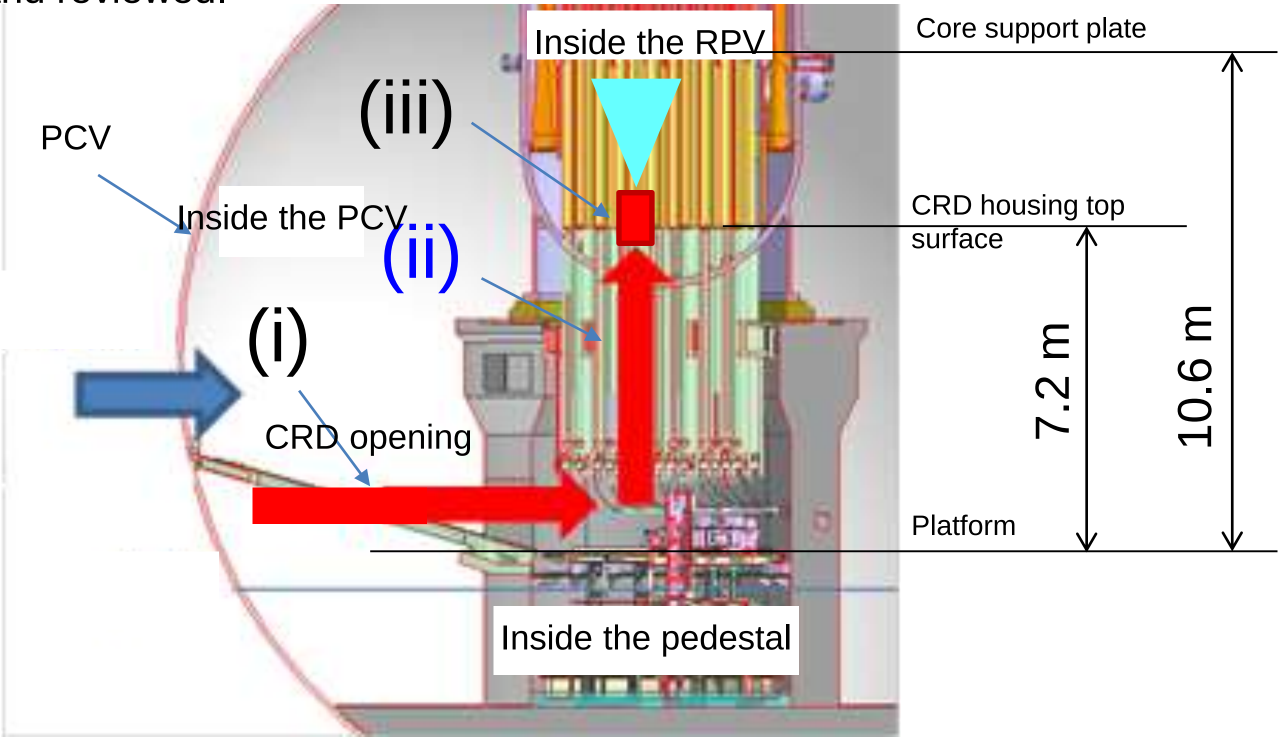
Schematic drawing of equipment for operating on reactor internals (studied in FY2019)

6. Implementation details

(2) Development of the bottom access investigation method

Definition of development items: definitions of access equipment and investigation equipment

The technology applied to RPV interior investigation method from the bottom was divided into the following three categories and reviewed.



(i) Access equipment inside the pedestal ⇒ appropriation of technology developed in other projects

(ii) Access equipment from inside the pedestal to inside the RPV ⇒ new development item

(iii) Investigation equipment ⇒ appropriation of technology developed in other projects

Based on the FY2020 study results, access equipment to inside the RPV using a drone for Unit 1 and telescopic equipment for Units 2 and 3 were identified as new development items

6. Implementation details

(2) Development of the bottom access investigation method (drone)

Unit 1: Development of drone for accessing inside RPV

<Summary of implementation in the second half of FY2021>

Element tests for wired/wireless drones were conducted to address the issues from the previous fiscal year and the studies from the first half of the fiscal year.

<Details of implementation in the second half of FY2021>

Research technology	Details of implementation	
Wired/wireless drone/ancillary system	①	Manufacturing of prototype
	②	Planning of element tests
	③	Conducting of element tests

<Results>

Wired Drone:

- Improved flight performance → Achieved target flight height of 7 m (*).
- Improved investigation performance → verified that in dark/rainy environments investigation can be performed by panning and tilting the camera.

Wireless drone:

- Improved flight performance → Achieved target flight height of 7 m (*) or more. Capable of approx. 6 minutes of continuous flight.
- Improved investigation performance → verified that in dark/rainy environments investigation can be performed by panning and tilting the camera.
- Communications verification → Based on tests and analyses, prospects of communication with the actual drone are verified.

Ancillary system:

- Cable drum → Verified electrified cable drum performance.
- Overhead view camera → Overhead camera monitored drones in flight to improve operability.

(*) For Unit 1, the distance from the platform to the top surface of the CRD housing is approx. 6.9 m, so a setting of 7 m is selected

6. Implementation details

(2) Development of the bottom access investigation method (drone)

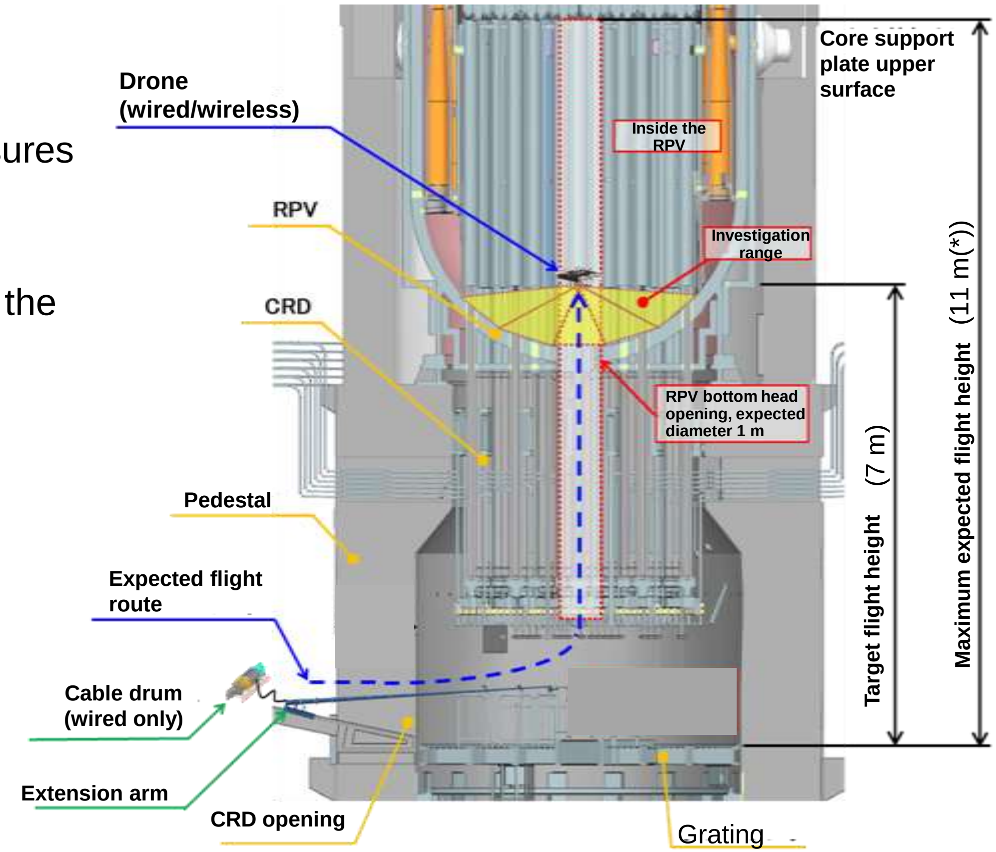
1) Summary of results through the first half of FY2021

Measures for addressing the failure to achieve the 7 m target flight height due to voltage drop in the power cable, and other issues raised in FY2020 simplified tests were considered.

In addition, other items for new verification this year were examined, including a configuration study of the actual drone and the ancillary system, and pertinent test plans were discussed.

Implementation details and results (See next page for details)

- Summary of issues and discussion of countermeasures proposed based on FY2020 test results
- Review of items to be newly verified in FY2021
- Study of actual drone and the ancillary system that the above two items were reflected
- Review of test plans to confirm proposed countermeasures and new verification items



(*) For Unit 1, the distance from the platform to the upper surface of the reactor coresupport plate is approx. 10.9 m, so a setting of 11 m is selected

Illustration of actual investigation equipment

6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021 (addressing issues from FY2020 test results)

Issues from FY2020 test results	Implementation details for the first half of FY2021	Implementation details for the second half of FY2021	Achieving goals	Wired	Wireless
Insufficient flight height due to voltage drop in the power cable	• Study of voltage drop countermeasures (High voltage cable adopted, DC-DC converter installed)	• Element test using prototype	Ability of flight at least 7 m height	Conducted	—
There were events of the drone colliding into the test system during flight and crashing	• Review of flight monitoring method (In addition to the control camera mounted on the drone, an overhead view camera is installed at the tip of the extension rod to monitor the position between the drone and the test system)	• Element test using prototype	Ability of operating the drone without test system collisions by monitoring with an overhead view camera.	Conducted	Conducted
Difficulty in investigation for the bottom of RPV due to drone turning movements	• Addition of a pan/tilt camera to the underside of the drone for investigation purposes considered (Investigation by drone turning movements is not implemented)	• Element test using prototype	Ability of covering the scope of investigation inside the RPV bottom by keeping the drone within a diameter of 1 m in the RPV opening and panning and tilting the survey camera.	Conducted	Conducted
Insufficient flight time relative to target flight time	• Consideration of flight time extension (Increased battery capacity, more batteries installed, etc.)	• Element test using prototype	- Based on measurements of investigation duration, review of target duration of 10 minutes - Evaluation of flight time against reset target time	—	Conducted
Study of radio wave communication verification test	• Examination of communication verification method	• Verification test of communication acceptability threshold • Analysis of radio wave strength inside the pedestal and RPV	Ability of determining the transceiver setting position from the communication acceptability threshold and radio wave strength analysis.	—	Conducted

6. Implementation details

Unit 1

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021 (implementation items added in FY2021)

Additional implementation items	Implementation details in FY2021	Wired	Wireless
Combined wired drone cable	Test manufacturing of composite cable for operation system, power, and camera	Conducted	—
Cable drum electrification	Test manufacturing of motor-driven cable drum	Conducted	—
Evaluation of radiation resistance	Irradiation testing at the drone component level	Conducted	Conducted
Dark environment effects	Flight test in a dark environment	Conducted	Conducted
Rainy environment effects	Flight test in a rainy environment	Conducted	Conducted
Verification of the scope of investigation	Investigation scope verification test by survey camera operation	Conducted	Conducted
Verification of minimum flight space	Minimum flight space verification test	Conducted	Conducted

6. Implementation details

(2) Development of the bottom access investigation method (drone)

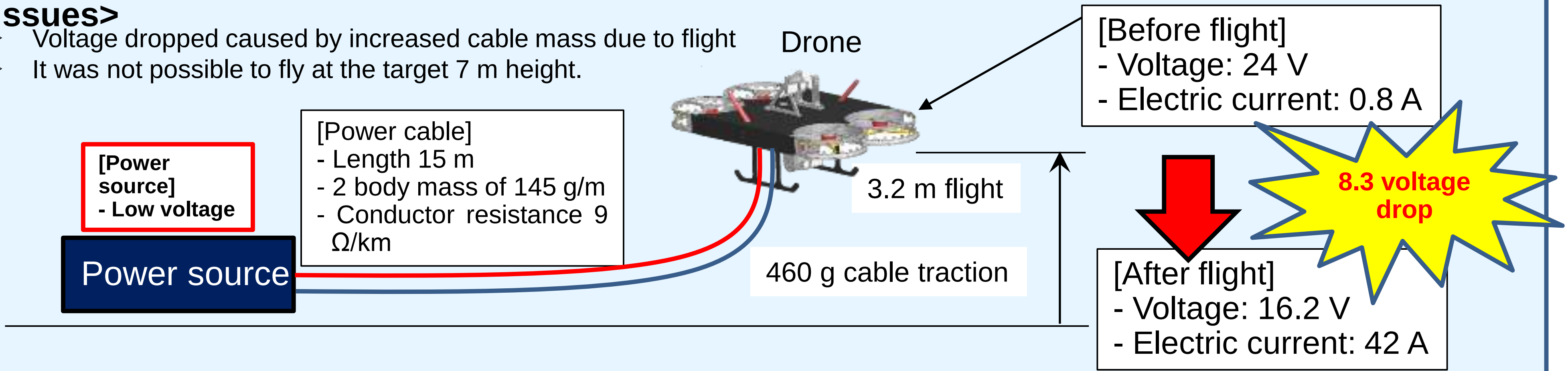
2) Implementation details for the second half of FY2021

① Manufacturing of improved prototype (1/3)

(Countermeasures for voltage drop of power cable/wired drone)

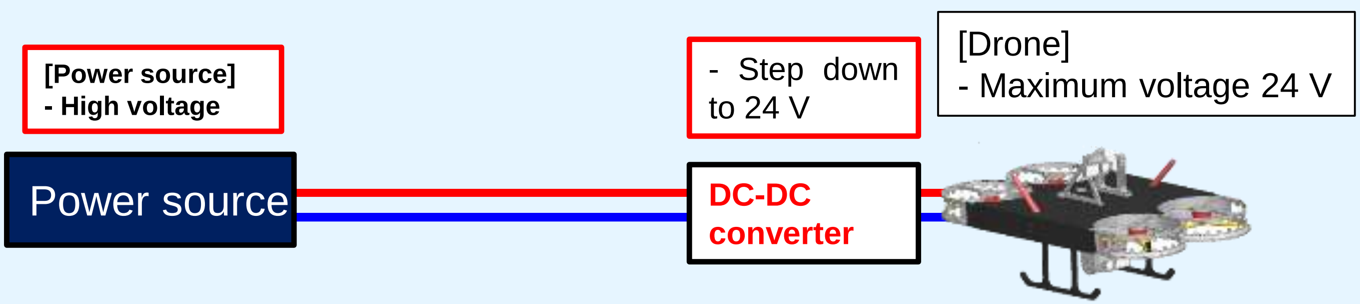
<Issues>

- Voltage dropped caused by increased cable mass due to flight
- It was not possible to fly at the target 7 m height.



<Countermeasures>

- The voltage of the power source was increased and decreased just before the drone.
- A step-down converter **(DC-DC converter) was installed in the drone**



6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

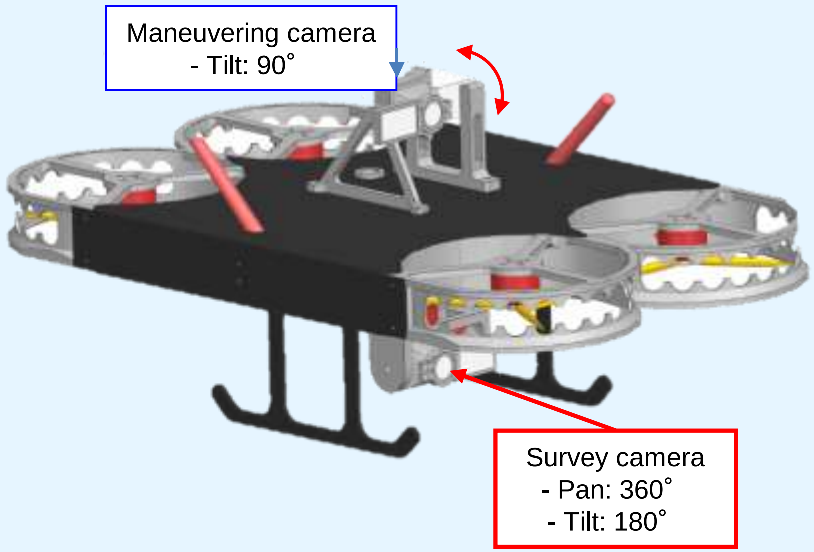
① Manufacturing of improved prototype (2/3) (**Countermeasures for turning performance/common to wired and wireless drones)**

<Issues>

- It was not possible to turn over within the expected Φ1 m of the RPV opening.
- It was not possible to investigate around 360° circumference of the RPV bottom.

<Countermeasures>

- A pan/tilt survey camera was attached to the underside of the drone
- Pan and tilt operations were used to investigate the inside of the RPV bottom, and drone turning operations were discontinued.



Drone survey camera installation position

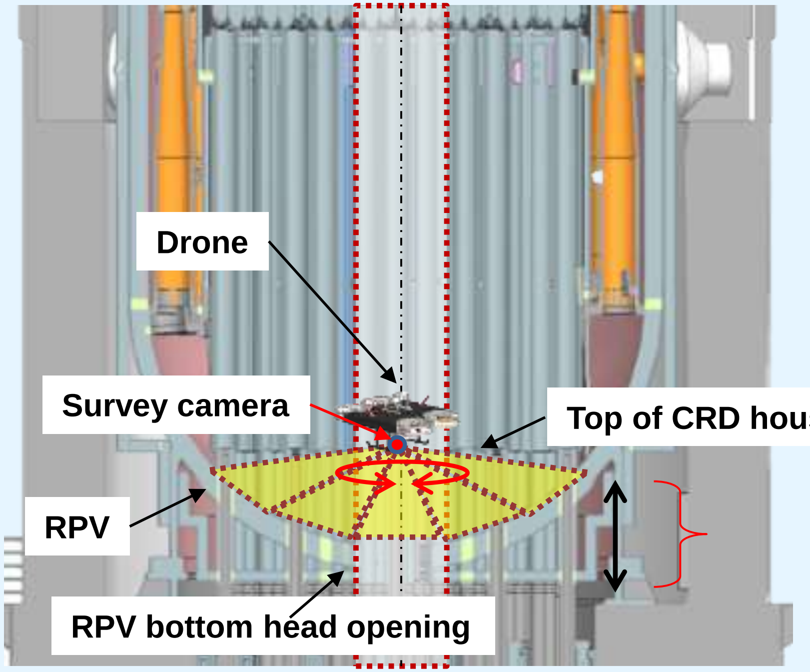


Illustration of RPV bottom investigation

6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

① Manufacturing of improved prototype (3/3)

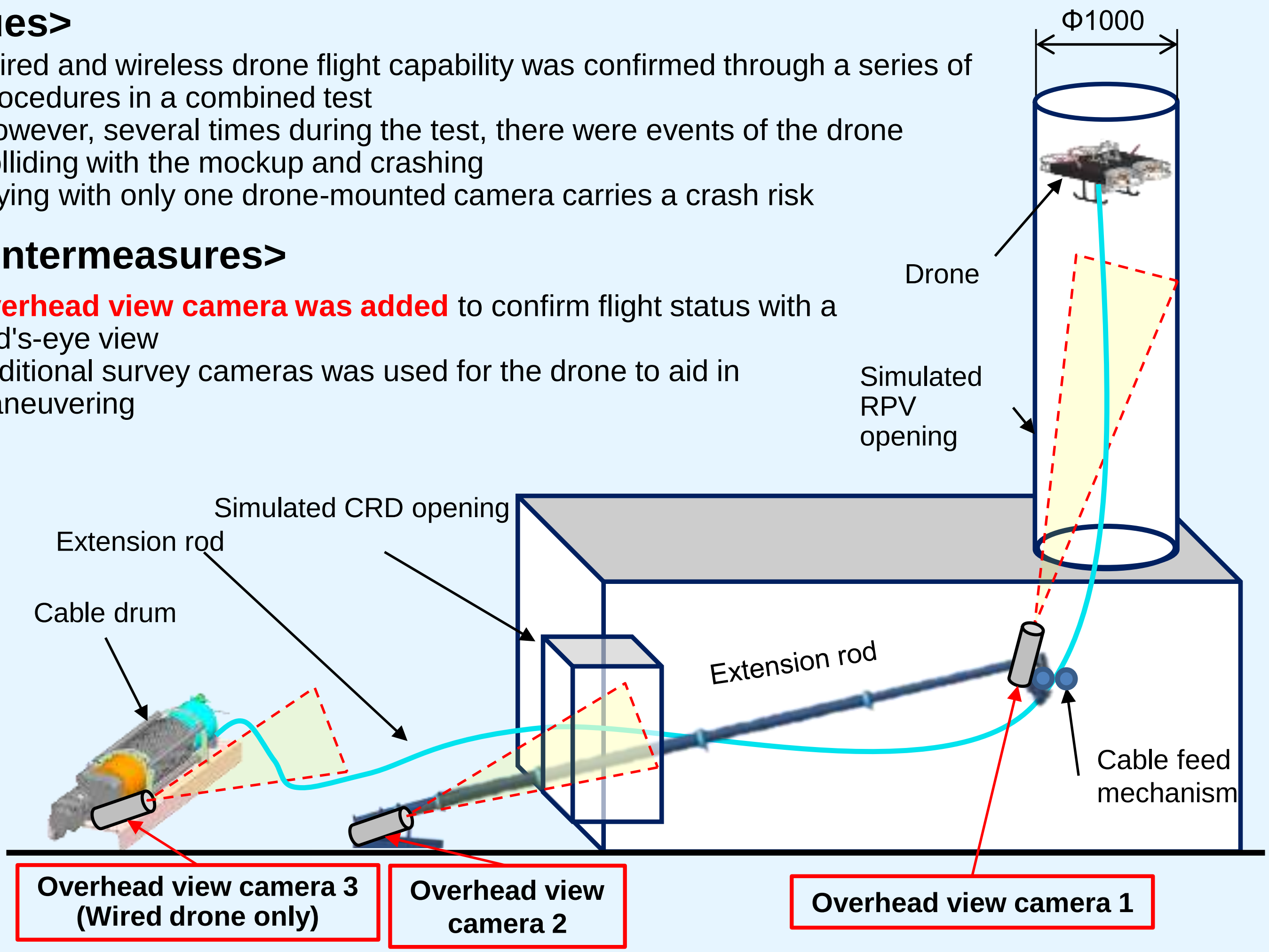
(Countermeasures for operability: common to wired and wireless drones)

<Issues>

- Wired and wireless drone flight capability was confirmed through a series of procedures in a combined test
- However, several times during the test, there were events of the drone colliding with the mockup and crashing
- Flying with only one drone-mounted camera carries a crash risk

<Countermeasures>

- **Overhead view camera was added** to confirm flight status with a bird's-eye view
- Additional survey cameras was used for the drone to aid in maneuvering



Drone overhead view camera installation position

Example picture from overhead view camera image 1

Example picture from overhead view camera image 2

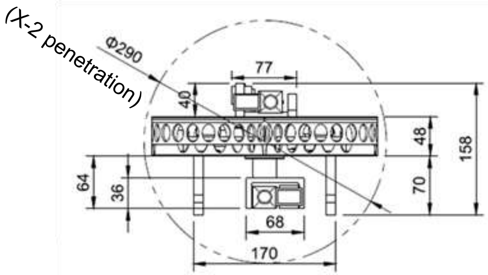
Example picture from overhead view camera image 3

6. Implementation details

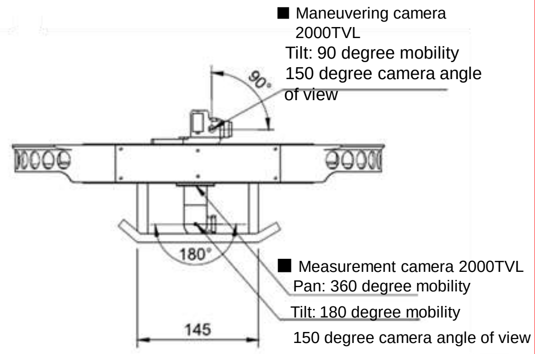
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

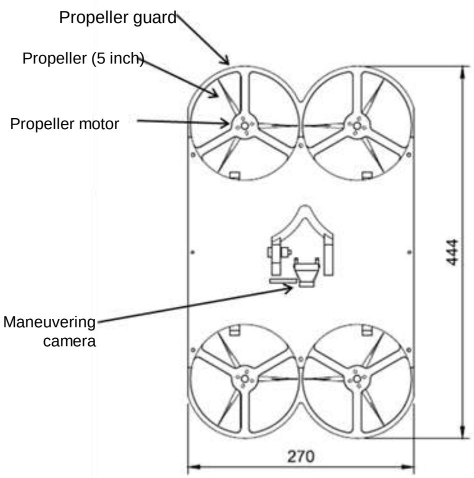
② Drone configuration (Exterior view of FY 2021 wired drone prototype)



Front view



Side view



Top view

[Main differences from the actual equipment plan]

- Φ20 camera (built-in LED) not installed (Commercial camera and external LED lighting substituted)
- Dosimeter not installed
- Connector integration

⇒ Adding weight of mass difference of the above stated value does not result in any issues

- Omission of fiber-optic dosimeter cable from composite cable

⇒ The fiber-optic cable is lightweight (0.04 g/m) and the protective PEEK tube is quite rigid, so there are no problems in the flight test

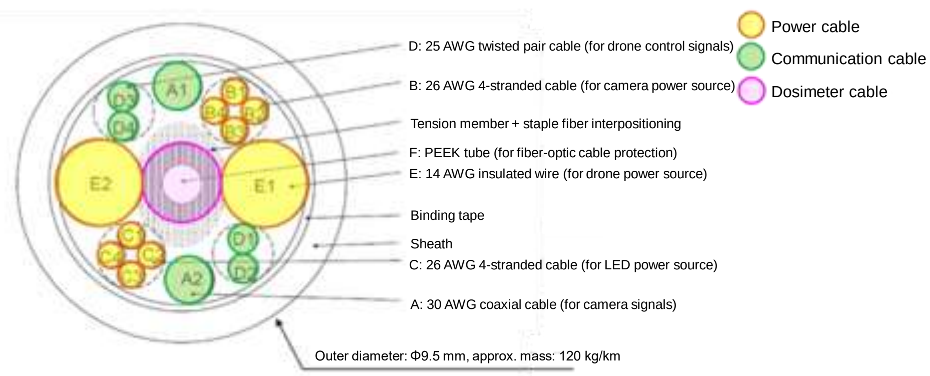


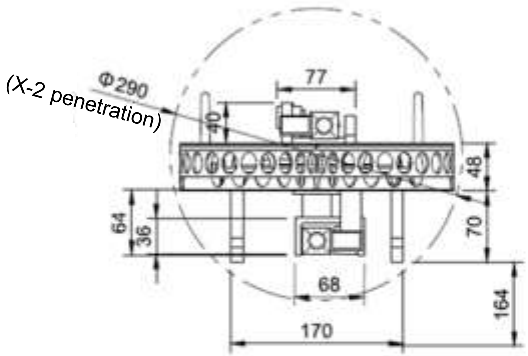
Illustration of composite cable arrangement

6. Implementation details

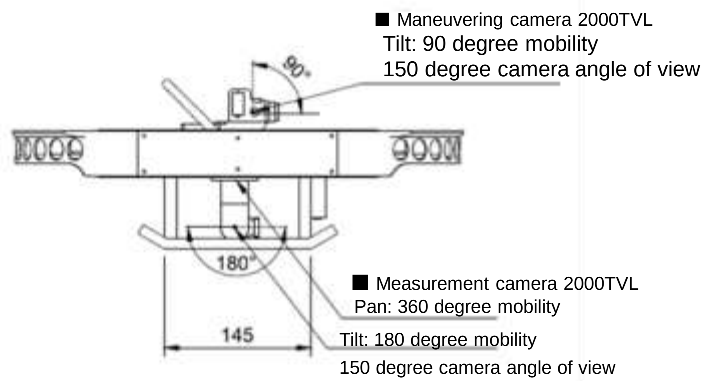
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

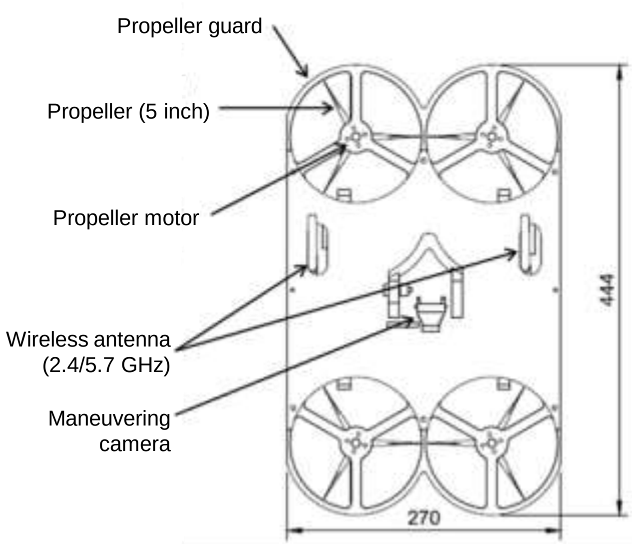
② Drone configuration (Exterior view of FY2021 wireless drone prototype)



Front view



Side view



Top view

[Main differences from the actual equipment plan]

- Φ 20 camera (built-in LED) not installed
  (Commercial camera and external LED lighting substituted)
- Dosimeter not installed

⇒ Adding weight of mass difference of the above stated value does not result in any issues

6. Implementation details

Unit 1

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

③ Test plan (test items)

Test No.	Test classification		Test item	Test purpose	Wired	Wireless
1	Stand-alone performance test	Flight performance test	Flight height verification test	Verification of target flight height (7 m) capability/maximum flight height	Conducted	Conducted
2			Continuous flight time verification test	Verification of continuous flight time	-	Conducted
3			Flight travel time verification test	Verification of flight time from X-2 penetration to CRD opening	-	Conducted
4			Minimum flight space verification test (vertical/horizontal directions)	Verification of the minimum dimensions of passable horizontal and vertical openings	Conducted	Conducted
5		Visual performance test	Verification tests of the investigation (normal)	Verification of the scope of investigation under normal environmental conditions	Conducted	Conducted
6			Verification tests of the investigation (darkness)	Verification of the scope of investigation in a dark environment	Conducted	Conducted
7			Verification tests of the investigation (rainfall)	Verification of the scope of investigation in a rainy environment	Conducted	Conducted
8		Ancillary system test	Cable drum performance verification test	Verification of feeding/winding mechanism and random winding prevention function	-	-
9			Cable drum and extension arm combined performance verification test	Verification of the functional linkage between the cable drum and the cable feeding/winding mechanism at the extension arm tip	-	-
10	Combined test	Once-through test	Once-through test (normal)	Verification of the functions of equipment under normal environmental conditions via a series of investigation procedures, and formulation of final investigation procedure	Conducted	Conducted
11			Once-through test (darkness)	Verification of the functions of equipment in a dark environment via a series of investigation procedures, and formulation of final investigation procedure	Conducted	Conducted
12			Once-through test (darkness + rainfall)	Verification of the functions of equipment in a dark and rainy environment via a series of investigation procedures, and formulation of final investigation procedure	Conducted	Conducted
13	Others	Radiation resistance test	Irradiation test	Verification of radiation resistance of each component	Conducted	Conducted
14		Communication performance test	Threshold verification test	Verification of transmitted and received power thresholds for maneuvering/video system wireless equipment	-	Conducted
15			Radio wave propagation analysis	Verification of electric field strength distribution of maneuvering/video system wireless radio waves in actual equipment system	-	Conducted

6. Implementation details

(2) Development of the bottom access investigation method (drone)

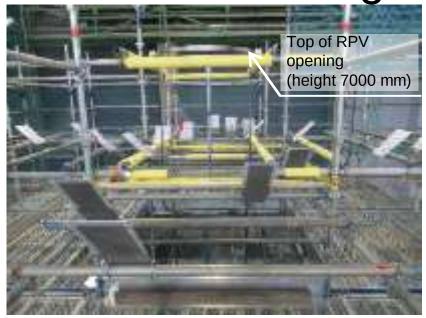
Unit 1

2) Implementation details for the second half of FY2021

③ Test plan (test facility)

: Overview of mockup facility

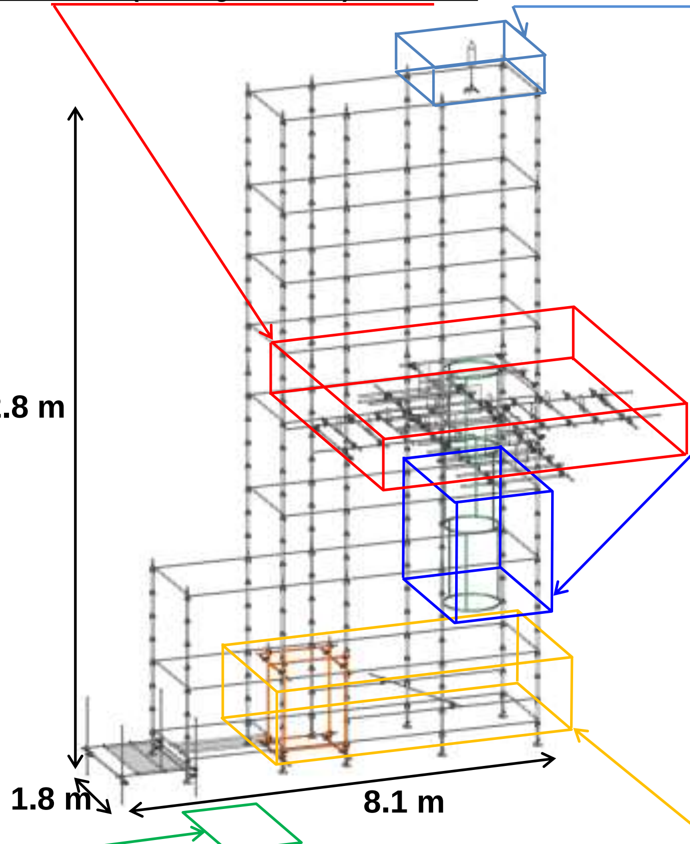
Exterior view of mockup facility

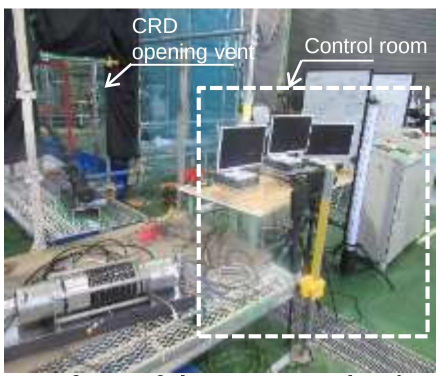


RPV interior (investigation area) simulation

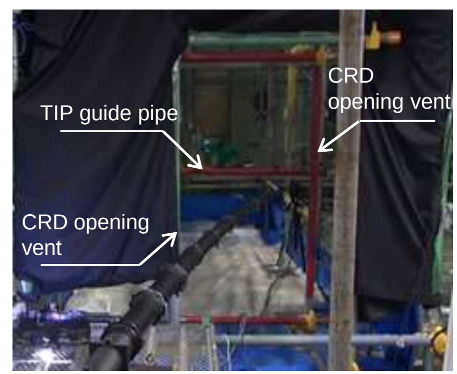
Rainfall (dripping water) simulation

Simulated RPV opening





In front of the CRD opening / Simulated control room



CRD opening / TIP guide pipe simulation

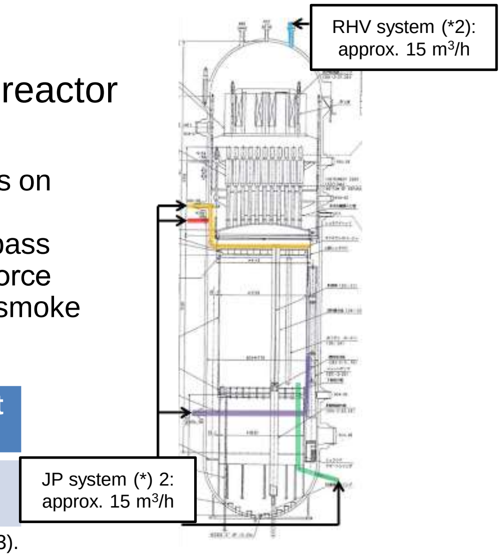
Front view of mockup facility

6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

③ Test plan (test environment): Simulability of nitrogen and water injection into actual reactor



Nitrogen injection location in RPV

1. The effects of nitrogen (wind) injection
   1) The distance between the drone survey location and the nitrogen outlet is large enough to preclude impacts on drone flight.
   2) The wind velocity conversion value at the RPV bottom opening, assuming that all of the injected nitrogen pass through, is 0.02 m/s. A wind speed of 0.02 m/s corresponds to "wind scale 0 (calm)" in the Beaufort wind force scale, which is an index of the Japan Meteorological Agency. This is an environmental condition in which smoke rises straight up, and is not expected to affect drone flight.

Wind velocity conversion

Nitrogen injection volume (*1)	Expected dimensions of RPV bottom opening	Wind velocity conversion value at RPV bottom opening
Normal: 30 m^3/h, Maximum: 50 m^3/h	Diameter: Φ1 m, cross-sectional area: 0.785 m^2	0.02 m/s

(*1) Operational upper limit (limited by flow rate meter range, common to Units 1 to 3).
(*2) Quoted from the plant operational parameters on the TEPCO website.

Due to the above considerations, wind conditions due to nitrogen injection are not taken into account in this test.

2. The effects of water injection (rainfall)
   1) The amount of water injection into the reactor is equivalent to 189.8 mm/h of rainfall water conversion value in the Reactor Pressure Vessel, which corresponds to "heavy rain (80 mm/h or more)" according to the Japan Meteorological Agency's index.
   These precipitation conditions are the environmental condition in which umbrellas are completely useless, making drone flight difficult.
   2) As a countermeasure, suspension of water injection is proposed during the investigation. In the 2019 water injection test for Unit 1, water injection was suspended for 49 hours without any issues. However, even when water injection is suspended, water dripping from the wet structure continues to be an environmental condition.
   3) Therefore, this test is conducted in a dripping water environment, and the drip rate is set at 100 cc/min. When reviewing the video during the investigation inside the Unit 2, it was verified that the drip rate was acceptable: 100 cc/min, similar to the drip rate in this test. In addition, the drone should be designed to withstand dripping water.

Rainfall volume conversion

Reactor water injection amount (*3)	Reactor pressure vessel	Rainfall volume conversion value inside the Reactor Pressure Vessel
Feedwater system: 2.0 m^3/h, Cesium (CS) system: 1.4 m^3/h → Total: 3.4 m^3/h	Inner diameter: Φ4.775 m, Cross-sectional area: 17.91 m^2	189.8 mm/h

Based on the above considerations, this test was conducted with the condition of dripping water (drip rate: 100 cc/min, equivalent to rainfall of 8 mm/h).

6. Implementation details

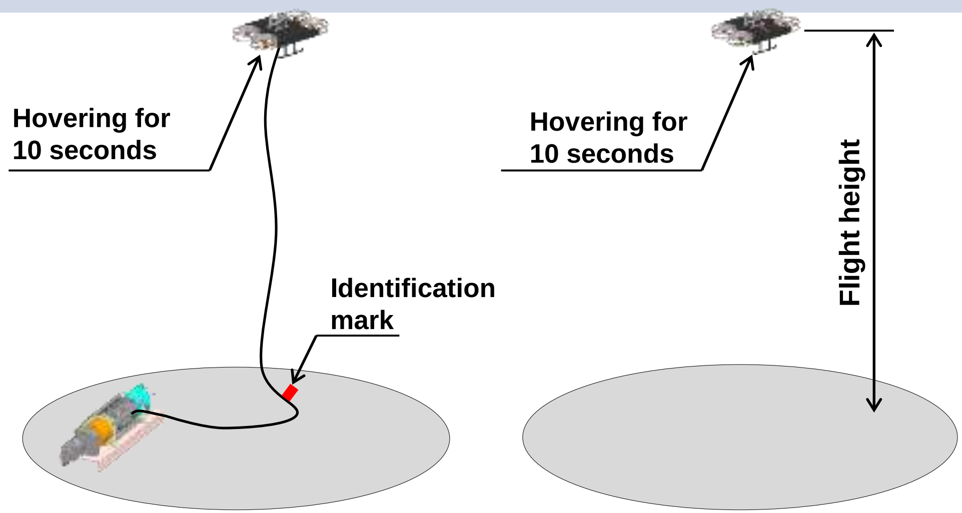
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test results (Test No.1: Flight height verification test)

Test purpose	Test details	Test methods	Test results	
			Wired drone	Wireless drone
Verification of target flight height (7 m) capability/maximum flight height	① The ability of the target flight height of 7 m was verified by the flight test. ② A maximum flight height was verified by the flight test.	① For the wired drone, the composite cable (15 m) is marked, and the drone is raised. ② For the wireless drone, the flight height is marked on the test facility, and the drone is raised. ③ After the drone rises, if it can hover for 10 seconds at each arrival point, it is deemed capable of flight.	① Target flight height of 7 m was possible. ② Although the maximum flight height was 9 m, there was a case in which the drone lost control and crashed due to a rise in ESC (*1) temperature when flying at 9 m. Therefore, 8 m is considered the actual flight height limit.	① Target flight height of 7 m was possible. ② Capable of flying up to a maximum expected flying height of 11 m (*2).

(*1) Abbreviation of Electric Speed Controller. Part that controls drone motor speed.
(*2)Core support plate upper surface position: A target of 11 m (exceeding approx. 10.9 m) was set.



Wired drone

Wireless drone

Overview of the test

[Wired drone]

[Wireless drone]

Test conditions

6. Implementation details

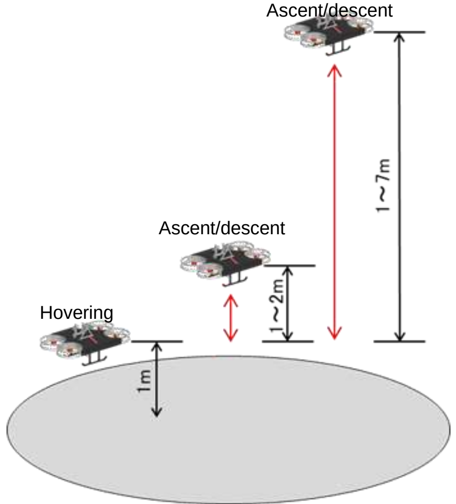
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

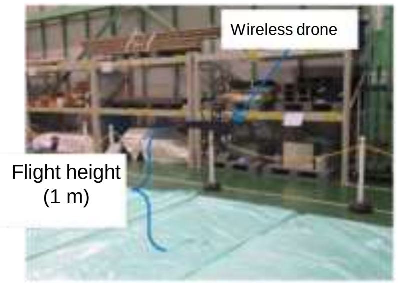
④ Test results (Test No. 2: Continuous flight time verification test)

Test purpose	Test details	Test methods	Test results
			Wireless drone
Verification of continuous flight time	The available flight time using selected battery is verified by flight test.	① The flight time until landing caused by running out the battery (3500 mAh x 2 units) was verified. The flight state should be hovering or repeated ascent/descent. ② As a reference data, the battery of 4600 mAh x 2 units (*1) was also verified.	[Flight time] (*2): - Hovering: 5 minutes 48 seconds (8 minutes 54 seconds) - Repeated ascent/descent (1 to 2 m): 6 minutes 4 seconds (8 minutes 49 seconds) - Repeated ascent/descent (1 to 7 m): 5 minutes 57 seconds (8 minutes 51 seconds) → Average 5 minutes 56 seconds. [Number of round trips]: - Repeated ascent/descent (1 to 2 m): 31.5 times (49.5 times) - Repeated ascent/descent (1 to 7 m): 16.5 times (26.0 times) Figures in parentheses are results of 4600 mAh x 2 units, and for reference only

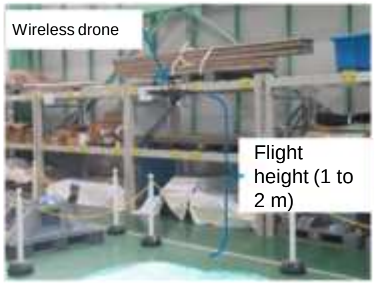
(*1) This values is a reference, as the 4600 mAh battery was too large for the drone cover to shut completely.
(*2) The lack of a large impact of flight form on continuous flight duration can be attributed to smooth maneuvering, with no sudden ascent or descent.



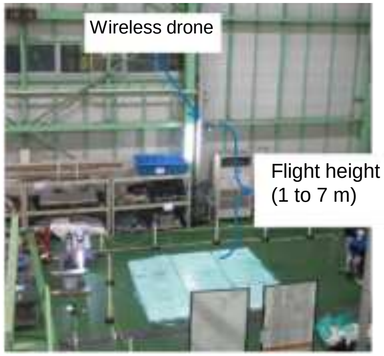
Overview of the test



[Hovering]



[Ascent/descent (1 to 2 m)]



[Ascent/descent (1 to 7 m)]

Test conditions

6. Implementation details

Unit 1

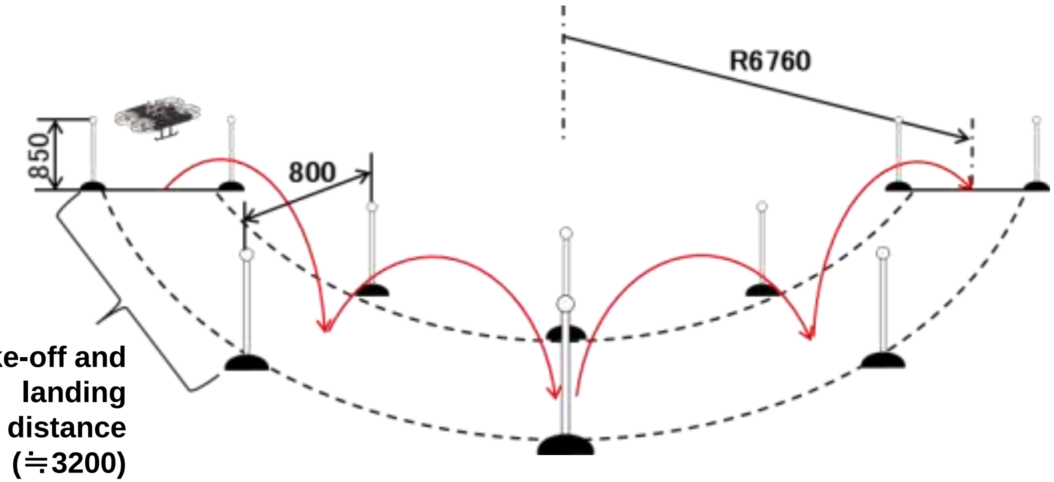
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

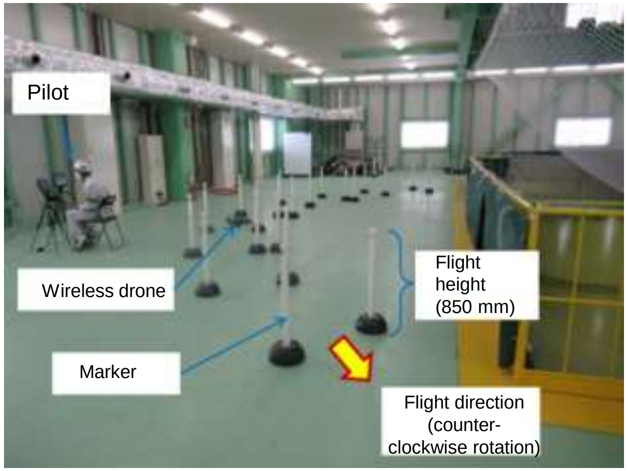
④ Test results (Test No.3: Flight travel time verification test)

Test purpose	Test details	Test methods	Test results Wireless drone
Verification of flight time from X-2 penetration to CRD opening	After installing through the PCV penetration, the time and battery consumption were verified when moving to the CRD opening are verified by the flight test.	The drone flies while taking off and landing at equal intervals between markers that simulate the route from the X-2 penetration to the CRD opening to verify the flight time and battery consumption from takeoff to landing.	① Flight time: (average) 1 minute 08 seconds (*1) ② Battery A consumption 7.3% / Battery B consumption: 6.7%: (average) 7% (*2) (The wireless drone is equipped with two batteries of the same type, which are referred to as battery A and battery B for convenience.)

(*1) One-way value for X-2 penetration to CRD opening. In the case of a round trip with the return trip taken into consideration, the flight time is 2 minutes and 16 seconds.
(*2) One-way value for X-2 penetration to CRD opening. In the case of a round trip with the return trip taken into consideration, battery consumption is 14%.



Overview of the test



Conditions of the test

6. Implementation details

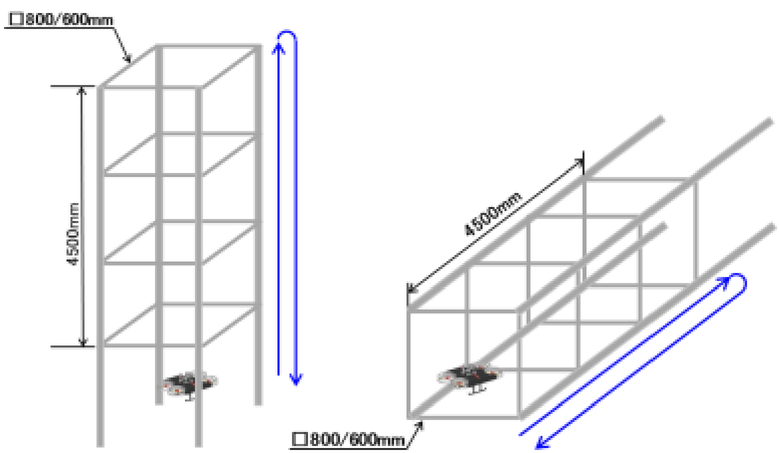
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test results (Test No.4: Minimum flight space verification test (vertical/horizontal directions))

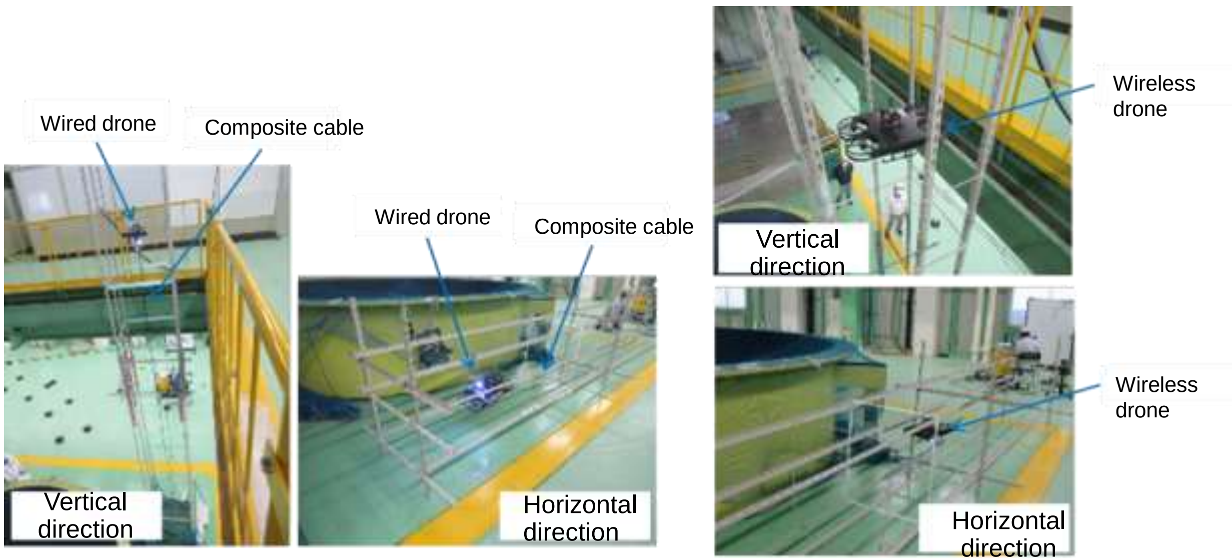
Test purpose	Test details	Test methods	Test results	
			Wired drone	Wireless drone
Verification of the minimum dimensions of passable horizontal and vertical openings	Vertical or horizontal flight inside the mock-up facility was verified.	① Flight performance of a round-trip flight from the bottom to the top of the inside of a 4.5 m long rectangular mockup facility with a □800 mm opening is verified. ② If the □800 mm opening can be passed, a modified test with a □600 mm opening is conducted. ③ The mockup is laid on its side to verify dimensions of the mockup that flight is possible.	□800 mm - Vertical: passable (*1) - Horizontal: passable □600 mm - Vertical: passable (*1) - Horizontal: passable	□800 mm - Vertical: passable (*1) - Horizontal: passable □600 mm - Vertical: not passable - Horizontal: passable

(*1) Although the drone passed through, there were instances when it lightly brushed against the mockup or protruded outside of flight path boundaries.



Vertical direction Horizontal direction

Overview of the test



Test conditions

6. Implementation details

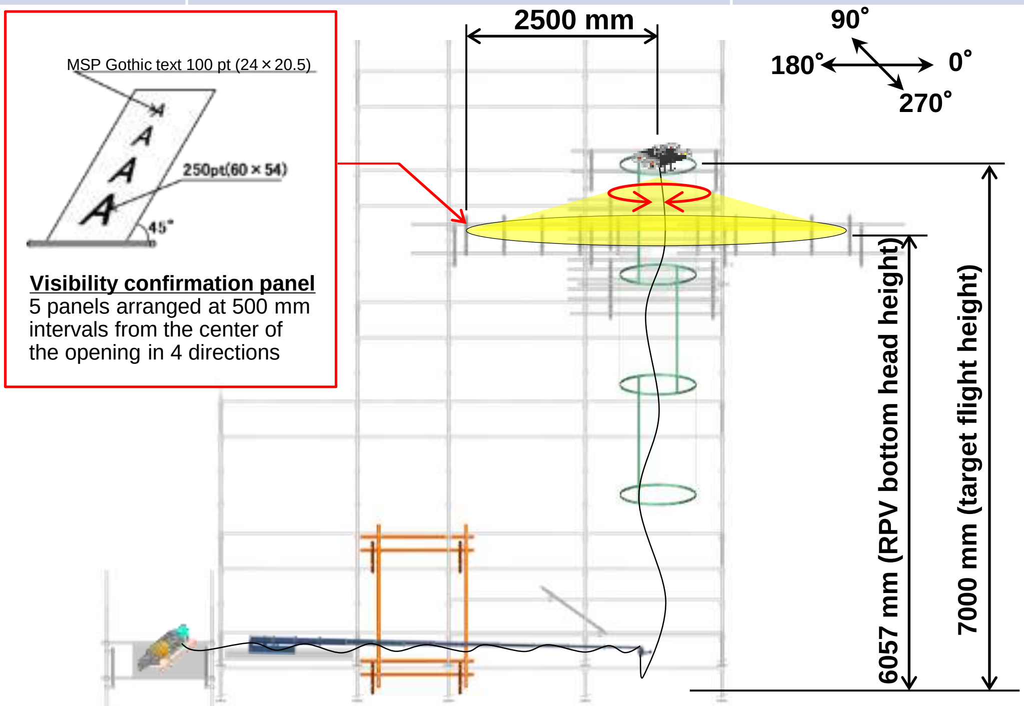
Unit 1

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

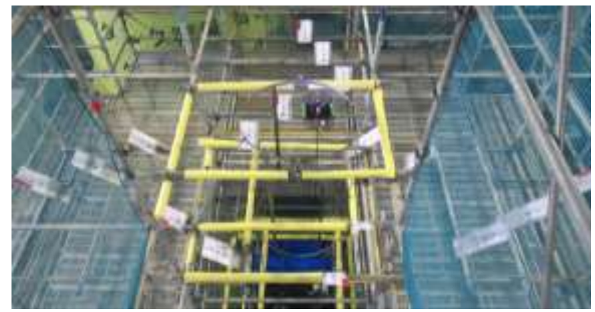
④ Test results (test No. 5, 6, 7: Verification tests of the investigation (normal, dark, rainfall))

Test purpose	Test details	Test methods
Verification of the scope of investigation (under normal/dark/rainy conditions)	The visibility range in a test facility that simulated the bottom of the RPV was verified while the drone maintained hovering and operating the pan tilt camera.	① In order to verify the visibility range, visibility confirmation panels are placed around the test facility of height equal to the RPV bottom, and the visibility range is verified while the drone maintains hovering at 7 m target height by operating the pan tilt camera. ② The three patterns of conditions are implemented in (1) normal, (2) dark, and (3) rainy environmental conditions.

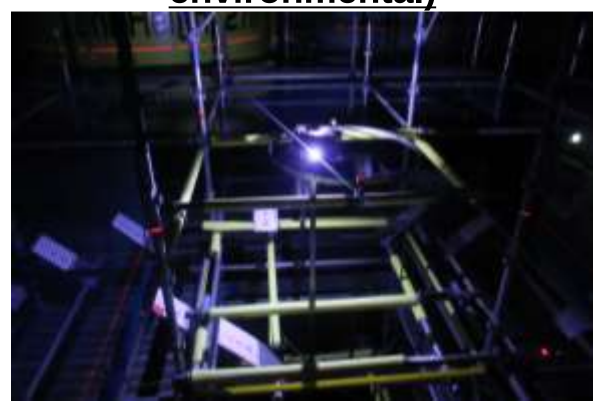


Remarks:
- For wireless, no cable drum or composite cable
- The dark environmental condition is simulated by turning off nearby lightings at night
- The rainy environmental condition (dripping water) is simulated by dripping water at 100 cc/min from the water dripping jig

Overview of the test



Test conditions (normal environmental)



Test conditions (dark environment)

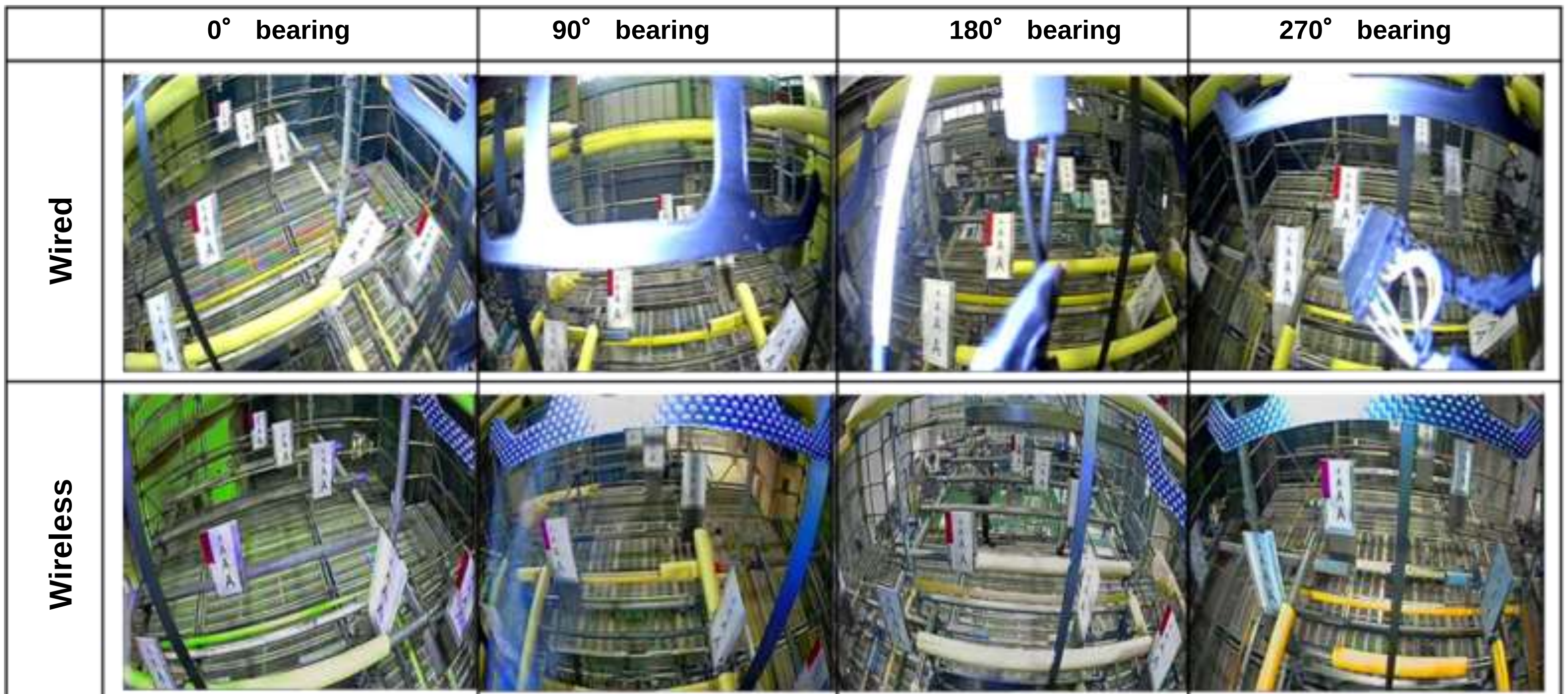
6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test results (Test No. 5: Verification tests of the investigation (normal))

Test results	
Wired drone (*1)	**Wireless drone (*2)**
① The observation of character shapes were verified at a panel position of 2500 mm. ② The smallest characters were clearly identified at a panel position of 1000 mm.	① The observation of character shapes were verified at a panel position of 2500 mm. ② The smallest characters were identified at a panel position of 1000 mm.
(*1) Composite cables obstruct visibility and can make it difficult to verify panels, so cable treatment is an issue. (*2) Interference from wireless radio waves can cause intermittent noise in the video feed, and video quality is inferior to that of wired systems.	



Survey video (normal environment)

6. Implementation details

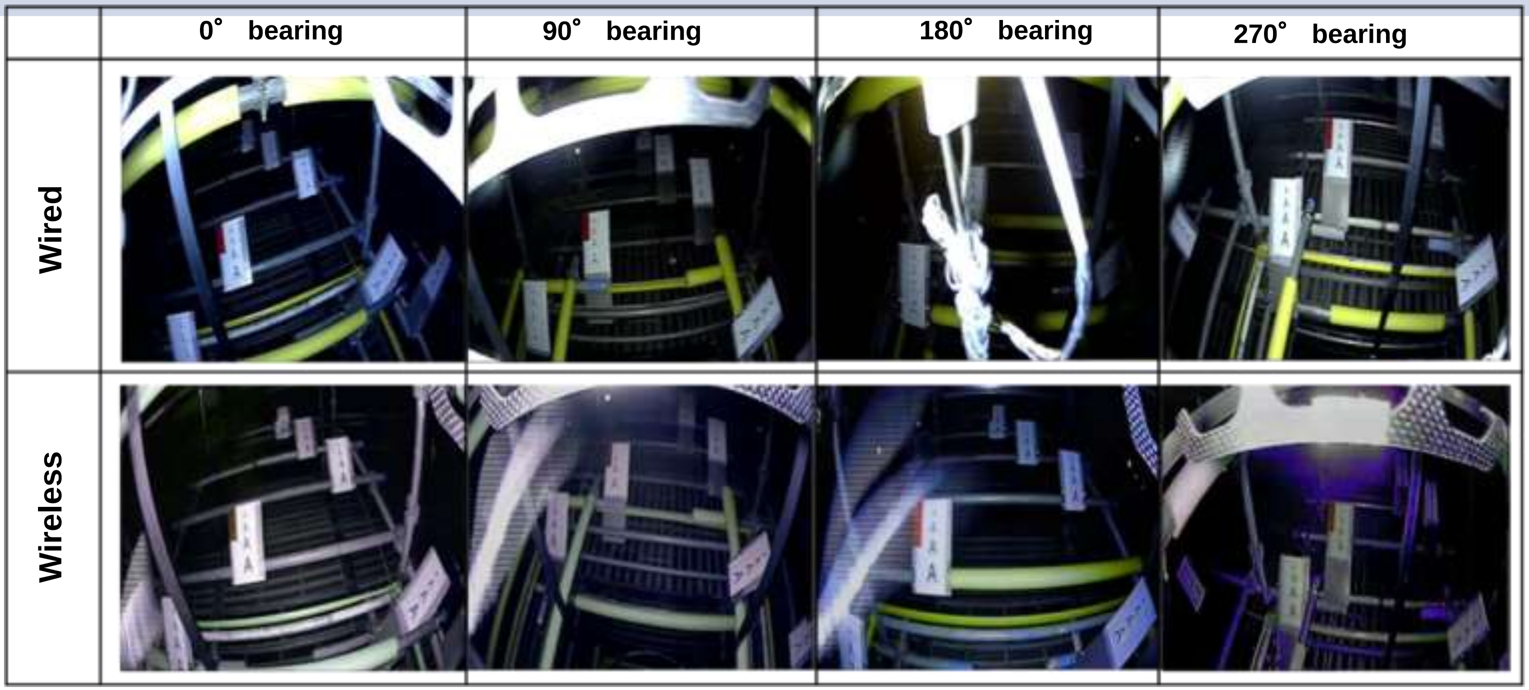
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test results (Test No. 6: Verification tests of the investigation (darkness))

Test results	
Wired drone (*1, 2)	**Wireless drone (*3)**
① The observation of character shapes were verified at a panel position of 2500 mm. ② The smallest characters were clearly identified at a panel position of 1000 mm.	① The observation of character shapes were verified at a panel position of 2000 mm. ② The shape of the panel itself was verified at a panel position of 2500 mm.

(*1) Composite cables obstruct visibility and can make it difficult to verify panels, so cable treatment is an issue.
(*2) LED lighting sometimes reflected off the drone's legs and composite cables, negatively impacting visibility.
(*3) Interference from wireless radio waves can cause intermittent noise in the video feed, and video quality is inferior to that of wired systems.



Survey video (dark environment)

6. Implementation details

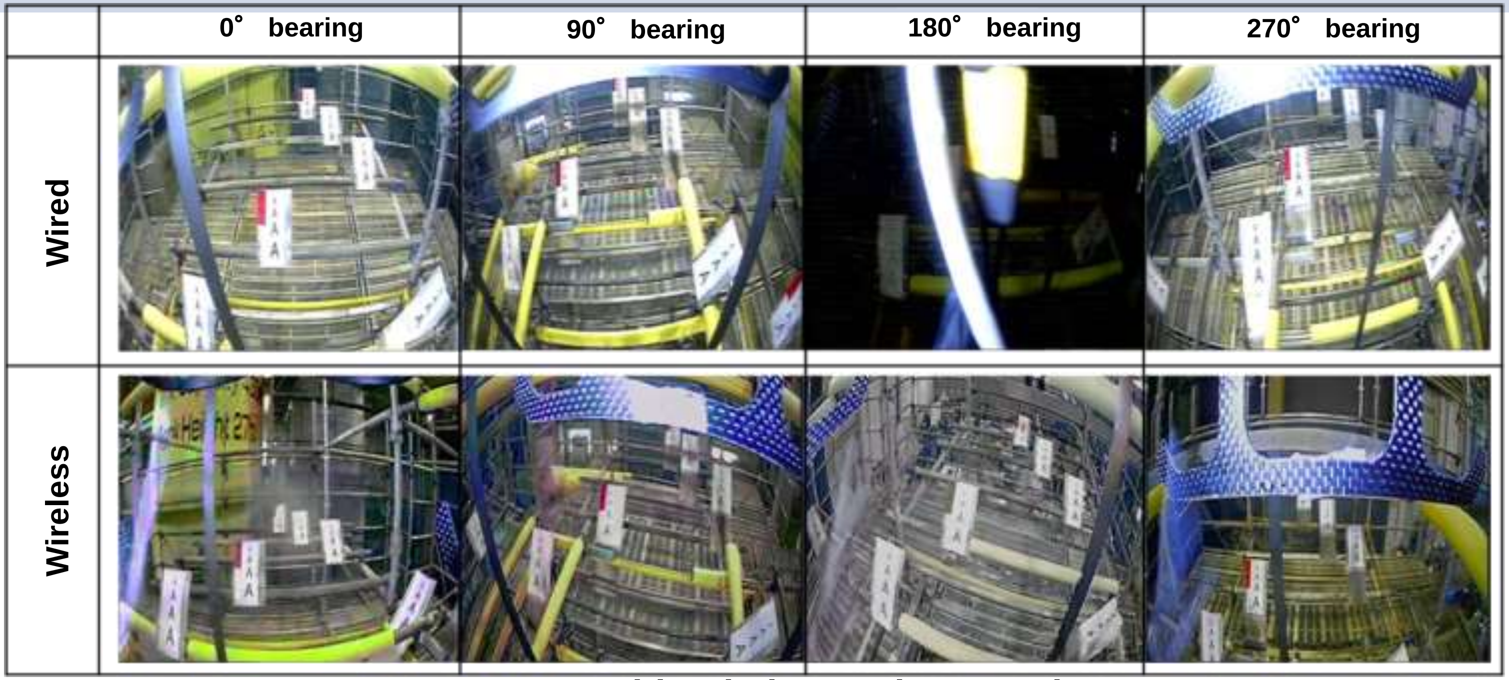
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test results (Test No. 7: Verification tests of the investigation (rainfall))

Test results	
Wired drone (*1, 3)	**Wireless drone (*2, 3)**
① The observation of the character shapes was verified at a panel position of 2500 mm. ② The smallest characters were clearly identified at a panel position of 1000 mm.	① The observation of the character shapes was verified at a panel position of 2500 mm. ② The smallest characters were identified at a panel position of 500 mm.

(*1) Composite cables obstruct visibility and can make it difficult to verify panels, so cable treatment is an issue.
(*2) Interference from wireless radio waves can cause intermittent noise in the video feed, and video quality is inferior to that of wired systems.
(*3) Since the survey camera is mounted on the bottom of the drone, water dripping from the top had virtually no impact.



Survey video (rainy environment)

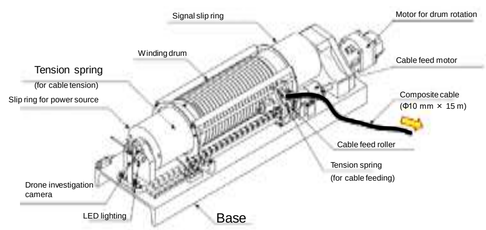
6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test results (Test No.8/9: Cable drum performance verification test/Cable drum and extension arm combined performance verification test)

Test item	Test purpose	Test details	Test methods	Test results
Cable drum performance verification test	Verification of feeding/winding mechanism and random winding prevention function	① The ability of feeding/winding was verified. ② The irregular winding during feeding/winding was verified.	① Feed and wind the cable, verify feeding/winding capability, drum cable condition, and cable appearance.	① Feeding/winding (without irregular winding) was possible, and there were no observed abnormalities that could affect cable performance. ② When feeding the cable, it sometimes caught the back side of the drum, so countermeasures for these issues are necessary.
Cable drum and extension arm combined performance verification test	Verification of the functional linkage of the cable drum and the cable feeding mechanism at the extension arm tip	It was verified that there is no problem in cable feeding and winding to confirm combined operations.	① According to the expected procedures of the actual equipment, performance verification tests were conducted to confirm operations of the cable drum, the feed mechanism at the extension arm tip, and performance (via flight test) of the wired drone.	Same as above



Cable drum

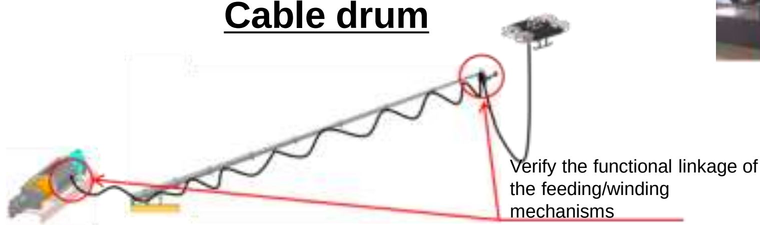


Illustration of the combined test overview

Test conditions

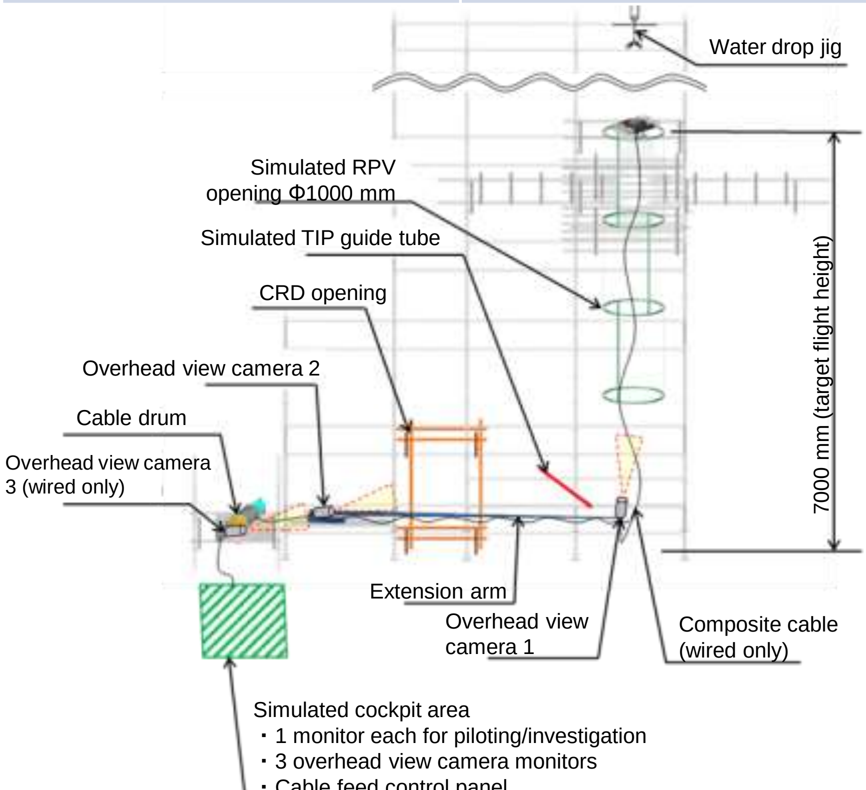
6. Implementation details

(2) Development of the bottom access investigation method (drone)

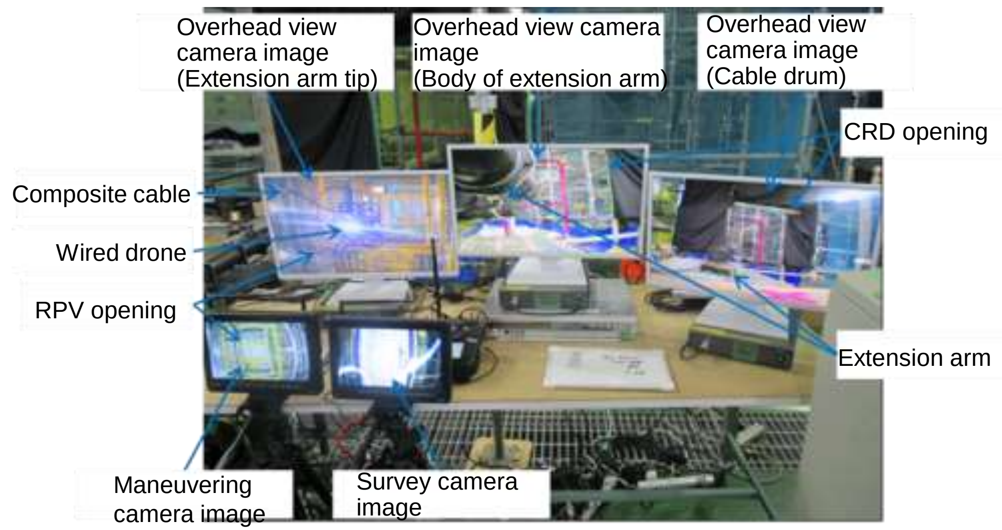
2) Implementation details for the second half of FY2021

④ Test results (Test No. 10/11/12: Once-through test (normal, darkness, darkness + rainfall))

Test purpose	Test details	Test methods
Verification of the functions of equipment via a series of investigation procedures, and development of the final investigation procedure (normal/dark/dark + rainy environment)	① Validity of the investigation procedure and implementation guidelines were confirmed. ② Flight capability, capability of investigation, and flight duration were verified. ③ Issues to be addressed were identified.	The series of operations were verified under normal/dark/dark + rainy environment conditions according to the investigation procedures and implementation guidelines expected for actual equipment.



Overview of the test



Test facility

6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

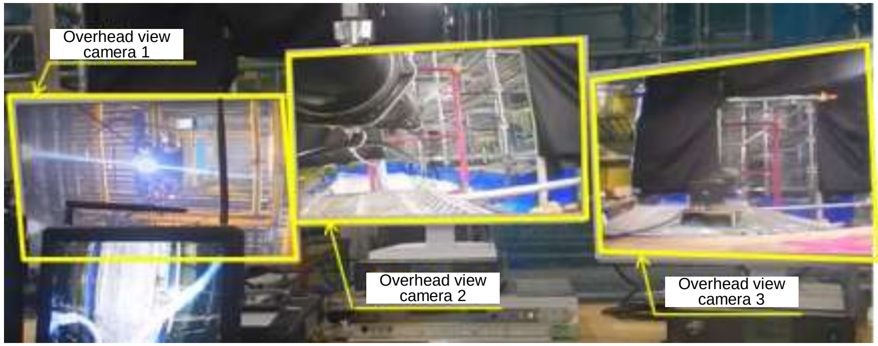
④Test results (Test No. 10: Once-through test (normal))

Test results	
Wired drone	**Wireless drone**
Flight capability: flyable (*1) Investigation capabilities: video verification possible (with cable reflection) Duration of investigation: 8 minutes 15 seconds (round trip) (*2)	Flight capability: flyable/Surveyable: video verification possible (with intermittent video noise) Duration of investigation: 2 minutes 9 seconds (round trip) (*2) Battery A consumption: 36%/Battery B consumption: 35% :: (average) 35.5%

(*1) There is an issue in cable treatment because cables may come in contact with the floor.
(*2) Excluding time for extension/retraction of extension arm. Flight duration may depend on pilot skill.

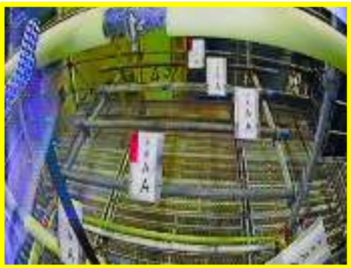
Maneuvering camera

Investigation camera

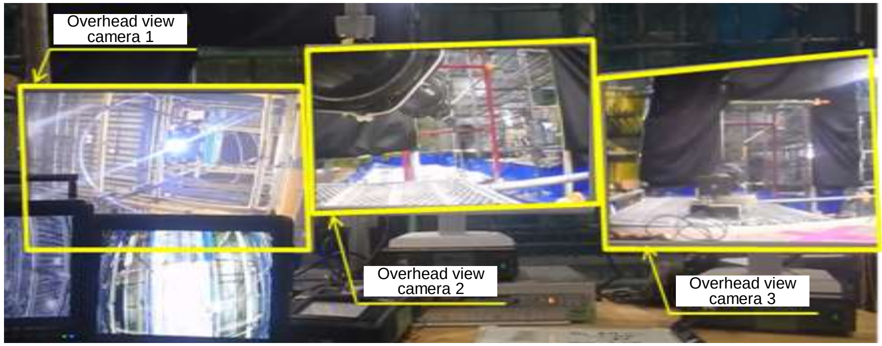


Video from wired drone camera

Maneuvering camera



Investigation camera



Video from wireless drone camera

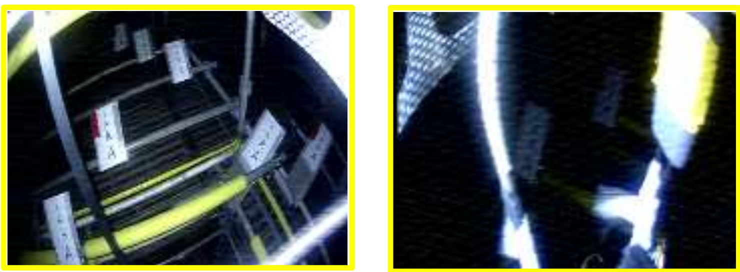
6. Implementation details

(2) Development of the bottom access investigation method (drone)

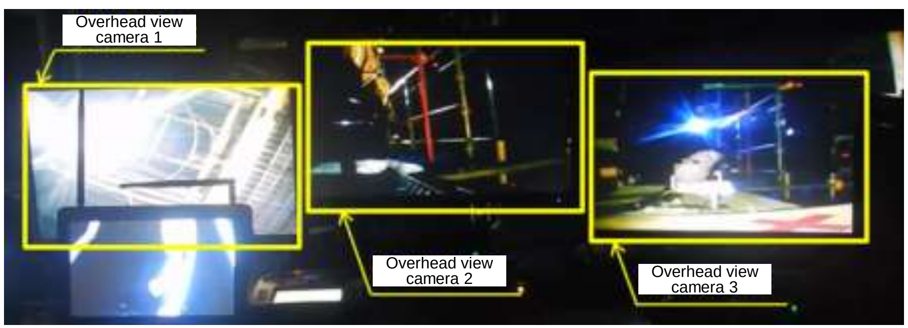
2) Implementation details for the second half of FY2021

④ Test results (Test No. 11: Once-through test (darkness))

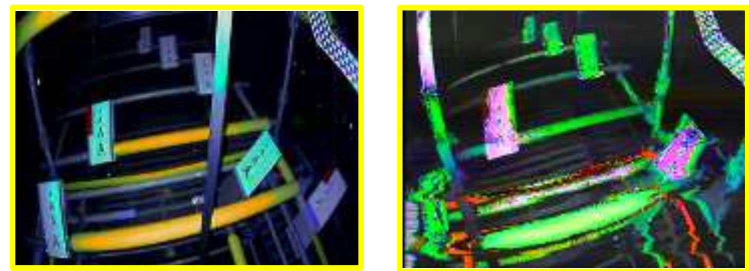
Test results	
Wired drone	**Wireless drone**
Flight capability: flyable (*1) Investigation capabilities: video verification possible (with cable reflection) Duration of investigation: 8 minutes 49 seconds (round trip) (*2)	Flight capability: flyable/Surveyable: video verification possible (with intermittent video noise) Duration of investigation: 2 minutes 24 seconds (round trip) (*2) Battery A consumption: 43%/Battery B consumption: 42%: (average) 42.5%
(*1) There is an issue in cable treatment because cables may come in contact with the floor. (*2)Excluding time for extension/retraction of extension arm. Flight duration may depend on pilot skill.	



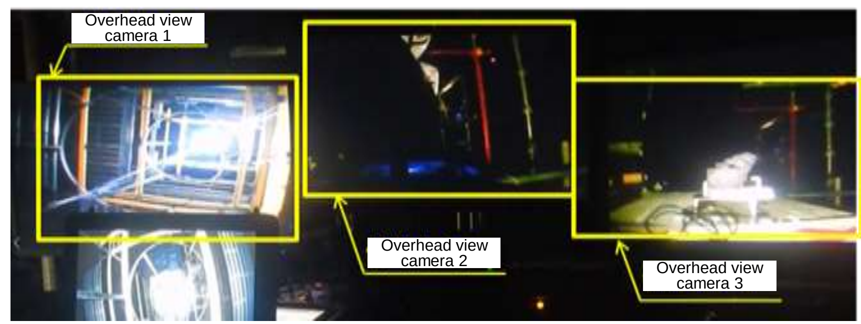
Investigation camera (right: when the cable is reflected)



Video from wired drone camera



Investigation camera (right: when noise occurs)



Video from wireless drone camera

6. Implementation details

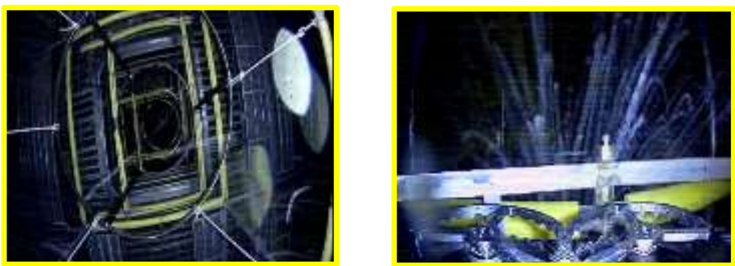
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

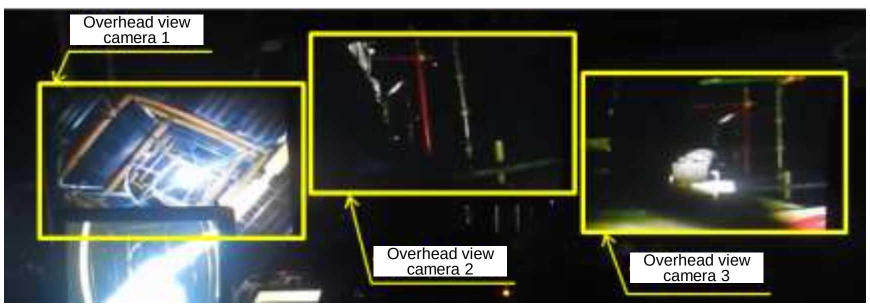
④ Test results (Test No. 12: Once-through test (darkness + rainfall))

Test results	
Wired drone	**Wireless drone**
Flight capability: Flight is available. (*1) Investigation capabilities: video verification possible (with cable reflection) (*2) Duration of investigation: 9 minutes 00 seconds (round trip) (*3)	Flight capability: Flight is available. /Investigation capabilities: video verification possible (with intermittent video noise) (*2) Duration of investigation: 2 minutes 11 seconds (round trip) (*3) Battery A consumption: 37%/Battery B consumption: 39%: (average) 38%

(*1) There is an issue in cable treatment because cables may come in contact with the floor.
(*2) The bottom-mounted drone survey camera was virtually unaffected by dripping water. On the other hand, top-mounted maneuvering camera's view was intermittently blocked by dripping water.
(*3) Excluding time for extension/retraction of extension arm. Flight duration may depend on pilot skill.



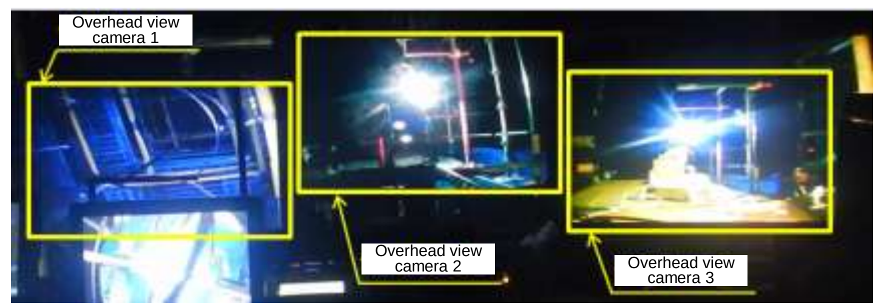
Maneuvering camera (while water is dripping)



Video from wired drone camera

Maneuvering camera

Investigation camera



Video from wireless drone camera

6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test results (actual equipment procedure): Based on the results of the once-through test, the actual equipment is operated in the following procedure.

Wired drone actual equipment procedure

Procedure No.	Operation of cable drum	Operation of extension arm	Operation of wired drone
Initial condition	8 m cable is wound-up	Extension arm is retracted. The cable is sent out 3 m from the extension arm tip	Standby just before entrance to the CRD opening
①	Send out 7 m of cable	Send out 2 m of cable from the extension arm tip	—
②	—	—	Take off and hover at the exit of the CRD opening
③		Extend the extension arm 5.3 m and point the overhead view camera towards the RPV opening	
④	—	—	Pass under the TIP guide pipe, move directly below the RPV opening and hover
⑤	—	Send out 2 m of cable from the extension arm tip	—
⑥	—	—	Ascend to the target height and investigate inside the RPV
⑦	—	—	After investigation, descend directly below the RPV opening and hover
⑧	Wind up 2 m of cable	Wind up 2 m of cable from the extension arm tip	—
⑨	—	—	Pass under the TIP guide pipe, move to the exit of the CRD opening and hover
⑩	—	Retraction of the extension arm	—
⑪	—	—	Return to the entrance of the CRD opening and land
⑫	Wind up 5 m of cable	Wind up 2 m of cable from the extension arm tip	—

Wireless drone actual equipment procedure

Procedure No.	Operation of extension arm	Wireless drone operation
Initial condition	Extension arm is retracted	Standby just before entrance to the CRD opening
①	Extend the extension arm 5.3 m and point the overhead view camera towards the RPV opening	—
②	—	Take off and fly to the survey location. After completing the investigation, return to the entrance of the CRD opening and land
③	Retraction of the extension arm	—

6. Implementation details

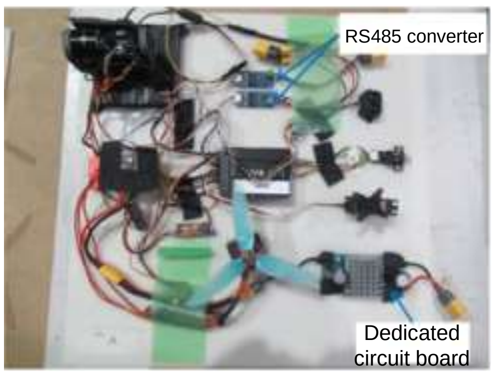
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test result (Test No. 13: Irradiation test)

Test purpose	Test details	Test methods	Test results	
			Wired drone	Wireless drone
Verification of radiation resistance of each component	The irradiation tests for the component level were conducted to verify the radiation resistance of each component.	The following items are applied to both wired/wireless drones ① Two sets of drones for the trial irradiation test were manufactured. Only one of the drones were irradiated with 100 Gy (*1). ② Each component of the irradiated drone was replaced one by one with the equivalent component from the non-irradiated drone to verify functional operation of each component.	The flight controller has a malfunction. (*2)	The flight controller has a malfunction. (*2)

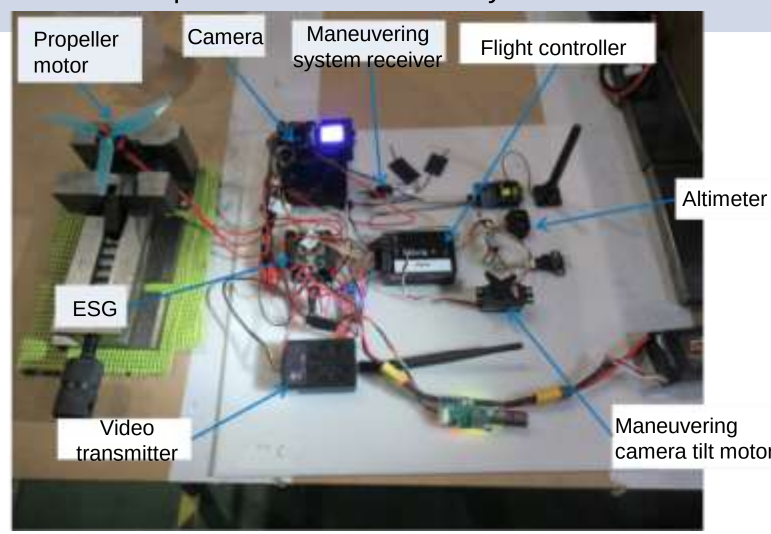
(*1) Estimated value assuming a survey duration of 10 minutes.
(*2) During the operation verification, an abnormality in the flight controller compass (function to verify the bearing of the aircraft) was identified. However, no compass sensor was used in this test. Therefore, manufacturing of a flight controller with no compass sensor is necessary.



[Wired drone]

[Wireless drone]

Test component configuration



Test conditions (wireless drone)

6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test result (Test No.14,15 Communication performance test)

Communication performance of wireless drones

1) In order to use wireless drones in the actual facility, it is necessary to evaluate maneuvering and video transmission capability of wireless drones.
2) In the actual equipment, a transceiver was installed at the extension arm tip for communication, but wireless radio waves may be shielded by the reactor internals, making communication impossible.
3) Moreover, the tests up to last fiscal year verified that simulating the actual wireless environment was difficult.

As described to the above, communication performance was evaluated by comparing the results of Test No. 14 (threshold verification test) and Test No. 15 (radio wave propagation analysis).

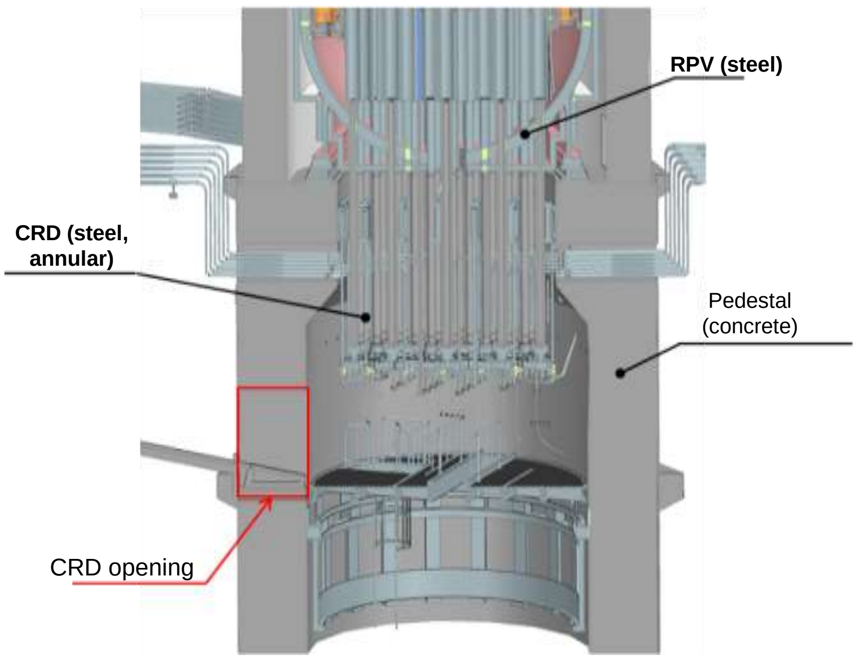
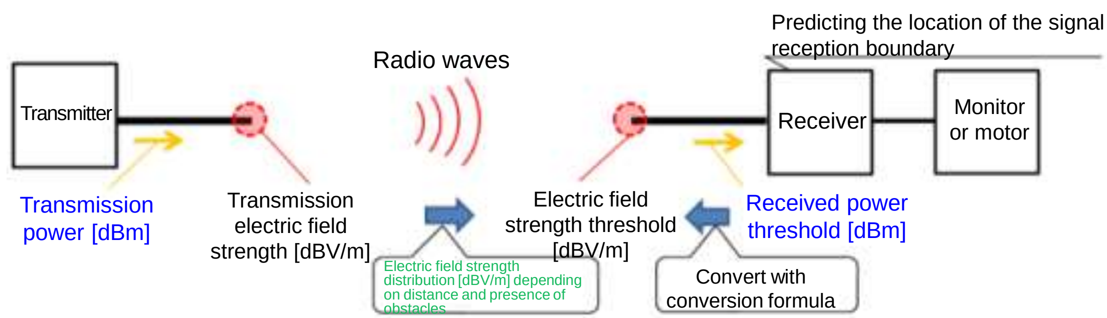


Illustration of actual equipment



The transmitted/received images of actual equipment signals show the method of obtaining each physical quantity (testing or analysis). Note that blue and green letters indicate data from the test and analysis, respectively.

Illustration of signal propagation and relationship between test data and analysis data

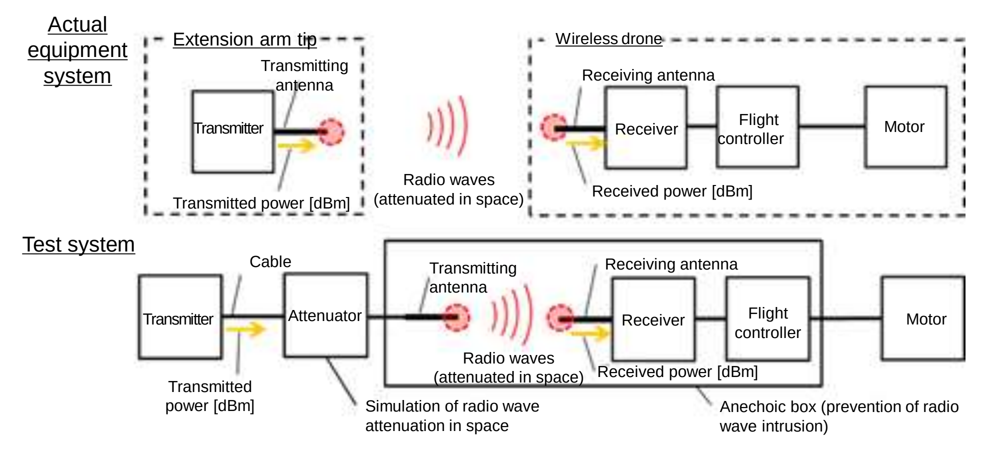
6. Implementation details

(2) Development of the bottom access investigation method (drone)

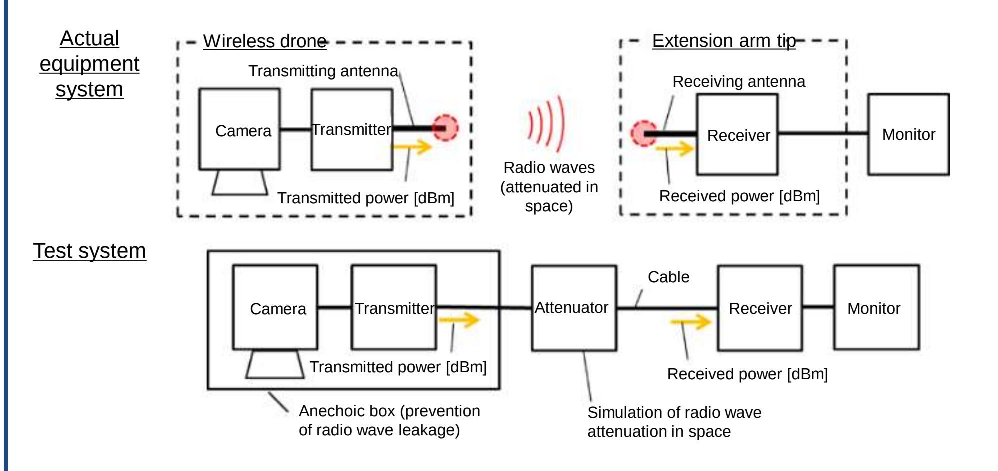
2) Implementation details for the second half of FY2021

④ Test result (Test No. 14 Threshold verification test)

Test purpose	Test details	Test methods
Verification of transmitted and received power thresholds for maneuvering/video system wireless equipment	The transmitted and received power thresholds of the transmitter for use as an analytical input were measured.	① Measure the transmission power of maneuvering system 2.4 GHz/Video system 5.7 GHz. ② Since the 2.4 GHz band is used for communication components such as wireless LAN, the transmission/reception antenna should be installed in an anechoic box. Increase the attenuation of the attenuator and measure the received power when motor function is disturbed. ③ The 5.7 GHz band requires a license and notification for use. The transmitter is installed in an anechoic box and the transceiver is connected by cable. Increase the attenuation of the attenuator and measure the received power when the video is disturbed.



Maneuvering system 2.4 GHz



Video system 5.7 GHz

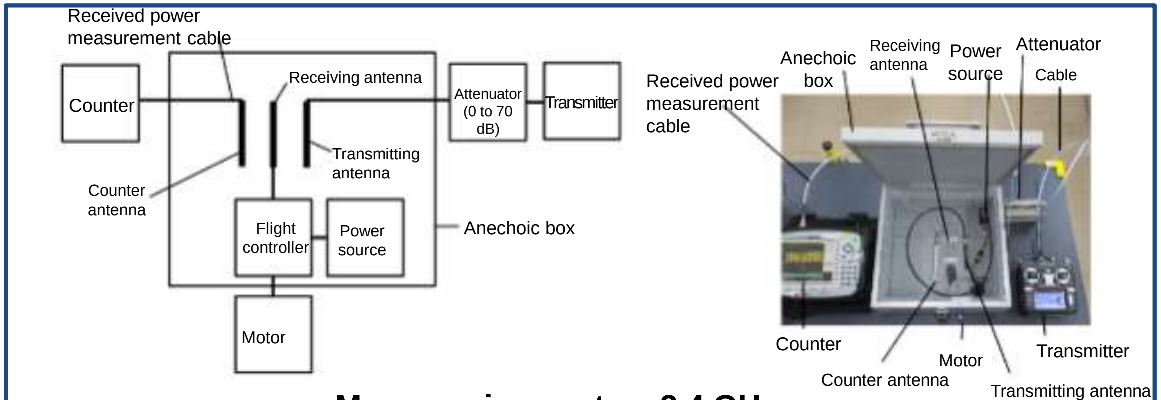
Comparison between actual equipment system and test system

6. Implementation details

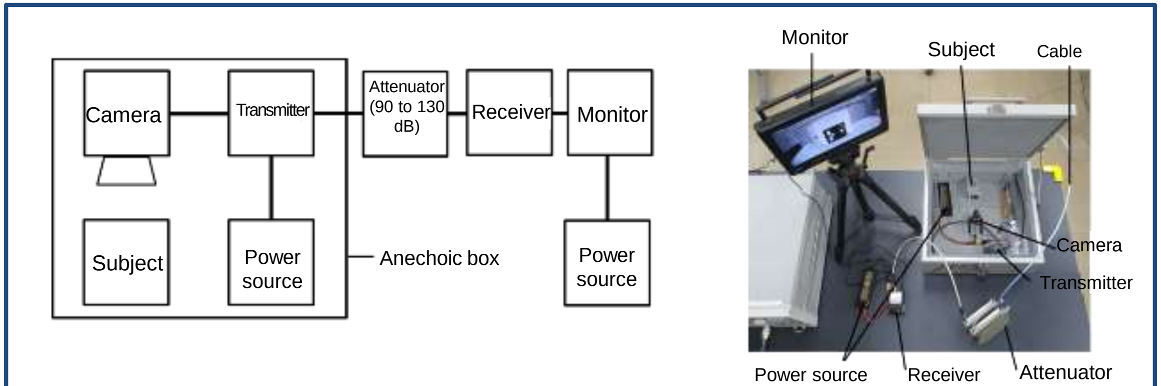
(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test result (Test No. 14 Threshold verification test)



Maneuvering system 2.4 GHz



Video system 5.7 GHz

Summary of testing status

Test results		
Frequency [GHz]	Transmitted power [dBm]	Received power threshold [dBm]
2.4	15.8	-95.1
5.7	28.4	-86.6

Changes in video state depending on the amount of attenuation

6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

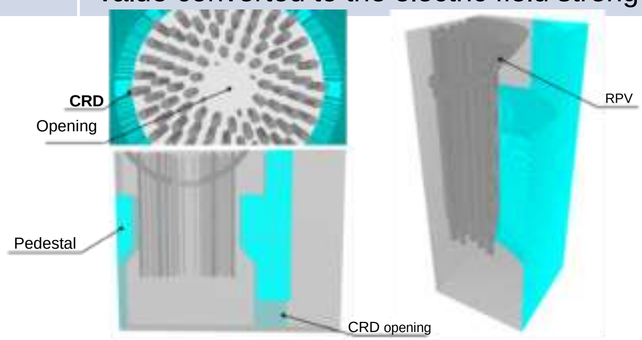
④ Test results (Test No. 15 Radio wave propagation analysis)

Analysis purpose	Analysis content	Analysis method
Verification of electric field strength distribution of maneuvering/video system wireless radio waves in actual equipment system	Analysis software conducts simulations of actual equipment to analyze the electric field strength distribution of the 2.4 GHz maneuvering system and the 5.7 GHz video system.	① For analysis conditions, the wave source input should be the transmitted power of the transmitter. In addition, 8 case analyses for both 2.4 and 5.7 GHz in total were conducted while changing the CRD shape, wave source position, and antenna orientation. ② At the transceiver position expected in the actual equipment, the received power threshold value obtained from analysis results and testing were compared with the value converted to the electric field strength.

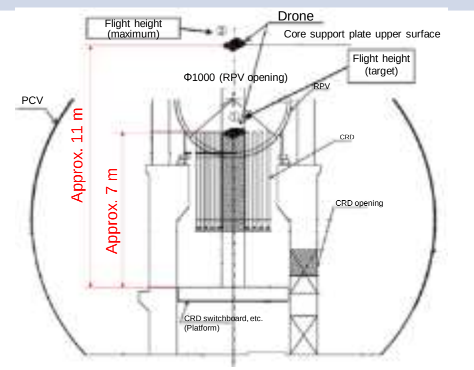
Analysis conditions for 2.4 GHz maneuvering system / 5.7 GHz video system

No.	CRD shape	Antenna orientation relative to CRD opening	Wave source height (*)
1	Cuboid	Parallel	Target (7 m)
2	Cuboid	Orthogonal	Target (7 m)
3	Cylinder	Parallel	Target (7 m)
4	Cylinder	Orthogonal	Target (7 m)
5	Cuboid	Parallel	Maximum (11 m)
6	Cuboid	Orthogonal	Maximum (11 m)
7	Cylinder	Parallel	Maximum (11 m)
8	Cylinder	Orthogonal	Maximum (11 m)

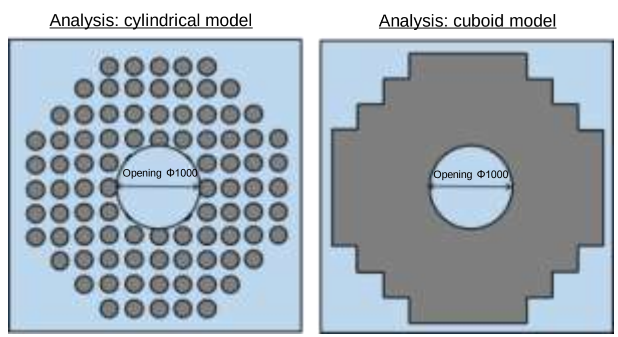
(*) Due to the reversibility of radio waves, the drone is used as the wave source location.



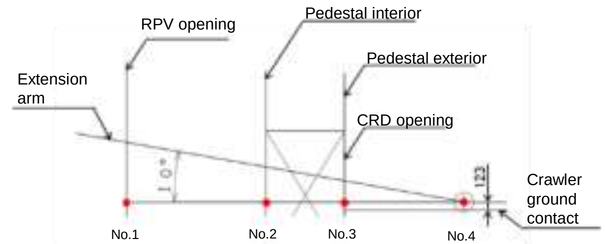
Analysis system overview



Wave source height (drone flight position)



CRD shape (left figure: cylindrical model, right figure: cuboid model)



Analysis evaluation positions

6. Implementation details

(2) Development of the bottom access investigation method (drone)

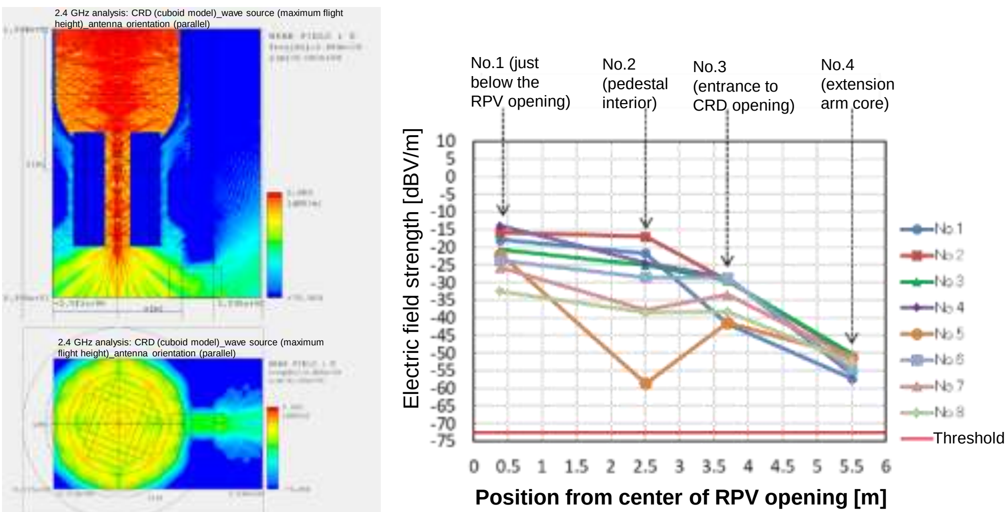
2) Implementation details for the second half of FY2021

④ Test results (Test No. 15 Radio wave propagation analysis)

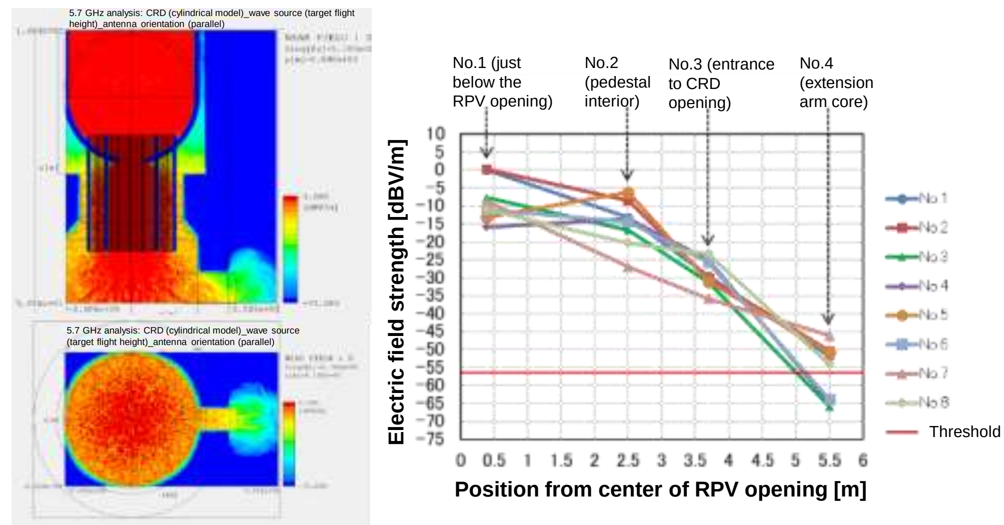
Analysis/threshold comparison results

① Comparison of tests and analyses suggests a high likelihood of maneuvering/video system communication capability inside the CRD opening.

② Communication with the 5.7 GHz video system may not be possible outside the CRD opening.



Analysis results (2.4 GHz operating system)



Analysis results (5.7 GHz video system)

Note: The threshold (red line) is the received power threshold from “Test No. 14 Threshold verification test,” converted from [dBm] to [dBV/m].

Based on the above results, both of maneuvering and video systems will be able to communicate when the transceiver inside the CRD opening (with the extension arm) is installed by using the extension arm.

6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test results (wired drone test results and evaluation of applicability to actual equipment)

Test No.	Test item	Wired drone	Evaluation of applicability to actual equipment
1	Flight height verification test	- Capable of 7 m target flight height and 8 m maximum flight height. - Crashed at 9 m flight height due to temperature rise in electronic speed controller (ESC).	- Capable of reaching the upper surface of the CRD housing. - Heat generation from the electronic components in the fuselage is an issue that needs to be addressed. (Ambient temperature must also be considered)
2	Continuous flight time verification test	-	-
3	Flight travel time verification test	-	-
4	Minimum flight space verification test (vertical/horizontal directions)	- Vertical: Capable of passing through □ 800 mm, 600 mm despite hitting the frame. - Horizontal: Capable of passing through □600 mm.	- Even at □800 mm, there is contact with the frame when passing through. Thus it is believed that 1 m, which is the current expected dimension, is necessary for the actual equipment. (The actual equipment applicability will be determined based on the results of the prior investigation inside the pedestal.)
5	Verification tests of the investigation (normal)	- Normal: It is possible to identify character shapes at a panel position of 2500 mm. - Darkness: It is possible to identify character shapes at a panel position of 2500 mm. - Rainfall: It is possible to identify character shapes at a panel position of 2500 mm. Water droplets have no effect. - There are cases where cables block the view for all of the above.	- Prospects to be able to verify structures at the bottom of the RPV. - There is background reflection from aircraft components in the survey image. → The drone legs structure needs to be reviewed, but the reflection from the wired cables is difficult to deal with.
6	Verification tests of the investigation (darkness)		
7	Verification tests of the investigation (rainfall)		
8	Cable drum performance verification test	- Feeding/winding is possible without irregular winding. - In some cases, cables get fed to the back side of the drum during feeding.	- A design is needed that better directs cables during feeding.
9	Cable drum and extension arm combined performance verification test		
10	Once-through test (normal)	(darkness + rainfall results below) - Flight capability: flight possible (no crashes thanks to monitoring by overhead view camera monitoring) - Investigation capabilities: video verification possible (no effects from water droplets) - Duration of investigation: 9 minutes 00 seconds (round trip) -There is contact between the cable and floor.	- With monitoring by an overhead view camera, the drone can fly in a series of procedures. However, it also depends on the pilot's skill, so sufficient training is required when using the actual equipment.
11	Once-through test (darkness)		
12	Once-through test (darkness + rainfall)		
13	Irradiation test	- There is something wrong with the compass in the flight controller.	- Necessity of using a flight controller that does not have a compass sensor. → It is necessary to investigate the components that can be mounted or consider custom manufacturing
14/15	Threshold verification test/Radio wave propagation analysis	-	-

6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

④ Test results (wireless drone test results and evaluation of applicability to actual equipment)

Test No.	Test item	Wireless drone	Evaluation of applicability to actual equipment
1	Flight height verification test	- Capable of flying 11 m.	- Capable of reaching the upper surface of the CRD housing. It can also reach near the maximum core support plate.
2	Continuous flight time verification test	- An average continuous flight duration of 5 minutes 56 seconds is feasible.	- Evaluated by once-through test items
3	Flight travel time verification test	- X-2 penetration CRD opening round trip time: 2 minutes 16 seconds - Round trip battery consumption: 14%	- Evaluated by once-through test items
4	Minimum flight space verification test (vertical/horizontal directions)	Vertical: □800 mm is passable although there is contact with the frame. Horizontal: □600 mm is passable.	- Even at □800 mm, there is contact with the frame when passing through. Thus it is believed that 1 m, which is the current expected dimension, is necessary for the actual equipment. (The actual equipment applicability will be determined based on the results of the prior investigation inside the pedestal.)
5	Verification tests of the investigation (normal)	- Normal: It is possible to identify character shapes at a panel position of 2500 mm. - Darkness: It is possible to identify character shapes at a panel position of 2000 mm. - Rainfall: It is possible to identify character shapes at a panel position of 2500 mm. Water droplets have no effect. - There is intermittent noise for all of the above.	- Prospects to be able to investigate the bottom of the RPV. - However, due to intermittent noise, the image quality is inferior to wired. - Image noise is caused by radio wave multipath, which is difficult to deal with at present.
6	Verification tests of the investigation (darkness)		
7	Verification tests of the investigation (rainfall)		
8	Cable drum performance verification test	-	-
9	Cable drum and extension arm combined performance verification test		
10	Once-through test (normal)	(darkness + rainfall results below) - Flight capability: capable of flying. (No crashes thanks to monitoring by overhead view camera) - Investigation capabilities: video verification possible (intermittent video noise, no effects from water droplets) - Duration of investigation: 2 minutes 11 seconds (round trip) - Battery consumption: 38%	- Monitoring by overhead view camera enables stable flight. - From the total with flight travel time, total flight duration is 4 minutes and 27 seconds. The continuous flight duration is 5 minutes and 56 seconds, so the prospect for investigation is favorable. - In an evaluation of battery consumption, a series of surveys consumed 52% of battery charge. - The above calculation does not take into account factors like time waiting for the crawler (between the X-2 penetration and CRD opening), or electrical tolerance, so further study is required.
11	Once-through test (darkness)		
12	Once-through test (darkness + rainfall)		
13	Irradiation test	- There is something wrong with the compass in the flight controller.	- Necessity of using a flight controller that does not have a compass sensor. → It is necessary to investigate the components that can be mounted or consider custom manufacturing.
14/15	Threshold verification test/Radio wave propagation analysis	- Communication is possible by installing a transceiver inside the entrance of the CRD opening.	- Both the 2.4 GHz maneuvering system and 5.7 GHz video system are expected to be able to communicate by installing the transceiver inside the CRD opening.

6. Implementation details

(2) Development of the bottom access investigation method (drone)

2) Implementation details for the second half of FY2021

Summary

- In the simplified FY2020 test, the wired drone failed to reach its target flight height due to a voltage drop in the power cable, and the wireless drone failed to extend flight time. Issues common to both drone types included drone monitoring methods and difficulty in investigating the RPV bottom due to turning movements of a drone. In response to these issues, countermeasures were examined and a drone was test-manufactured.
- Besides that, element tests were performed to verify the effect of these countermeasures, including proposed countermeasure for dealing with actual environments (darkness, dripping water, etc.).
- From the results of the element tests, the wired drone achieved the target flight height by revising the power supply method, and the wireless drone was able to remain in flight longer than the target time by revising the battery configuration.

Remaining issues

New issues from the FY2021 test results and other potential issues are shown below.

- Feasibility of a series of investigation methods (including access from X-2 penetration to CRD opening)
- Feasibility of extension rods under development for other projects and their combination with cable drum-equipped crawlers
- Radiation resistance of drone (wired/wireless) electronic components
- Investigation or surveying of lightweight radiation sensors that can be mounted on wireless drones

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

Units 2 and 3: Development of telescopic equipment for accessing inside RPV

<Summary of implementation in the second half of FY2021>
- In regards to the FY2020 development issues, the conceptual study and necessary element tests were conducted.
- Proposed countermeasures for FY2020 issues were reflected into equipment specifications, and a simplified test with a 3-stage telescopic guide pipe was conducted to verify the effect of the countermeasures.
- Element tests were conducted to evaluate the feasibility of all 14-stages of the access equipment, and to evaluate the feasibility of the telescopic access equipment as a stand-alone unit.

<Details of implementation in the second half of FY2021>
- Test to verify the effect of countermeasures
- Conceptual study and simplified test regarding development issues
- Feasibility verification test using the 14-stage telescopic guide pipe
- Feasibility evaluation

<Results>
- Conceptual design and element tests were conducted to address development issues, including the study of connections on arm-type access equipment for retrieval operations.
- Reflecting proposed countermeasures to last year's issues (leakage and high sliding resistance), the 14-stage telescopic guide pipe was manufactured and tested. Only telescopic access equipment was evaluated as feasible.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

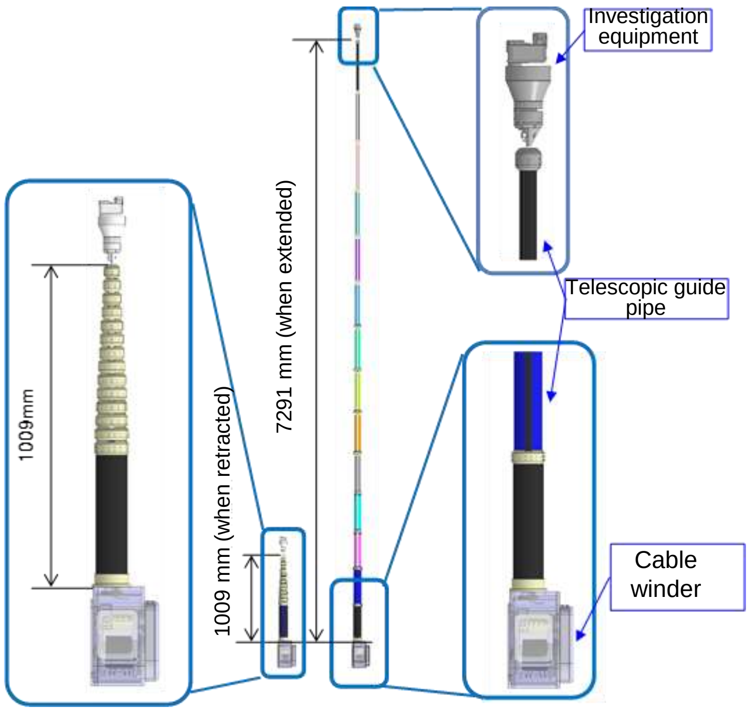
1) Summary of results through the first half of FY2021 (1/2)

In the simplified FY2020 test using a 3-stage telescopic guide pipe, factors of issues such as high leakage and sliding resistance at the sealing section were analyzed, and the proposed countermeasures were examined. Proposed countermeasures, such as inner pipe surface roughness reduction, were reflected in equipment specifications and the effect was verified by simplified 3-stage telescopic guide pipe testing.

Implementation details and results

1. Overview of telescopic access equipment

- The telescopic access equipment consists of a total of 14 thin-walled, multi-stages to enable extension from dimensional constraint of approx. 1 m to 7 m in length, and Φ100 mm to enable connection with the fuel debris retrieval access equipment. In addition, it is extended using air pressure and retracted by winding the cable inside the pipe.



Overview of telescopic access equipment

Schematic specifications of telescopic access equipment

Items	Specifications
Number of stages	14 stages
Material	Pipe: CFRP, aluminum Other components: aluminum components
Power source	Extension: air Retraction: cable winder Various motors: power source
Pipe thickness	1 mm
Dimensions when retracted (telescopic guide pipe only)	1100 mm or less
Dimensions when extended (telescopic guide pipe only)	7100 mm or greater
Outer diameter	Base: Φ97 mm Tip: Φ37 mm
Air pressure	Maximally extended: 0.1 MPa
Maximum transportable weight	2 kg (when air pressure is 0.1 MPa)
Cable	Built-in to telescopic guide pipe
Cable handling	Controlled by reeling the cable winder at the base
Clearance between pipes	0.3 mm (pipe and piston clearance)
Seal material	NBR
Camera	CCD or CMOS

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

1) Summary of results through the first half of FY2021 (2/2)

Implementation details and results

2. Examination of proposed countermeasures to address issues

- Proposed countermeasures against high leakage and sliding resistance at the sealing section were examined. Measures such as pipe inner surface roughness reduction were reflected in equipment specifications.

Events

- Separation between supplied pressure and adjustment pressure
- Insufficient tension force during retraction

Issues and presumed factors

Technical issue ①: leakage from packings

Technical issue ②: High sliding resistance

- Pipe surface roughness
- Piston surface roughness
- Increased resistance due to looseness
- Increased resistance due to sealing structure
- Increased resistance due to contact between pipe inner surface and lower piston
- Increased resistance due to contact between pipe inner surface and collar
- Increased resistance due to contact between pipe outer surface and scraper tip
- Increased resistance due to contact between dust seal and pipe outer surface
- Increased resistance due to contact between rail, scraper and top ring
- Increased resistance due to contact between top ring and pipe outer surface
- Inconsistent or non-uniform grease application method, location, amount, etc.
- Cable ends were not sealed
- Low cable winder tension force

Proposed countermeasures (The effect was verified in FY2021 test)

- **A**: Make the fold of the CFRP inner pipe surface material unidirectional; (Alternative) Adoption of aluminum for pipe material
- **B**: Adoption of aluminum for piston material
- **C**: Use of WR sealing structure / Use of GLY sealing structure → Use of hybrid sealing structure
- **D**:
  - Reduction of inner diameter of lower piston
  - Collar outer diameter reduction
  - Use of a coating to improve sliding on the pipe outer surface and scraper inner surface (*1)
  - Optimization of dust seal dimensions(*1)
  - Apply sliding material (*1)
  - Change of rail material(*1)
  - Fixing the top ring in place
  - Setting the location to be greased
- **E**: Cable ends sealed during testing
- **F**: Improvement of the cable winder torque

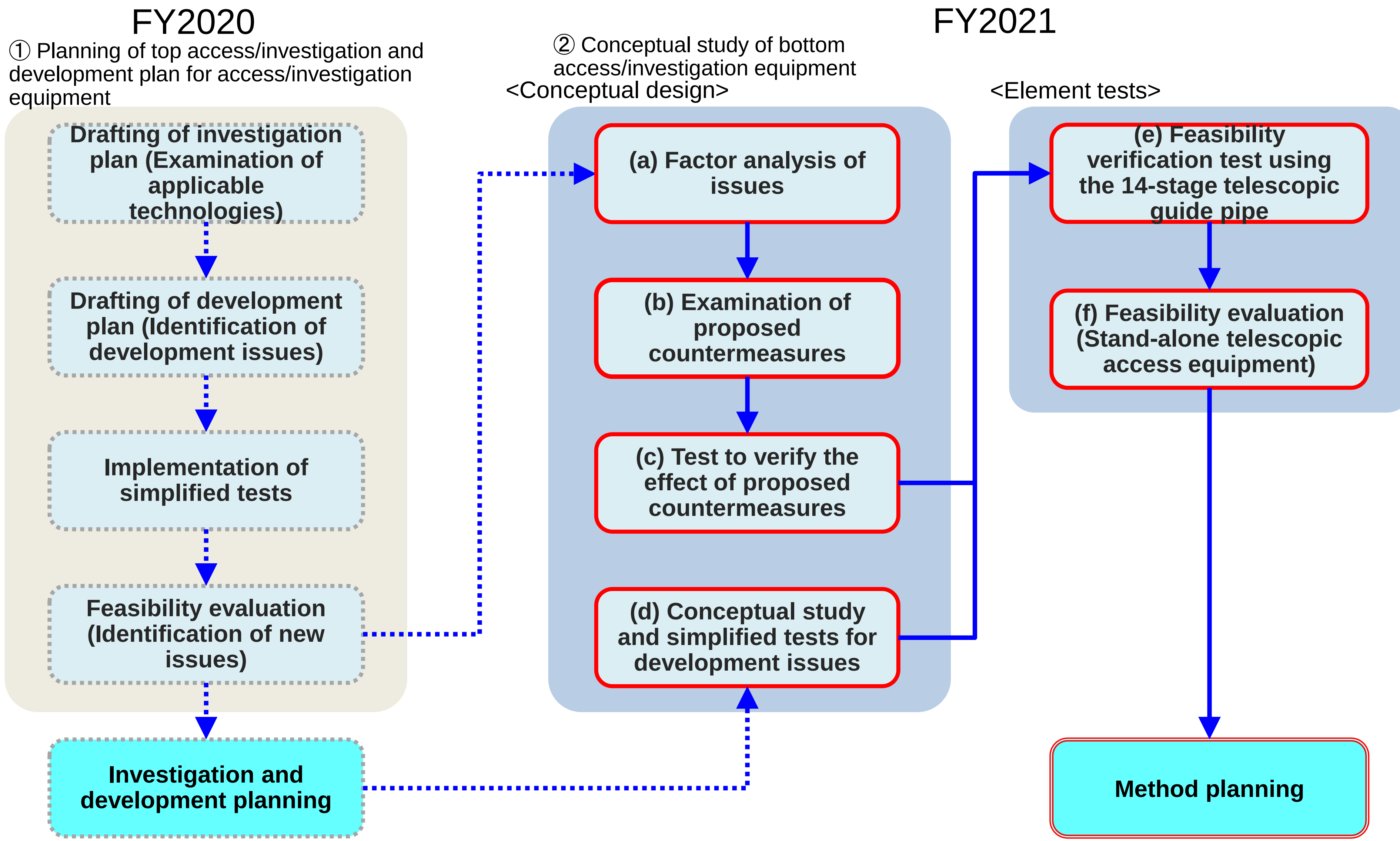
(*1) Items not applied

WR: Wear ring, GLY: Nitrile rubber (NBR) based packing

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

2) Flow of "② Conceptual study of bottom access/investigation equipment"



6. Implementation details

Units 2 and 3

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures

○ Test items

No.	Test item	Proposed countermeasures to test results of FY2020					
		A	B	C	D	E	F
1	Test to verify the sealing functions	Done	Done	Done	—	—	—
2	Test to verify strength of connecting part	Done	Done	—	—	—	—
3	Section verification test	Done	Done	Done	Done	Done	Done

○ Proposed measures for test results of FY2020 (from No. 84)

A

Issue ①: Leakage from packing

The CFRP folds of the pipe material of are changed to the unidirectional folds.
(Alternative) Adoption of aluminum for pipe material

B

Issue ①: Leakage from packing

Adoption of aluminum for piston material

C

Issue ②: High sliding resistance

Adoption of WR sealing structure
Adoption of GLY sealing structure

Adoption of hybrid sealing structure

D

Issue ②: High sliding resistance

Reduction of inner diameter of lower piston

Fixing the top ring in place

Setting the spot for grease application

E

Event ①: Separation between supplied pressure and adjustment pressure

Sealing of cable ends during testing

F

Event ②: Insufficient tension force during retraction

Improvement of the cable winder torque

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures <1. Test to verify the sealing functions>

○ Purpose

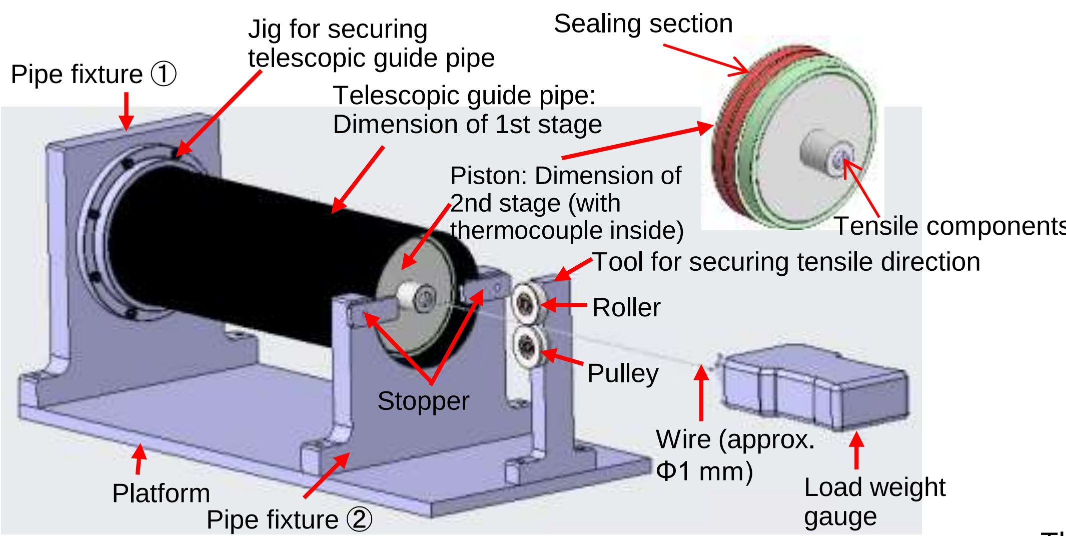
Regarding reduction of sliding resistance during extension/retraction, and pipe material and sealing structure candidates for air leakage reduction, the purpose of the test is to select a suitable combination of sliding resistance and sealing efficiency (leakage check, leakage volume) while verifying the effect.

Regarding new leakage volume verification to be implemented this fiscal year, it will be verified that the leakage flow rate from the packing/external air ingress is low relative to the supply flow rate during telescopic pipe extension or the exhaust flow rate during emergency retraction, and leakage volume is sufficient for smooth, reliable extension and emergency retraction operations.

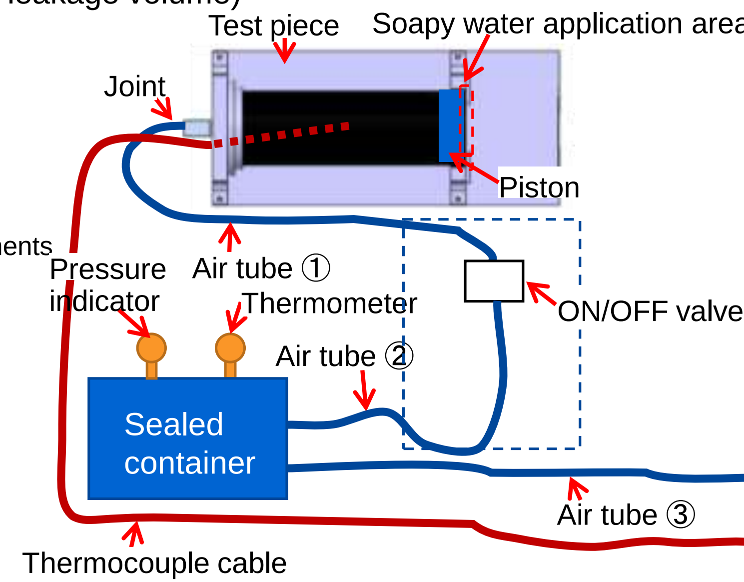
○ Test overview

The sliding resistance was measured by pulling the piston with a load weight gauge. The sealing capability (leakage check, leakage volume) was verified by investigating foaming of soapy water applied around the piston section after closing the ON/OFF valve to collect air in a sealed container and opening the ON/OFF valve to send compressed air to the telescopic guide pipe. In addition, the time variation of the pressure indicator (attached to the sealed container) readings during compressed air supply was recorded.

○ Test system: Verification of sliding resistance



○ Test system: Verification of sealing efficiency (leakage check, leakage volume)



Test piece

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures

<1 Test to verify the sealing functions>

The effect of proposed countermeasures were verified under the following conditions. Since performance of the hybrid sealing structure is direction-dependent, for the leakage volume verification test and leakage check, the piston was installed upside down and pressure was applied from the opposite direction.

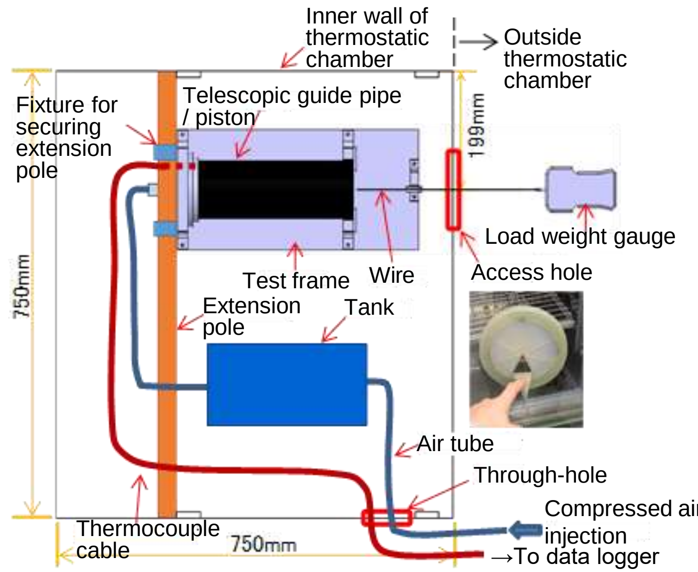
Condition ①: Pipe material CFRP plain weave, CFRP axial UD, CFRP circumferential UD
⇒ Verification of the effect of proposed countermeasure A, "Make the weave of the CFRP inner pipe surface material unidirectional"

Condition ②: Piston material CFRP plain weave, aluminum
⇒ Verification of the effect of proposed countermeasure B, "Adoption of aluminum for piston material"

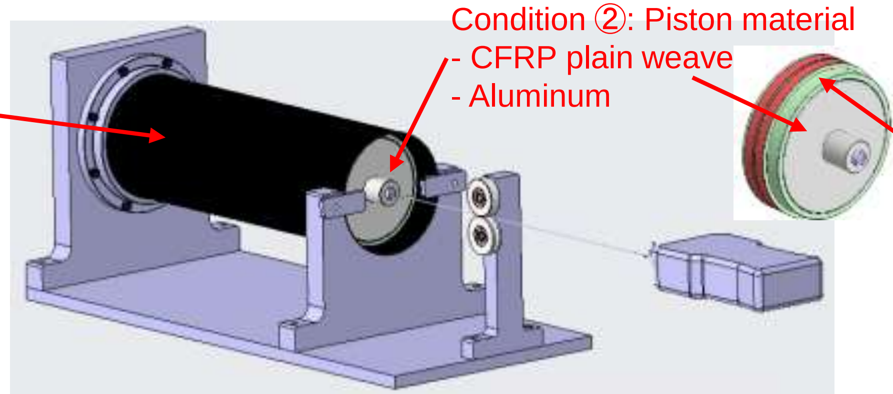
Condition ③: Sealing structure Normal type (GLY x 2), hybrid type (WR + GLY)
⇒ Verification of the effect of proposed countermeasure C, "Adoption of hybrid sealing structure"

Condition ④ (reference): Pipe material Aluminum
⇒ Verification of the effect of proposed countermeasure A, "(Alternative) Adoption of aluminum for pipe material"

In addition, simulation tests were conducted under simulated environmental conditions, with the sealing section configuration selected from the results of this test. To verify the effects of different environmental conditions, various tests were conducted under the conditions for doses of 0 Gy and 7200 Gy (assuming 100 Gy/h for 3 days), temperatures of 25℃ (room temperature) and 50℃, normal humidity and 100% humidity (simulated by immersing the furnace in room temperature water for 3 days), and with and without wetting of inside pipes by water drops in the reactor.



Test system under simulated environmental conditions



6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures <1. Test to verify the sealing functions>

○ Selection indices for the sealing section configuration based on results of the sealing functions verification test

Index ①: Sliding resistance

- The primary candidate for the sealing section structure is the one with the lowest sliding resistance that has a steady-state tension force less than the cable winder's 319 N.

Index ②: Leakage volume

- During extension: By increasing the source pressure, the leakage volume is expected to reduce the pressure inside the telescopic guide pipe to 0.10 MPa (upper limit 0.30 MPa)
- In case of emergency retraction: When the exhaust source pressure is set to -0.092 MPa (maximum exhaust pressure), after taking into account the dead weight of each pipe and the investigation equipment, the leakage volume is expected to be sufficient to create a negative pressure (-0.090 MPa) that produces tension force equivalent to the extension force (maximum extension force) when the pressure in the telescopic guide pipe is set to 0.10 MPa

In addition to the above indices, the sealing section configuration should be selected with consideration of operability.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures <1. Test to verify the sealing functions>

○ Summary of the sealing functions

Estimation scenarios			1 (Examined in FY2020)		2 (Condition ①)		3 (Condition ①)		4 (Condition ②)		5 (Condition ③)		6 (Condition ④, alternative)	
Sealing structure			Normal type GLY×2		Normal type GLY×2		Normal type GLY×2		Normal type GLY×2		Hybrid type WR+GLY (Proposed countermeasure C)		Hybrid type WR+GLY (Proposed countermeasure C)	
Pipe inner surface material			CFRP Plain weave		CFRP Axial UD (Proposed countermeasure A)		CFRP Circumferential UD (Proposed countermeasure A)		CFRP Axial UD (Proposed countermeasure A)		CFRP Axial UD (Proposed countermeasure A)		Aluminum (Proposed countermeasure A)	
Piston material			CFRP Plain weave		CFRP Plain weave		CFRP Plain weave		Aluminum (Proposed countermeasure B)		Aluminum (Proposed countermeasure B)		Aluminum (Proposed countermeasure B)	
Sliding resistance	Sliding resistance [N]	Transport frequency	Max. value	While sliding	Max. value	While sliding	Max. value	While sliding	Max. value	While sliding	Max. value	While sliding	Max. value	While sliding
		1	Omitted as was already reported in FY2020	Approx. 16 to 27	20.9	Approx. 6 to 9	21.4	Approx. 6 to 11	22.0	Approx. 5 to 8	15.4	Approx. 5 to 7	12.7	Approx. 3 to 4
		2			22.3		26.6		20.4		13.4		11.6	
		3			21.1		25.7		20.9		13.5		11.7	
		4			20.6		23.0		20.3		13.0		11.7	
		5			21.8		20.3		20.7		13.4		12.3	
	Average		34.9	—	21.3	—	23.4	—	20.9	—	13.7	—	12.0	—
Leakage volume	Piston direction		—		—		—		—		Front-facing	Rear-facing	Front-facing	Rear-facing
	Time from 0.10 MPa to 0.09 MPa		7 seconds		1 min. 12 sec.		1 min. 34 sec.		118 min. 22 sec.		113 min. 58 sec.	5 min. 16 sec.	131 min. 26 sec.	128 min. 41 sec.
	Leakage volume from 2nd stage pipe		6 liter/min		0.6 liter/min		0.5 liter/min		0.006 liter/min		0.006 liter/min	0.140 liter/min	0.006 liter/min	0.006 liter/min
	Leakage volume when converted to 14-stage telescopic guide pipe		55 liter/min		5 liter/min		4 liter/min		0.05 liter/min		0.06 liter/min	1.22 liter/min	0.05 liter/min	0.05 liter/min

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

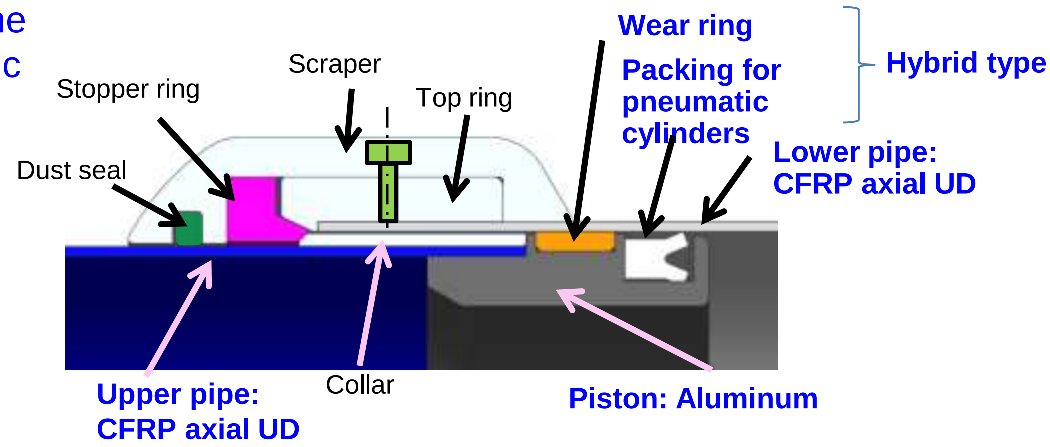
3) (c) Test to verify the effect of proposed countermeasures <1. Test to verify the sealing functions>

○ Summary: Planning of the sealing section configuration

- The main proposal for pipe material is CFRP axial UD pipe, which reduces sliding resistance and leakage volume compared to CFRP plain weave pipe.
  - The CFRP axial UD with the lowest sliding resistance is selected for CFRP axial UD/circumferential UD
  - Although aluminum is superior to CFRP in both sliding resistance and leakage volume, due to manufacturing issues, it is an alternative to the main proposal. The main proposal for piston material is aluminum, which can reduce leakage volume compared to CFRP plain weave pistons.
- The main proposal for a sealing structure is a hybrid sealing structure, which has lower sliding resistance than the normal type, and by using the above pipe and piston, the leakage volume during telescopic guide pipe extension and the amount of outside air ingress during emergency retraction are sufficiently small compared to the air tube's supply/exhaust flow rate (CAD results verified that the telescopic guide pipe can enter the reactor bottom opening without scraping, and is effective at controlling tilt).

Considering operability and results of the sealing functions verification test, the main proposals for the sealing section configuration used for the telescopic guide pipe are as follows.

Pipe material: CFRP axial UD (proposed countermeasure A)
Piston material: Aluminum (proposed countermeasure B)
Sealing structure: Hybrid type (proposed countermeasure C)



6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures <1. Test to verify the sealing functions>

○ Summary of the sealing functions verification test results (environmental simulation tests)

Environmental conditions			Normal environment		Simulated reactor environment 1		Simulated reactor environment 2	
Temperature			Room temperature		50℃		50℃	
Cumulative dose rate			0 Gy (unirradiated)		7200 Gy		7200 Gy	
Humidity			Normal humidity		100% (immersed in room temperature water for 3 days)		100% (immersed in room temperature water for 3 days)	
Wetting inside the pipe			None		None		Yes	
Sliding resistance	Sliding resistance [N]	Transport frequency	Max. value	While sliding	Max. value	While sliding	Max. value	While sliding
		1	15.4	Approx. 5 to 7	14.2	Approx. 5 to 7	22.6	Approx. 5 to 7
		2	13.4		16.7		22.1	
		3	13.5		13.4		23.3	
		4	13.0		14.3		24.2	
		5	13.4		15.9		23.6	
	Average		**13.7**	—	**14.9**	—	**23.2**	—
Leakage volume	Piston direction		Front-facing	Rear-facing	Front-facing	Rear-facing	Front-facing	Rear-facing
	Time from 0.10 MPa to 0.09 MPa		113 min. 58 sec.	5 min. 16 sec.	132 min. 47 sec.	11 min. 26 sec.	—	—
	Leakage volume from 2nd stage pipe		0.006 liter/min	0.140 liter/min	0.005 liter/min	0.063 liter/min	—	—
	Leakage volume when converted to 14-stage telescopic guide pipe		**0.06 liter/min**	**1.22 liter/min**	**0.05 liter/min**	**0.56 liter/min**	—	—

Environmental simulation tests were conducted with the combination described in pattern 5 (the main proposal). Conditions without environmental simulation were described as normal environment. Sliding resistance was also measured under conditions where the inside of the pipe was not wetted, as water droplets inside the pipe may lower sliding resistance. Since water droplets in the pipe are expected to increase sealing efficiency, leakage volume verification was conducted only for non-wetting conditions.

When the inside of the pipe was wet, sliding resistance was approx. 10 N greater than in the normal environment, but there was no difference in resistance when the piston was sliding.

Leakage volume did not affect the extension/retraction of the telescopic guide pipe, and the simulated reactor environment was less likely to leak.

Sliding resistance tends to increase in the reactor environment, but leakage volume is reduced. The feasibility will be evaluated in conjunction with the results of "(e) Feasibility verification test using the 14-stage telescopic guide pipe."

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

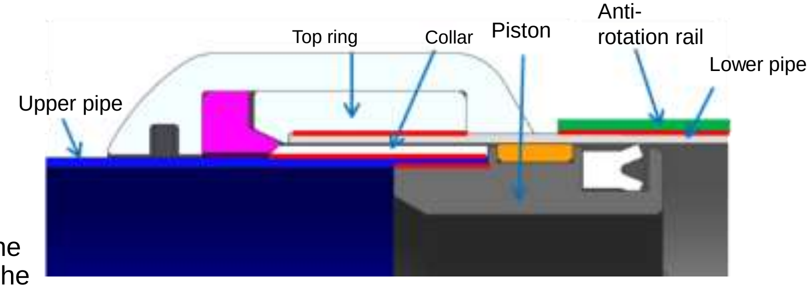
3) (c) Test to verify the effect of proposed countermeasures

<2. Adhesive strength verification test>

○ Purpose

The purpose of the test is to verify the strength of telescopic connecting part under expected environmental conditions.

The pipe material (CFRP axial UD material: proposed countermeasure A) and piston material (aluminum material: proposed countermeasure B) that were proposed in No. 91 will be used for the telescopic components.



○ Test overview

Using a small connecting sample piece, a shear load was applied to the connecting part to verify the breaking stress. The radiation environment simulated by pre-irradiating the connecting test piece. The effects from storing samples for 72 hours under irradiation dose conditions of 0 Gy and 7200 Gy (assuming 72 hours at 100 Gy/h), at 50℃, 90% humidity, are verified

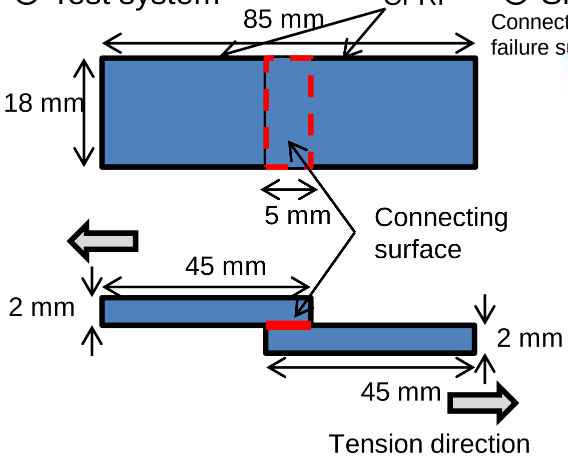
○ Evaluation items, etc.

No.	Test name	Evaluation items	Objective (evaluation criteria)	Verification method
1	Verification of strength of connecting part	- Breaking stress when shear load is applied to the connecting section - CFR pipe and each component - Aluminum pipe and each component	- The breaking stress when a shear load is applied is Pipe/top ring: 4.7 MPa or more*1 Pipe/piston: 4.7 MPa or more*1 Pipe/collar: 0.2 MPa or more*2 Pipe/rail: 0.3 MPa or more*2	- The stress at failure is measured by applying a shear load to both irradiated and unirradiated samples and then gradually increasing the load (all samples stored at constant temperature and humidity).

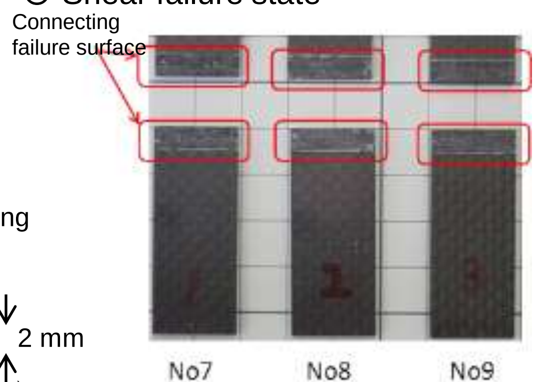
*1: The maximum stress in the connecting part is 0.26 MPa, based on the maximum piston thrust of approx. 709 N (air pressure: 0.1 MPa x maximum pressure-receiving area (2nd stage slider part)) and the area of the connecting part: 2743 mm^2 . Impacts of adhesive length on adhesive strength reduction: (3) multiplied by the safety factor (6); the target is 4.7 MPa or more

*2: The maximum force needed to break the bond between collar and rail is approx. 73 N, which is equivalent to the sliding resistance during extension/retraction, and the target value is set by multiplying the safety factor as in *1

○ Test system



○ Shear failure state



7200 Gy of cumulative irradiation, 50℃, humidity: 95%, shear failure test results after 24 hours of exposure

○ Simulated scope of test system

Simulant target	Points to simulate	Points not to simulate	Reason for not simulating
Connecting parts of CFRP/CFRP CFRP/aluminum Aluminum/aluminum	- Material - Adhesive	- Area of connecting part	Because the measurement is possible in terms of breaking stress by area.
		- Test piece thickness	Because it does not affect the breaking stress
Surrounding environment	- Irradiation dose	- Darkness	Because it does not affect the breaking stress

6. Implementation details

Units 2 and 3 **No.94**

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures

<2. Adhesive strength verification test>

① Pipe/top ring

Pipe: CFRP axial UD
Top ring: Aluminum (A5052) — Adhered with POLYMETAC

The cutting process produces aluminum pipes as one piece, so no connecting is required

② Pipe/rail

Pipe: CFRP axial UD
Rail: CFRP plain weave — Adhered with epoxy

Pipe: Aluminum (A7075)
Rail: CFRP plain weave — Adhered with epoxy (*1)

③ Pipe/collar

Pipe: CFRP axial UD
Collar: CFRP plain weave — Adhered with epoxy

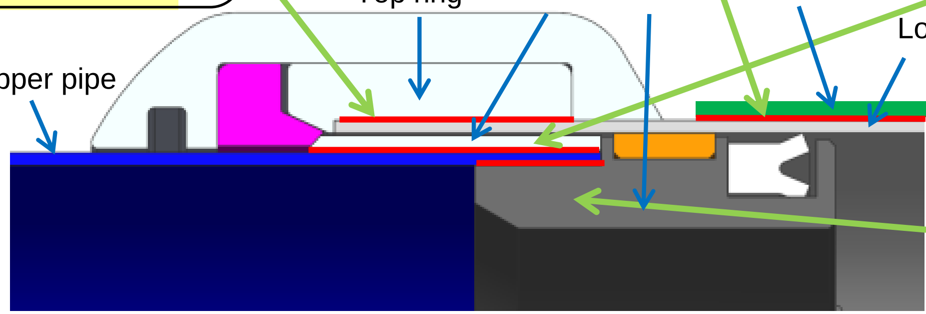
Pipe: Aluminum (A7075)
Collar: CFRP plain weave — Adhered with POLYMETAC

④ Pipe/piston

Pipe: CFRP axial UD
Piston: Aluminum (A5052) — Adhered with POLYMETAC

Pipe: Aluminum (A7075)
Piston: Aluminum (A5056) — Adhered with POLYMETAC

Connecting part
CFRP pipe
Aluminum pipe



The adhesive strength of the 5 types, “a” to “e”, to be used in telescopic equipment was evaluated.

	CFRP pipe		Aluminum pipe	
① Pipe/top ring	Adhered with CFRP axial UD/Aluminum (A5052) POLYMETAC	a	No adhesion	—
② Pipe/rail	Adhered with CFRP axial UD/CFRP plain weave epoxy	b	Adhered with aluminum (A7075)/CFRP plain weave epoxy	c
③ Pipe/collar	Adhered with CFRP axial UD/CFRP plain weave epoxy	b	Adhered with aluminum (A7075)/CFRP plain weave POLYMETAC	d
④ Pipe/piston	Adhered with CFRP axial UD/Aluminum (A5052) POLYMETAC	a	Adhered with aluminum (A7075)/aluminum (A5056) POLYMETAC	e

(*1) Pretreatment is not possible due to dimensional restrictions after anodizing, and POLYMETAC connecting is not possible. (The required strength is low due to rotation control, so POLYMETAC connecting is not necessary)

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures <2. Adhesive strength verification test>

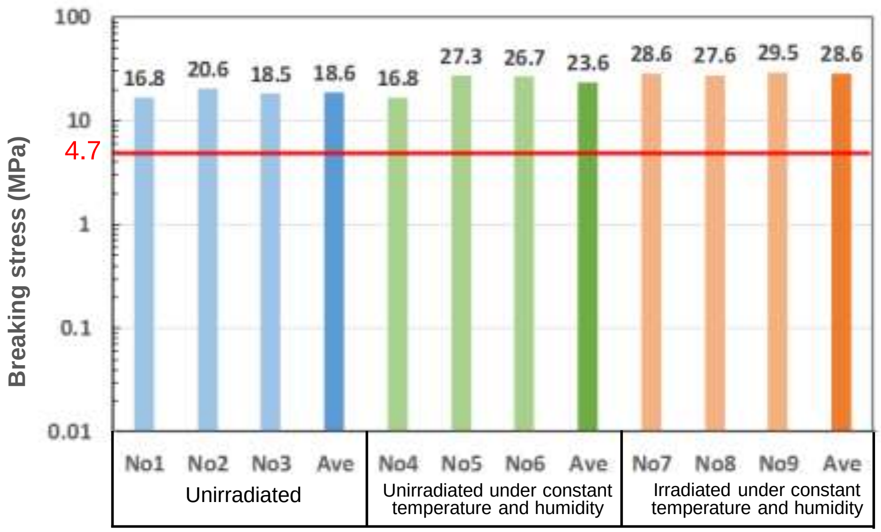
○ Test results

- CFRP pipe

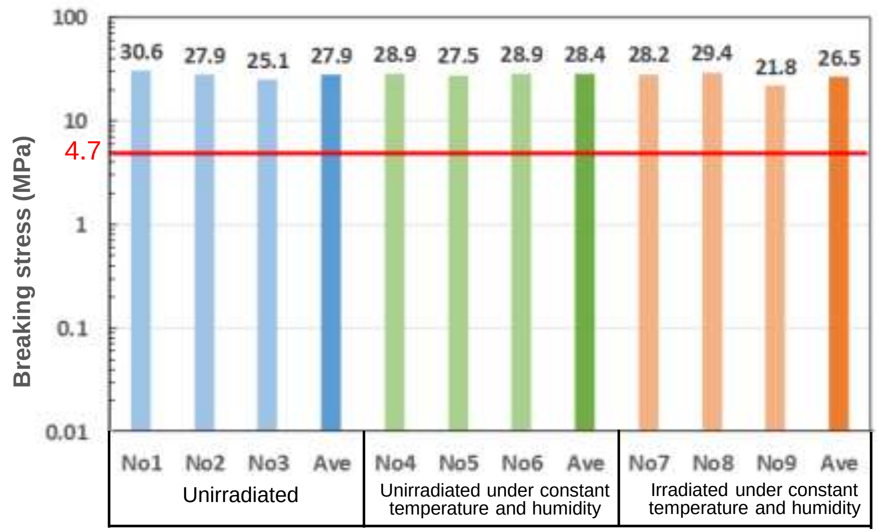
The shear failure stress after irradiation ranged from 27.6 to 29.5 [MPa] with an average of 24.6 [MPa], while the unirradiated samples ranged from 16.6 to 20.6 [MPa] with an average of 18.6 [MPa]. There was no significant difference in bond strength. All samples were stored at constant temperature and humidity. In both irradiated and non-irradiated test pieces, cohesive failure occurred within the adhesive bed, indicating that there was no degradation of the adhesive due to irradiation.

- Aluminum pipe (alternative)

The shear failure stress after irradiation ranged from 21.8 to 29.4 [MPa] with an average of 26.5 [MPa], while the unirradiated samples ranged from 25.1 to 30.6 [MPa] with an average of 27.9 [MPa], showing no significant difference in connection strength. In both irradiated and non-irradiated test pieces, cohesive failure occurred within the adhesive bed, indicating that there was no degradation of the adhesive due to irradiation.



CFRP pipe/top ring & piston



Aluminum pipe/piston

Based on the above results, it was evaluated that there was no shear failure stress degradation of the connecting part within 72 hours (*) under the environment expected for the investigation inside the RPV (temperature: 50[℃], humidity: 90%, and dose rate: 100[Gy/h]).

*From the result of cohesive failure (the adhesive strength test of previous fiscal year gave the same results), it was evaluated that adhesion strength can be maintained for about 24 hours even in an irradiation environment

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures <3. Section verification test>

The 3-stage telescopic guide pipe tests were conducted as in the previous fiscal year.

Proposed countermeasures were reflected to the 3-stage telescopic guide pipe.

A

Issue ①: Leakage from packing

Pipe material: CFRP axial UD adopted

B

Issue ①: Leakage from packing

Piston material: Aluminum adopted

C

Issue ②: High sliding resistance

Adoption of WR sealing structure
Adoption of GLY sealing structure
→ Adoption of hybrid sealing structure

D

Issue ②: High sliding resistance

Reduction of inner diameter of lower piston
Fixing the top ring in place
Setting the spot for grease application

E

Event ①: Separation between supplied pressure and adjustment pressure

Sealing of cable ends during testing

F

Event ②: Insufficient tension force during retraction

Improvement of cable winder torque

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

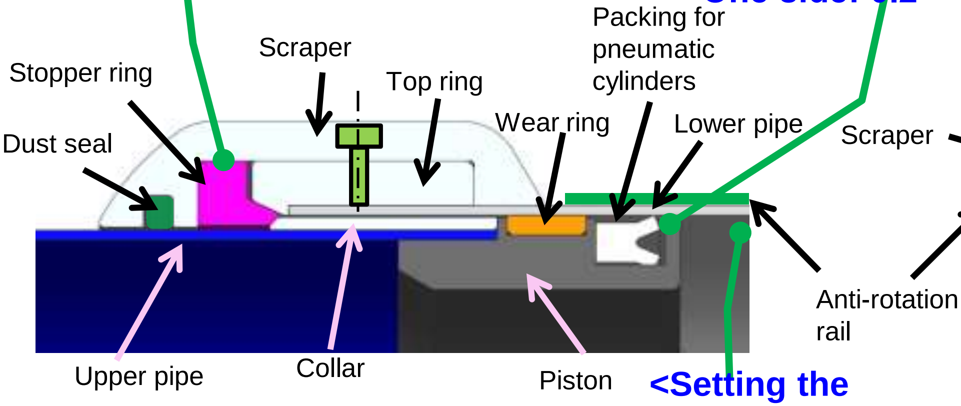
3) (c) Test to verify the effect of proposed countermeasures <3. Section verification test>

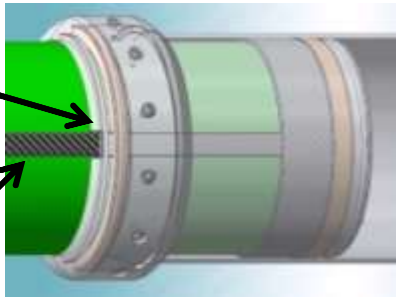
D

<Reduction of inner diameter of the piston lower bottom>
<Adoption of slide-enhancing coatings on the pipe outer surface and the scraper inner surface>
< Optimization of dust seal dimensions >
<Apply a sliding material to the pipe outer surface>
<Change in rail material>
<Fixing the top ring in place>
<Setting the location for grease application>

<Fixing the top ring in place>
Outer diameter from general tolerance to fit tolerance
One side: 0.3 → 0.035 mm

<Reduction of inner diameter of the piston lower bottom>
Larger gap between pipe inner surface and lower end of piston
One side: 0.2 → 0.5 mm





<Setting the location for grease application>

Only the above three items were reflected in the design.

Not reflected in the design for the following reasons

<Adoption of slide-enhancing coatings on the pipe outer surface and the scraper inner surface>
⇒ Each of the following items were considered but not adopted due to respective issues

- Fluorine coating Film thickness: 1 μm
  The firing temperature of the coating is 120℃. The operating environment temperature for CFRP pipes is 80 to 100℃, so it is difficult to apply a coating (low-temperature coatings are too thick and cannot be used).
- Plating
  Film thickness 0.6 mm (copper plating 0.5 mm + chrome plating 0.1 mm)
  The feasibility of the plating treatment on CFRP pipes is uncertain. In addition, since the thickness of the CFRP pipe is 1 mm, there is a possibility that the CFRP pipe will not be strong enough due to shrinkage of plating from the plating treatment. Not adopted because the effect of the final improvement is unknown.

<Optimization of dust seal dimensions>
⇒ The gap between the dust seal and the pipe was not enlarged, giving priority to the dust seal's function of preventing foreign substances from entering the pipe.

<Apply a sliding material to the pipe outer surface>
⇒ Not adopted because dust adheres easily.

<Change in rail material>
⇒ Not adopted due to significant impact of design changes on adhesive strength, thermal expansion, etc.

6. Implementation details

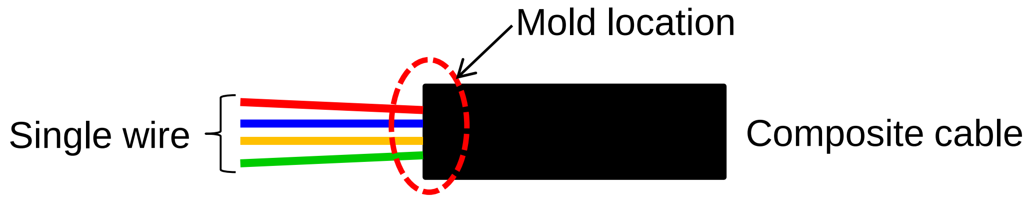
(2) Development of the bottom access investigation method (telescopic pipe)

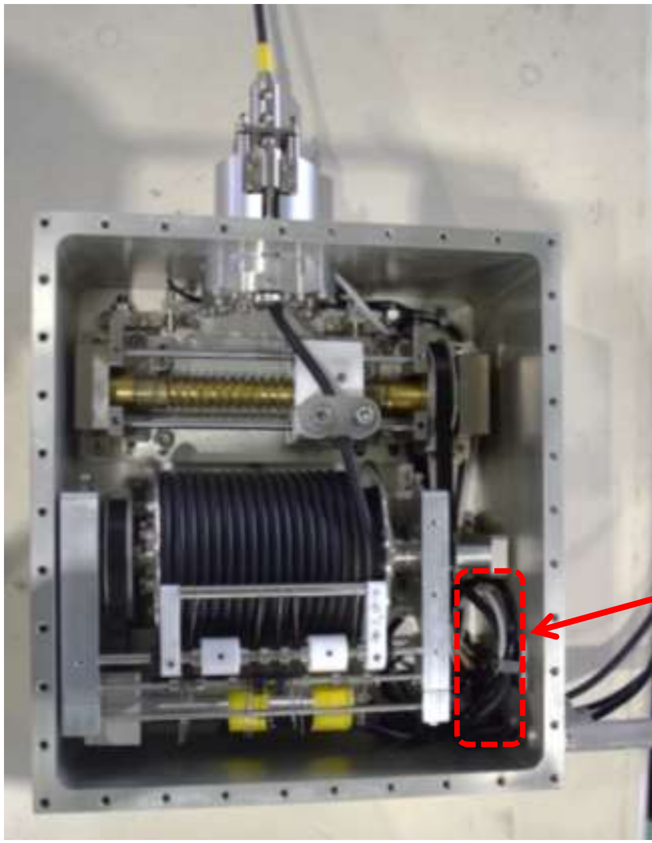
3) (c) Test to verify the effect of proposed countermeasures <3 Section verification test>

E <Sealing of cable ends during testing>

In order to prevent the compressed air supplied to the cable winder from leaking out through the cable, the part of the composite cable that will become a single wire is sealed (mold), excluding coating

○ Sealed spot
① Cables for cable winder drive
② Cables for investigation equipment





Location of object to be sealed

Cable winder examined in FY2020

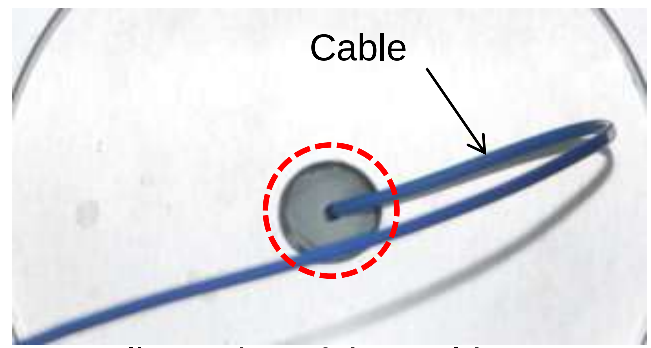


Illustration of the mold

6. Implementation details

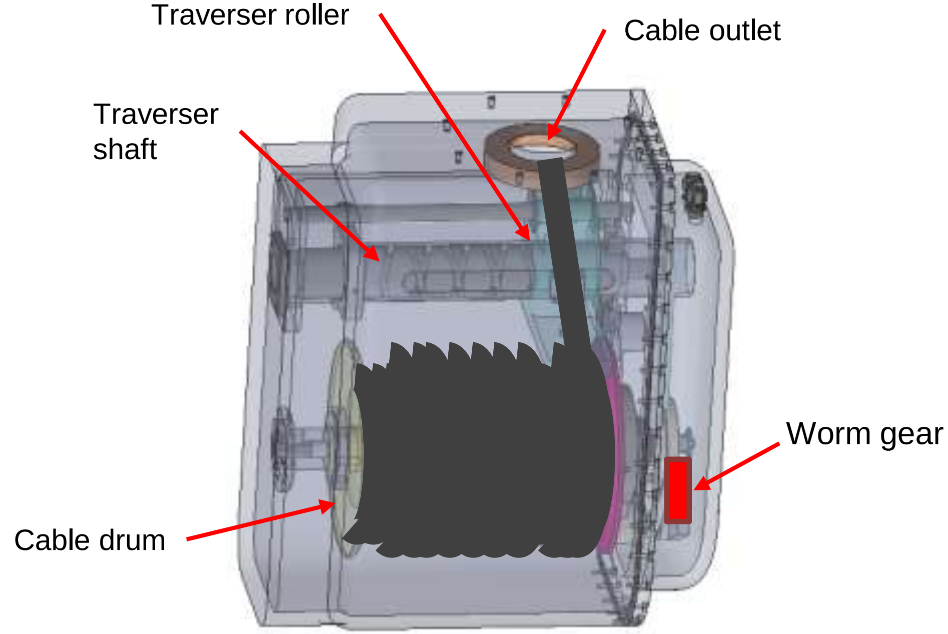
(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures <3. Section verification test>

F <Improvement of the cable winder torque>

To improve tension as much as possible within the dimensional constraints, the torque was increased by increasing the reduction ratio of the drive. As a result, the constant tension force was able to reach 319 N (83 N for the equipment designed in FY2020), which is larger than the required maximum tension force of approx. 270 N verified in the FY2020 test.

Another modification was a structure with constant load on the motor, in order to maintain propulsion of the telescopic guide pipe by cables. Therefore, the cable drum was structured to move through a worm gear so that the load is not directly applied to the motor, and not to rotate when the power is lost, making it possible to prevent the telescopic guide pipe from protruding.



Conceptual drawing of the cable winder examined in FY2021

6. Implementation details

Units 2 and 3

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures <3. Section verification test>

Tests for a 3-stage telescopic guide pipe were conducted as in the previous fiscal year.

Test items/outline		Confirmation items	Evaluation items	Objective (evaluation criteria)	Results	Judgement
3.1	**Test to verify the extension/retraction operations of telescopic guide pipe**	—	—	—	—	—
3.1.1	**Verification of extension/retraction operations** Verify whether the telescopic guide pipe can be vertically extended and retracted, and identify any features unique to vertical operation	Tensile force required from maximum extension	Cable tension required during retraction	319 N or less	Tensile force during retraction: 10 N to 80 N Maximum tension force: 110 N	Good
		Supplied pressure required for extension	Air pressure required during extension	0.1 MPa or less	0.03 MPa or less	Good
		Whether it is possible to supply the desired pressure to inside the pipe	Difference between supplied pressure and the pressure inside the telescopic guide pipe	No significant pressure difference	There was no difference between the supplied pressure and the pressure inside the telescopic guide pipe	Good
3.1.2	**Verification of rigidity when horizontal load is applied** With the telescopic guide pipe fully extended, apply a horizontal load to each pipe joint and verify the degree of tip misalignment	Tilt control of each sealing section structure during extension	Amount of tip misalignment	20 mm or less	1.5 mm (Previous fiscal year result: 7 mm)	Good
3.2	**Test to verify extension/retraction operations when the telescopic guide pipe is inclined** Tilt the telescopic guide pipe and verify the maximum angle at which extension/retraction is possible (max. 5 degrees)	Tensile force required from maximum extension	Cable tension required during retraction	319 N or less	Tensile force during retraction: 20 N to 80 N Maximum tension force: 110 N	Good
		Supplied pressure required for extension	Air pressure required during extension	0.1 MPa or less	0.03 MPa or less	Good
		Whether it is possible to supply the desired pressure to inside the pipe	Difference between supplied pressure and the pressure inside the telescopic guide pipe	No significant pressure difference	There was no difference between the supplied pressure and the pressure inside the telescopic guide pipe	Good
3.3	**Verification of pressure resistance (0.2 MPa supply)** With the telescopic guide pipe fully extended, apply air pressure of 0.2 MPa for 2 hours, disassemble and visually inspect for damage or deformation of components such as the stopper rings at the pipe ends	Must be able to withstand a pressure of 0.2 MPa	Whether main components are deformed 2 hours after supplying 0.2 MPa	No deformation before or after 0.2 MPa supply	There was no deformation of the main load-bearing components	Good
		Whether it is possible to supply the desired pressure to inside the pipe	Difference between supplied pressure and the pressure inside the telescopic guide pipe	No significant pressure difference	Even at 0.2 MPa, there was no difference between the supplied pressure and the pressure inside the telescopic guide pipe	Good

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures <3. Section verification test>

Comparison of the section verification test results (extension/retraction operations verification) for telescopic guide pipe base section (1st to 3rd stages)
(FY2020 test manufacturing / FY2021 improved test manufacturing)

- ✓ It was verified that, by applying measures to reduce sliding resistance, the telescopic guide pipe can be extended with less pressure and retracted with less cable tension force.
- ✓ In the test manufacturing of FY2020 telescopic guide pipe, the pressure in the pipe was less than the source pressure, but in the test manufacturing of FY2021 improved model, the pressure was the same, verifying the effectiveness of measures to reduce leakage volume from the sealing section.
- ✓ It was also verified that the telescopic guide pipe can be extended and retracted even at a greater inclined angle (previous fiscal year: 3° ⇒ this fiscal year: 5°)
- ✓ It was thought that the telescopic guide pipe would be retracted by negative internal pressure in cases of cable winder malfunction but the test manufacturing of FY2021 improved model can be retracted solely by its weight, at an internal pressure of 0.004 Mpa.

During retraction

During extension

Test manufacturing of FY2021 improved telescopic model (3-stages on the base side)

The above results verified the effectiveness of the proposed countermeasures.

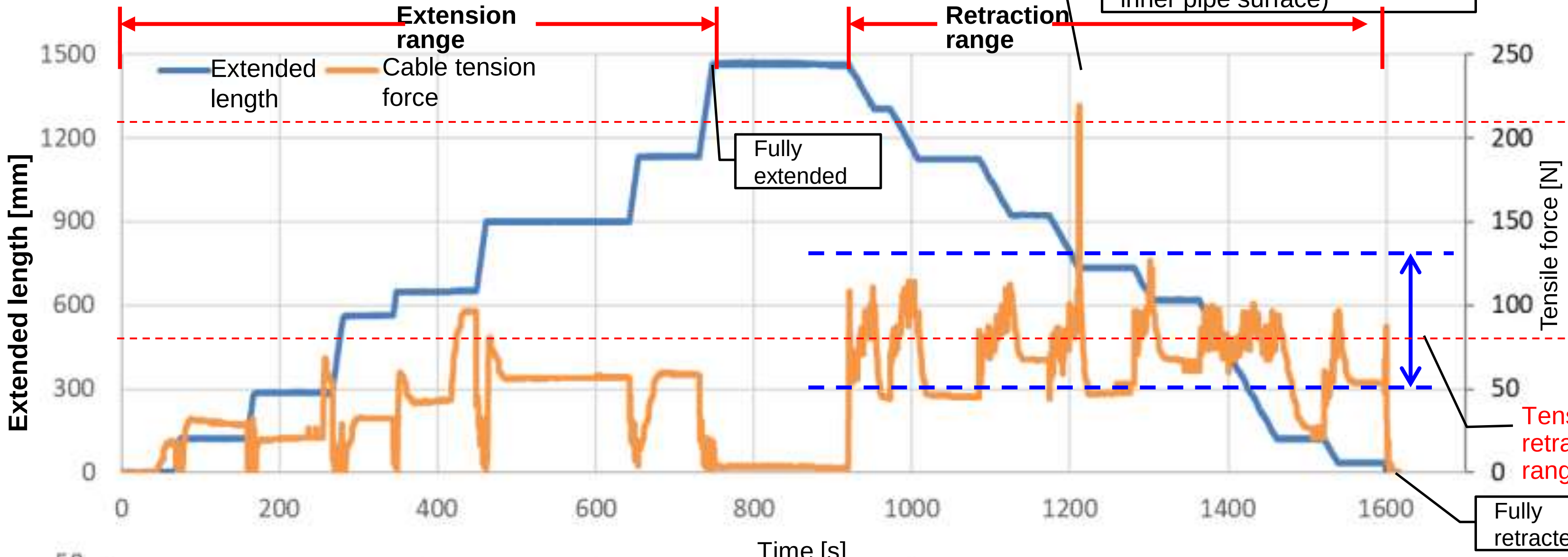
Compared items		FY2020	FY2021
During extension (telescopic vertical)	Supplied pressure (pressure inside telescopic guide pipe)	0.040 MPa	0.030 MPa
	Source pressure	0.050 MPa	0.030 MPa
During retraction (telescopic vertical)	Air pressure during retraction	0.005 MPa	0.010 MPa
	Tensile force during retraction	50 N to 130 N	10 N to 80 N
Telescopic inclined angle at which extension/retraction is possible		3 degrees	5 degrees (expected operational upper limit)

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures <3. Section verification test>

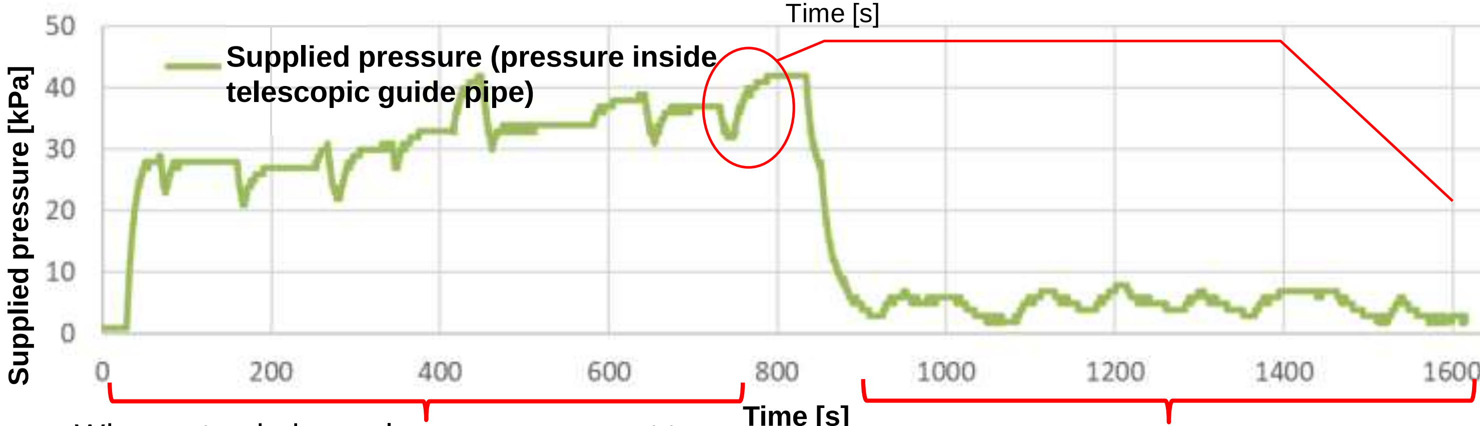
Test results of extension/retraction operations for the test manufacturing of FY2020 telescopic guide pipe



Upper tension limit: 208 N

Rated tension force: 83 N

Tensile force during retraction: roughly in the range of 50 N to 130 N



Issue ①:
The cable tension force intermittently exceeds the rated tension force. There may be cases of overload and motor shutdown, exceeding upper tension force limit.

Issues ②:
The telescopic extension operation increases the volume in the pipe and decreases the pressure in the telescopic guide pipe, but it takes time to return to the source pressure due to high leakage.

When extended, supply pressure was set to 30 kPa to 40 kPa, and applied source pressure: 30 to 50 kPa

The telescopic guide pipe was operated with supplied pressure of 5 kPa when retracted

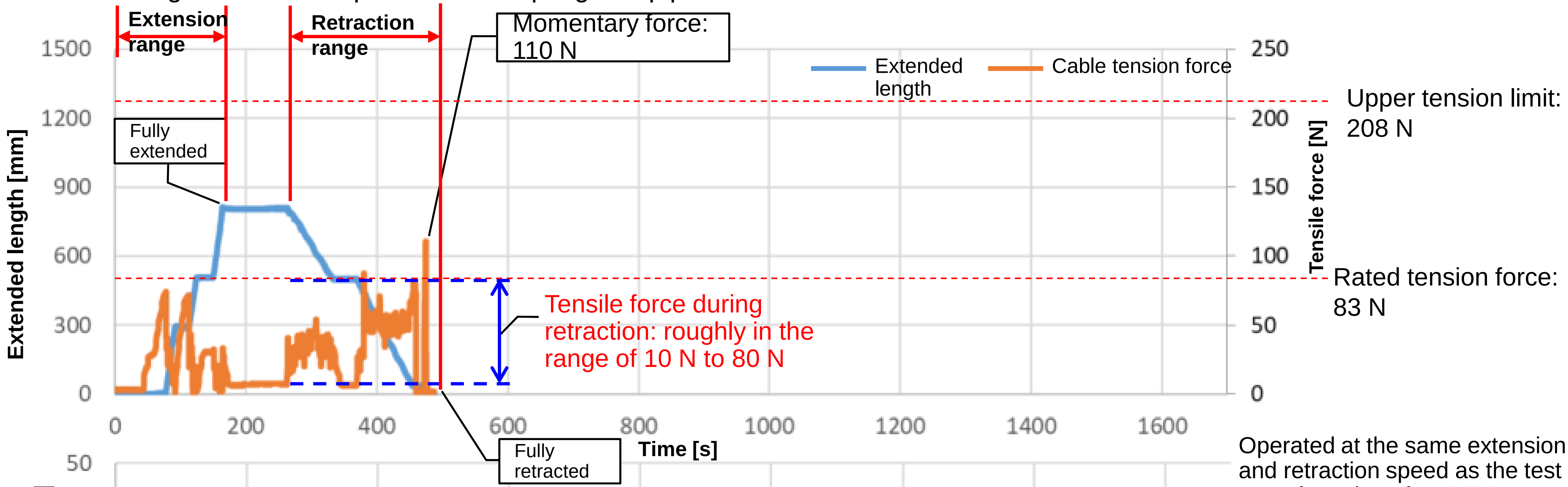
6. Implementation details

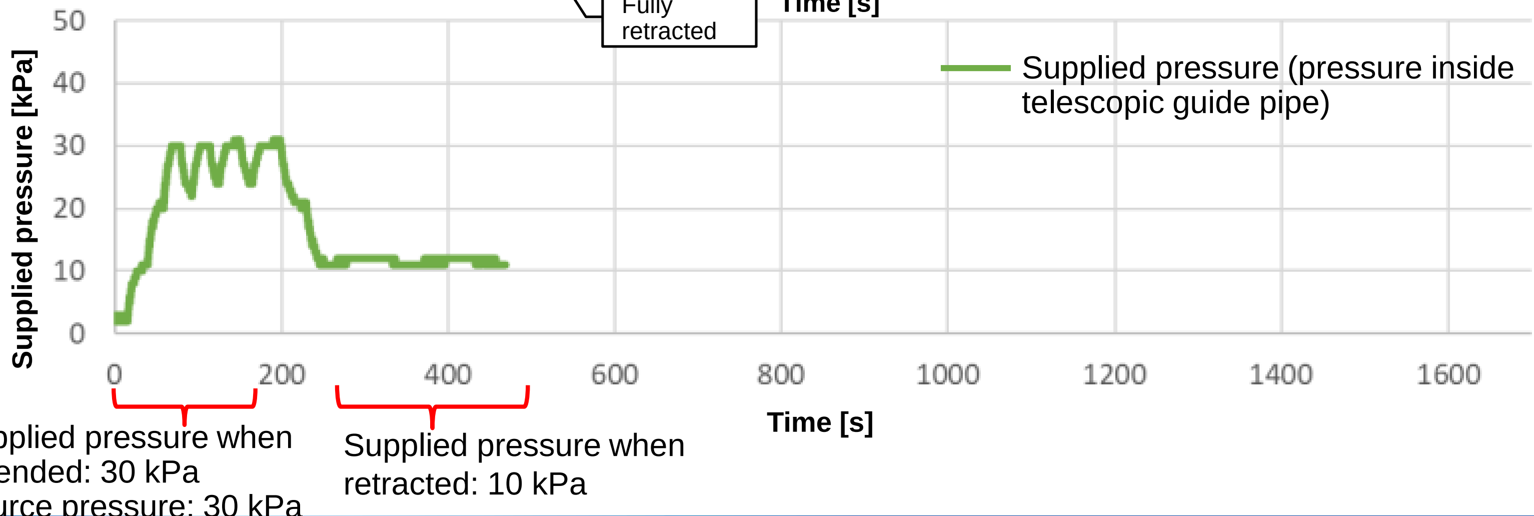
(2) Development of the bottom access investigation method (telescopic pipe)

3) (c) Test to verify the effect of proposed countermeasures

<3. Section verification test>

Test results of extension/retraction operations for the test manufacturing of FY2021 improved telescopic guide pipe





Operated at the same extension and retraction speed as the test manufacturing of FY2020 telescopic guide pipe (extension: 20 mm/s, retraction: 5 mm/s).
When the pressure decreased due to extension operation, the time to reach the desired pressure (30 kPa) was shorter than that of the test manufacturing of 2020 telescopic guide pipe.
The tension force during retraction could be kept within a range roughly equal to or less than the rated tension force of the cable winder.

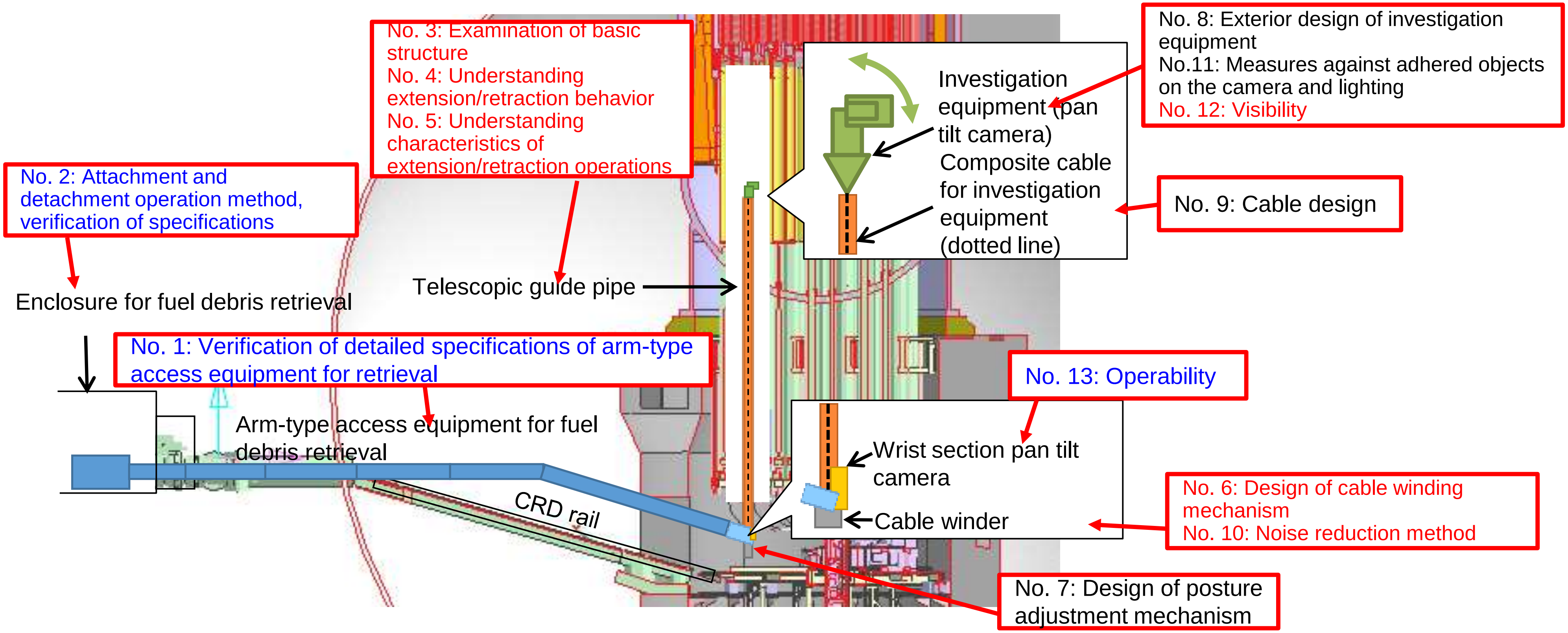
6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

(4) (d) Conceptual study and simplified test for development issues: Development plan formulated last fiscal year

Red: Items to be verified by testing in FY2021

Blue: Items related to specifications of the access equipment under development in other projects



The feasibility of the unit of telescopic access equipment was evaluated in FY2020 and FY2021.

IRID

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues: Development issues and action policy 1/2

No.	Major items	Intermediate items	Minor items	Development issues	FY2021 action policy	FY2021 test/implementation items
1	Access equipment into the pedestal	Verification of connection with the arm-type access equipment for retrieval	Verification of detailed specifications of arm-type access equipment for retrieval	- Tip positioning accuracy - Arm deflection/oscillation - Range of motion of each axis - Transportable weight - Arm external cable specifications - Emergency action policy	- The information that contributes to the study of equipment specifications is confirmed by the project team of "Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris."	Interviewing from other projects
2			Attachment and detachment operation method, verification of specifications	- Verification of feasibility of procedures/transport casks for transfer in and out of the enclosure - Installation and removal methods using the maintenance arm	- The information that contributes to the study of equipment specifications is confirmed by the project team of "Development of Technology for Further Increasing the Retrieval Scale of Fuel Debris."	Interviewing from other projects
3	Access equipment from inside the pedestal to inside the RPV	Telescopic access equipment design	Examination of basic structure	- Structural feasibility under the dimensional constraints imposed by use of an arm-type access equipment for retrieval	- Design review - The impact of environmental conditions on the strength of connecting parts depending on changes of materials and more are understood by verification tests of a prototype.	Verification test of the strength of the connecting part
4			Understanding extension/retraction behavior	- Joint connection accuracy (pipe tilt) - Swaying during extension (investigation equipment section) - Amount of tip misalignment (looseness/deflection) during vertical extension - Verification of extension/retraction behavior when telescopic pipe is inclined - Verification of extension/retraction behavior when snagged (whether telescopic pipe can expand/retract when snagged, and whether telescopic pipe can retract when investigation equipment is snagged) - Effects of adhered objects on extension/retraction behavior	- Design review - Behaviors of the proposed 3-stage telescopic pipe that is improved for the sliding resistance are understood as information that contributes to the examination of equipment specifications. - Verification of the 14-stage telescopic pipe prototype	Verification test of parts⇒ (c) Feasibility verification test of the 14-stage telescopic pipe⇒ (e)
5			Understanding characteristics of extension/retraction operations	- Required air pressure during extension - Positioning control - Sliding resistance between air packing and telescopic pipe - Sliding resistance of telescopic rotation control guide	- Design review - The sliding resistance of the seal under the assumed environmental conditions (dose and temperature) and the effect on sealing efficiency are determined through test manufacturing verification. This information contributes to the study of equipment specifications to determine whether or not to adopt the proposed countermeasures - Behaviors of the proposed 3-stage telescopic pipe that is improved for the sliding resistance are understood as information that contributes to the examination of equipment specifications. - Verification of the 14-stage telescopic pipe prototype	Verification test of sealing function ⇒ (c) Verification test of parts ⇒ (c) Feasibility verification test of the14-stage telescopic pipe⇒ (e)

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues: Development issues and action policy 2/2

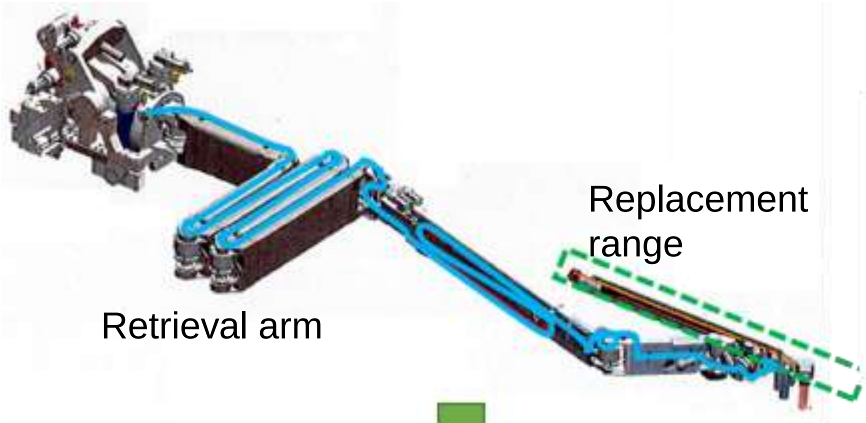
No.	Major items	Intermediate items	Minor items	Development issues	FY2021 action policy	FY2021 test/implementation items
6	Access equipment from inside the pedestal to inside the RPV	Telescopic access equipment design	Design of cable winding mechanism	- Accuracy of wire tension force measurement (whether slack can be detected) - Coordinated control of cable winding force and air pressure during telescopic extension and retraction - Limit detection - Mechanical arrangement (X6 penetration passage, arm interference) - Pressure-resistant box design (approx. 0.1 MPa)	- Design review - Confirm improved cable winder torque through test manufacturing verification - Test manufacturing verification using a 14-stage telescopic pipe	Test to verify cable winder torque improvement 14-stage feasibility verification test ⇒ (e)
7			Design of posture adjustment mechanism	- Mechanical arrangement (X6 penetration passage, arm interference)	- Design review	Theoretical study
8	Investigation equipment	Investigation equipment design	Exterior design of investigation equipment	- X6 penetration, interference with reactor internals	- Design review	Theoretical study
9			Cable design	- Diameter reduction (target: Φ6 or less) - Tensile strength	- Design review	Theoretical study
10			Noise reduction method	- Noise during rotation when using slip rings (dosimeter)	- Design review - Evaluation of dosimeter noise using slip rings	Slip ring noise evaluation
11			Measures against adhered objects on the camera and lighting	- Effects of water droplets and adhered objects, etc. on the camera and lighting	- Design review	Theoretical study
12			Visibility	- Verification of long-distance visibility when there is machinery/structures near the camera (halation problem) - Understanding characteristics of visibility deterioration due to radiation dose	- Design review - Evaluation of camera visibility for consideration of CMOS camera adoption	Evaluation of camera visibility
13	Others	Operability	Operability with camera	- Whether the operational situation (such as contact with structures) can be determined clearly enough, by investigation equipment/wrist section camera, to enable operation	- Design review	Theoretical study
14		Emergency response	Examination of items to be expected in case of emergency	- Response to power cutoff (disconnection, etc.), control failure (software excursion), control line disconnection, etc. - What kind of events, such as seismic activities and blackouts, should be expected?	- Design review	Theoretical study

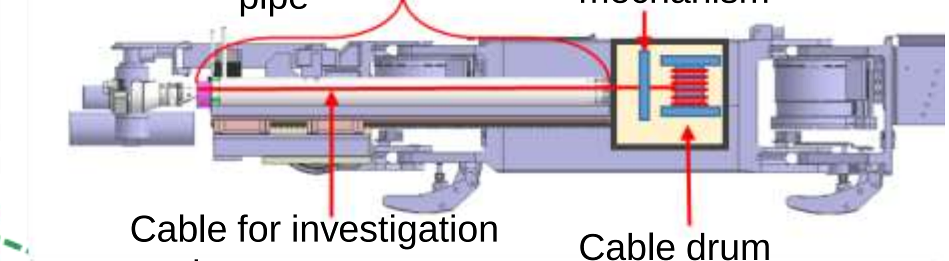
6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

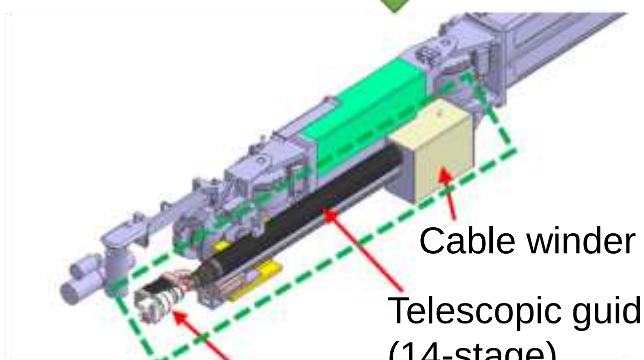
4) (d) Conceptual study and simplified test for development issues

<1, 2 Verification of connection with arm-type access equipment for retrieval>

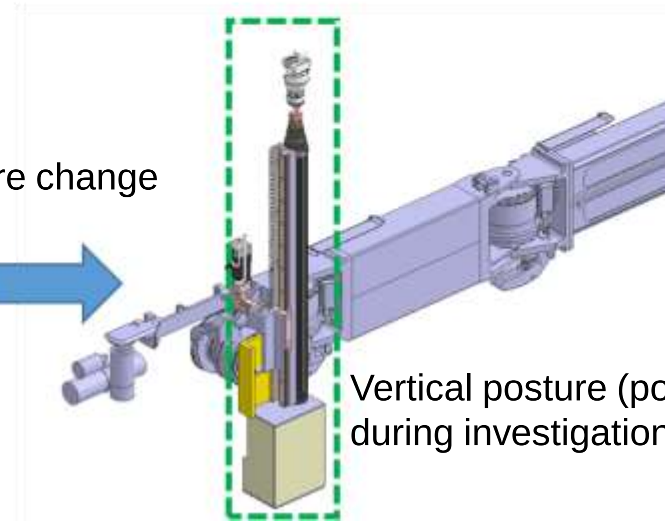




Replacement



Posture change



6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

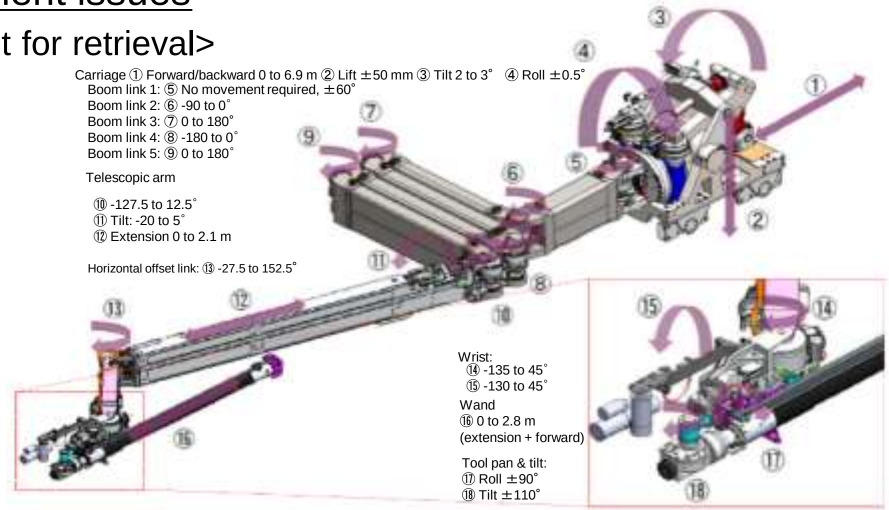
4) (d) Conceptual study and simplified test for development issues

<1, 2. Verification of connection with arm-type access equipment for retrieval>

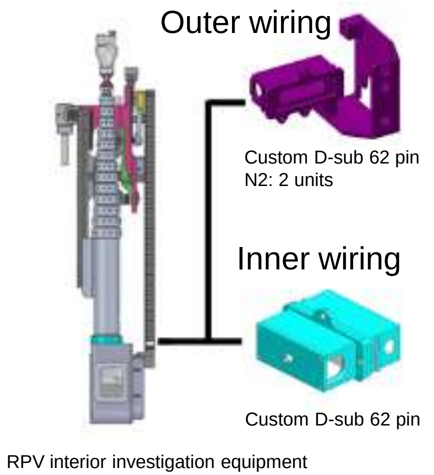
In meetings with other project teams, RPV interior investigation equipment is being adjusted to specifications for installation to replace the wand. In regards to retrieval arms, it will be necessary to feedback on detailed specifications in reference to various design and evaluation information.

○ Main future verification items
- Arm wrist posture of the expected investigation equipment (just below the opening)
- Minor adjustment accuracy and vibration of the arm
- Interference between inner wiring connector and 14-axis actuator
- Automatic attachment/detachment method for outer wiring
- Others

Items		Specifications
Tip positioning accuracy		±50 mm or less
Arm deflection		140 mm or less Boom link tip: approx. 80 mm or less Single telescopic arm: approx. 60 mm or less
Arm vibration		±10 mm (within 5 minutes: target value) * Detailed survey arm result
Range of motion of each axis		See figure on the right
Wrist axis carrying capacity	Transportable weight	40-45 kg (Wand: 25-30 kg, Tool: 15 kg)
	Allowable torque	1263 Nm
Cable specifications	For wand (inside)	Twisted pair: 18 Pair (36 core) Parallel: 24 core
	For tools (outside)	Control cable: 3 (20 core, 8core, 2 core) Motor cable: 1 (16 core) Coaxial cables: 8 N2 hose: 2 hoses (O.D. 6 mm × I.D. 4 mm) Water hose: 1 (O.D. 6 mm × I.D. 4 mm)
Emergency action policy		Cut the wand and throw it into the pedestal



Range of motion of retrieval arm



Types
Survey camera control (camera, lighting, pan & tilt)
Dosimeter
Control of cable winding
N2

Types
Survey telescopic pipe forward/backward control
Survey telescopic pipe attitude control (α axis)
Survey telescopic pipe attitude control (β-axis)

Cable specifications (outer, inner wiring)

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues

<3. Examination of basic structure>

Consideration of adopting aluminum as an alternative pipe material

Main target specifications			CFRP (inner and outer UD surface)	Aluminum (A7075)	Remarks
Operability	Pipe outer diameter	Φ100 (1st stage) to Φ35 (14th stage)	Manufacturable	Manufacturable	Since manufacturing issues were expected with the CFRP pipe, a 3-stage aluminum tip was test-manufactured as an alternative Aluminum is difficult to manufacture with 1 mm wall thickness, and only one company accepted the order under target precision conditions (test manufacturing), so the evaluation was performed on the test manufacturing of a thin pipe (12th, 13th, and 14th stages: inner diameter Φ40 to Φ30 test manufactured), which is difficult to make more rigid with CFRP. Result: approx. 0.3 mm warp in the 13th stage, preventing full retraction into the 12th stage. The previously manufactured aluminum telescopic pipe (investigation inside the 1F2_PCV (A2)) has a 2.5 mm wall thickness. With this thickness, if the maximum outer diameter is less than Φ100, only a 7-stage structure can be made, which has insufficient reach even at full extension (cannot access the bottom of the reactor)
	Pipe length	431.5 mm (1st stage) to 658.2 mm (14th stage)	Manufacturable	Manufacturable	
	Number of pipe stages	14	Manufacturable	Manufacturable	
	Pipe thickness	1 mm or less	Manufacturable	Difficult to guarantee shape tolerance	
	Outer diameter tolerance	+0.2/0 mm	Manufacturable	Manufacturable	
	Inner diameter tolerance	H9 1st stage: Φ95 +0.087 to 0 13th stage: Φ35 +0.062 to 0	Difficult to guarantee accuracy After manufacturing at +0.4/0 mm, match up the components that join together (pistons, etc.) in order to adjust their dimensions	Manufacturable	
	Linearity	0.1 mm or less	Manufacturable	Processing difficulties 13th stage actual result: 0.3 mm	
	Roundness	0.2 mm or less	Manufacturable	Manufacturable	
	Inner surface roughness	Ra 3.2 or less	1.6 (actual result)	0.3 (actual result)	
Strength	Tensile strength (axial direction)	100 MPa or more	Pipe stages 2 to 9: 796 MPa Pipe stages 10 to 14: 618 MPa	570 MPa	
	Tensile strength (circumferential direction)	100 MPa or more	Pipe stages 2 to 9: 603 MPa Pipe stages 10 to 14: 129 MPa	570 MPa	CFRP: High-strength pre-preg (*1) cannot be used for stages 10 to 14 because of the small pipe diameter, so circumferential tensile strength is low
	Safety factor (0.3 MPa pressure resistance)	15 or higher	Pipe stages 2 to 9: 45 Pipe stages 10 to 14: 20	38	CFRP: High-strength pre-preg(*1) cannot be used for stages 10 to 14 because of the small pipe diameter, so the safety factor is low, but not low enough to be an issue
	Deflection	10 mm or less Looseness of each stage not included	2.0 mm	3.4 mm	Structural analysis assuming zero looseness (adhesion condition) for each telescopic stage
Weight	14-stage weight	9 kg or less	8.0 kg	9.4 kg	Investigation equipment not included Excluding pipes; scrapers, pistons, stopper rings, etc. included
Robustness	Cumulative dose resistance	7200 Gy or higher	7200 Gy or higher	7200 Gy or higher	3 days or more at 100 Gy/h
	Abrasion/repeatability	1 or more surveys possible	Required evaluation	Required evaluation	

*1: Pre-preg: A sheet-like intermediate material in which carbon fiber, etc., is pre-impregnated with resin. Pre-pregs are laminated to form the product.

There is an issue in manufacturing (processing) for adopting aluminum.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

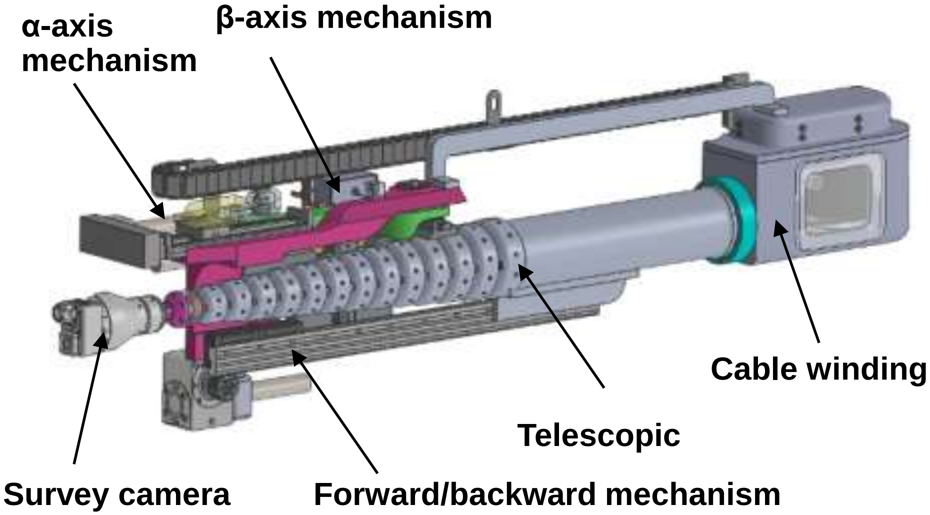
4) (d) Conceptual study and simplified test for development issues <7 Design of posture adjustment mechanism>

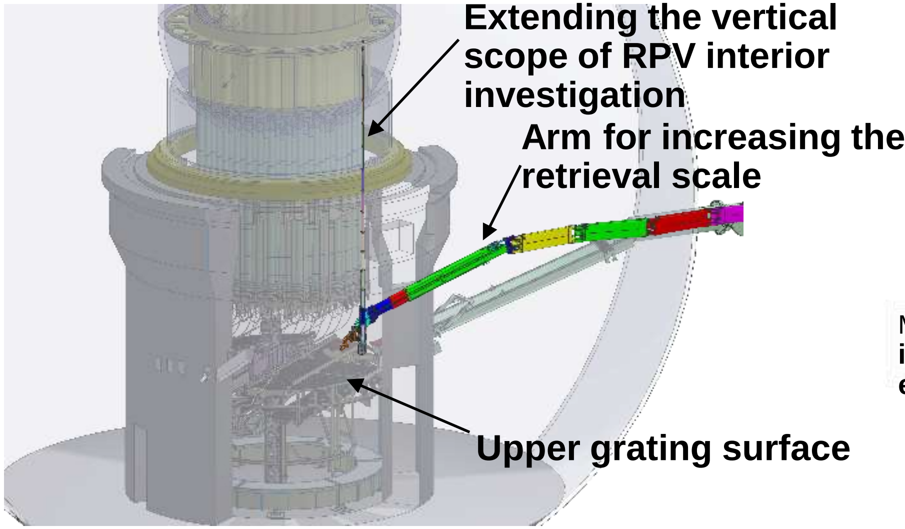
○ Posture adjustment mechanism

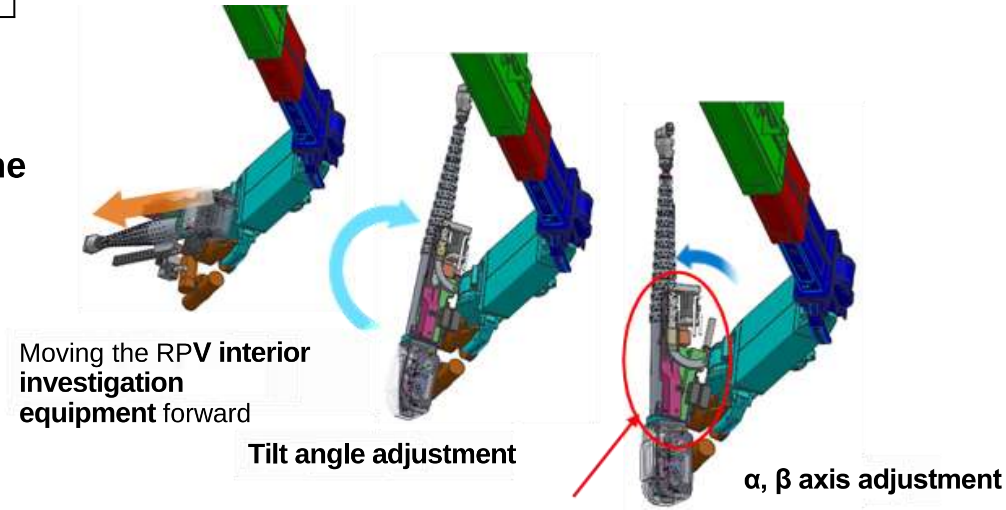
Due to the degree of freedom of the retrieval arm, it may be difficult to set the RPV interior investigation equipment in a vertical position at the expected survey location. Therefore, installation of a 2-axis posture adjustment mechanism on the same side of the RPV interior investigation equipment was considered.

○ Specifications of posture adjustment mechanism

		Forward/backward drive	α-axis	β-axis
Range of motion		581 mm or greater	13° or more	20 mm or more
Positioning accuracy		±1 mm or less	±0.01° or less	±1 mm or less
Weight (kg)		8 kg or less	7 kg or less	5.5 kg or less
Size (mm)		W: within 1100 mm H: within 400 mm D: within 150 mm	W: within 600 mm H: within 250 mm D: within 200 mm	W: within 430 mm H: within 150 mm D: within 200 mm
Radiation resistance	Dose rate (Gy/h)	100	100	100
	Cumulative dose (Gy)	7200	7200	7200







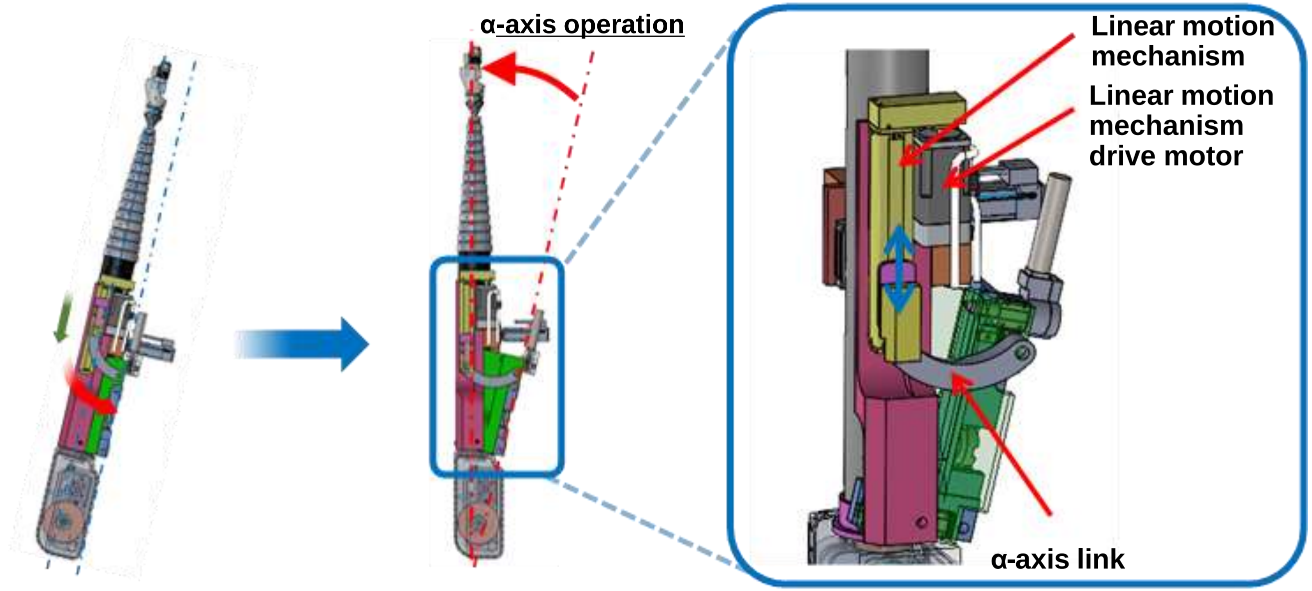
Telescopic posture adjustment mechanism

6. Implementation details

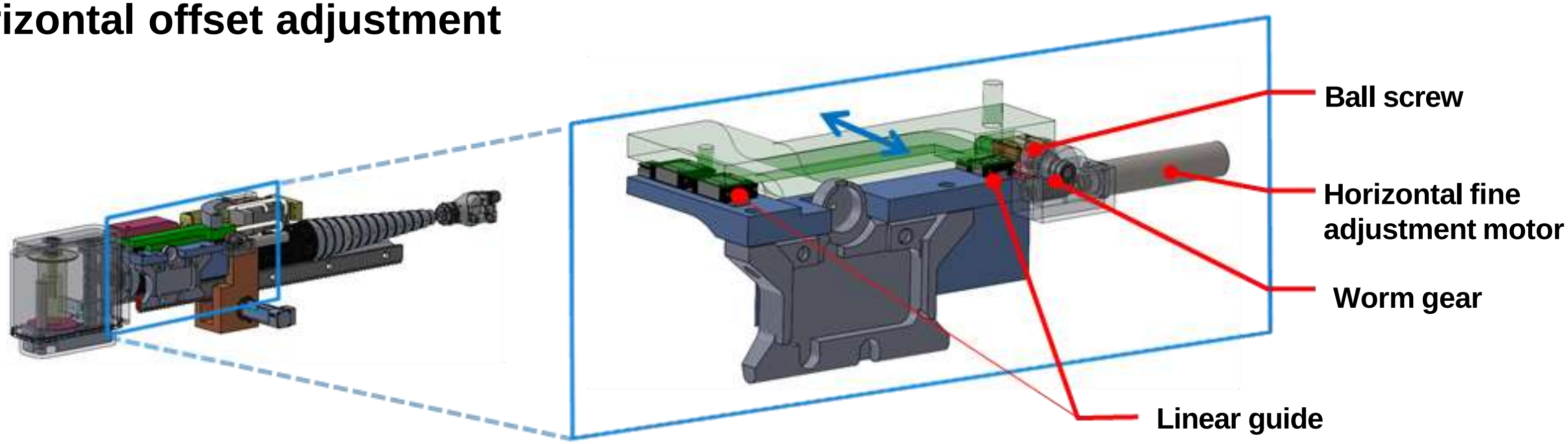
(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues <7. Design of posture adjustment mechanism>

α-axis mechanism: angle adjustment



β-axis mechanism: horizontal offset adjustment



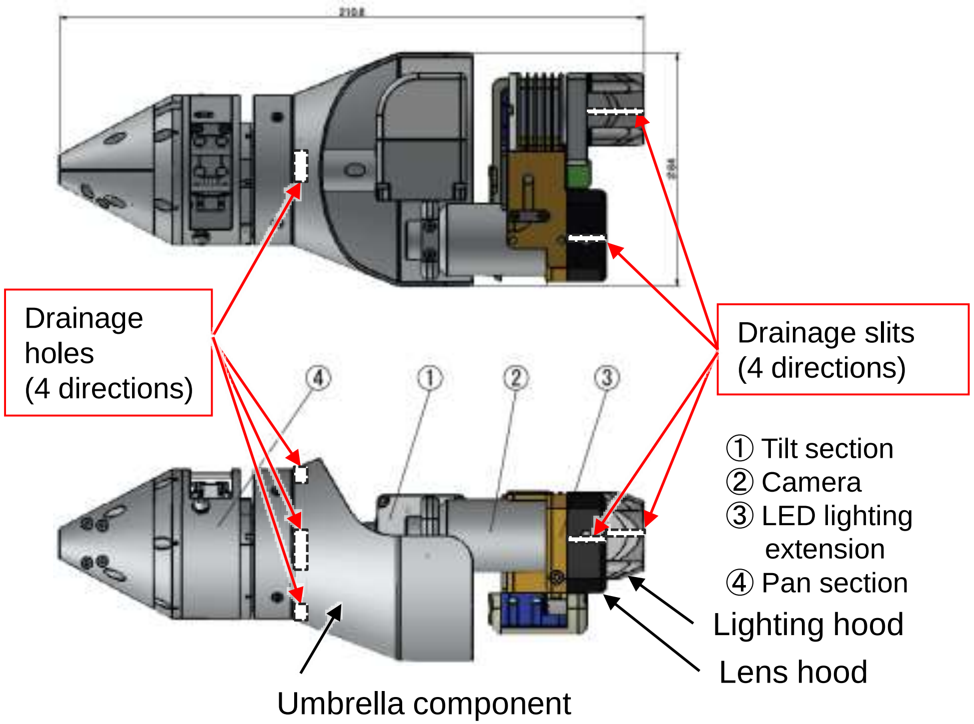
6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues <8. Exterior design of investigation equipment>

For investigation equipment, the policy is to use a camera with a pan/tilt drive shafts developed for the investigation inside the PCV. The investigation inside the PCV was carried out by suspending the cable for investigation equipment, but in this investigation, the cable is used facing upward, so countermeasures to address issues arising from the difference in orientation were considered.

The umbrella component served to prevent the investigation equipment from getting caught on structures during the investigation inside the PCV, and to prevent dripping reactor cooling water from splashing on the camera and drive unit. In this investigation, the same functions can be expected in terms of preventing snagging, but there is a risk of dripping water accumulating inside the umbrella component. Expecting that water will accumulate in the camera lens section and lighting hood, it was decided to provide drainage holes and slits. In addition, when used in the upward direction, there is a risk of water intrusion into pan/tilt drive shafts and joints of combined components. A policy of devising countermeasures such as sealing reinforcement and mold treatment for each component was adopted.



Investigation equipment specifications

Items	Specifications
Outer dimensions	Φ84 [mm] × L210 [mm]
Weight	0.7 [kg]
Mounted camera	Color CCD camera or color CMOS camera
Lighting	LED lighting (10 [W] x 1, variable distance between camera and optical axis, maximum 105 [mm])
Visible range	238[°] (vertical angle of view 17.8[°] + tilt 110[°], pan ±180[°])
Mounted sensors	Dosimeter (1 [Gy/h] to 2000 [Gy/h] measurable), thermometer (0 to 50 [℃], accuracy ±0.5 [℃] (obtained as reference information))
Radiation resistance	1000 [Gy] (from radiation resistance of CCD camera)

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

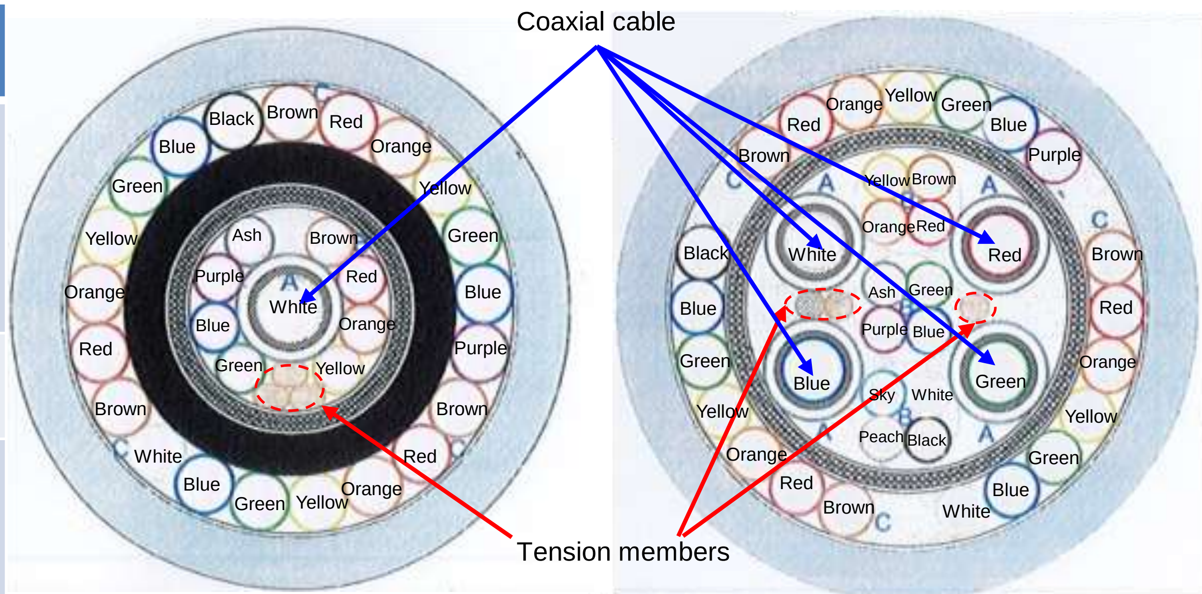
4) (d) Conceptual study and simplified test for development issues <9. Cable design>

In order to extend the telescopic guide pipe to its maximum length, the cable must be wound for 6.1 m + winding allowance (approx. 700 mm) with a small cable winder. In FY2020, a thinner cable was designed, with a permissible bending radius of R35 mm or less so that it can be wound by a Φ70 mm cable drum of a small cable winder. On the other hand, since the extension/retraction operation test of the 3-stage telescopic guide pipe revealed that the cable needs to be pulled with a force of about 270 N, which is larger than expected when the cable is pulled to retract the telescopic guide pipe, an improved design to increase the cable's tensile strength was implemented this year.

Camera options for inclusion in the investigation equipment include CMOS and CCD cameras, so both cables were considered. The diameter of a cable was reduced to a level that allows it to be wound up to the required length with a small cable winder, and a cable with a tensile strength of 750 N was designed.

Cable specifications

Items	Required specifications	Design result for CMOS	Design result for CCD	Remarks
Diameter	Target 6 mm or less	5.8 mm	6.5 mm	If CCD cable is used, verification is necessary because it may be possible to wind the required length to 8 mm
Tensile strength	270 N or greater	750 N	750N	FY2020 design is 250 N
Number of cores	CMOS 29 single wires 1 coaxial cable	29 single wires 1 coaxial cable	29 single wires 4 coaxial cables	—
	CCD 29 single wires 4 coaxial cables			



Cross section view of CMOS camera cable

Cross section view of CCD camera cable

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues

<10. Noise reduction method: Evaluation of dosimeter noise using slip rings>

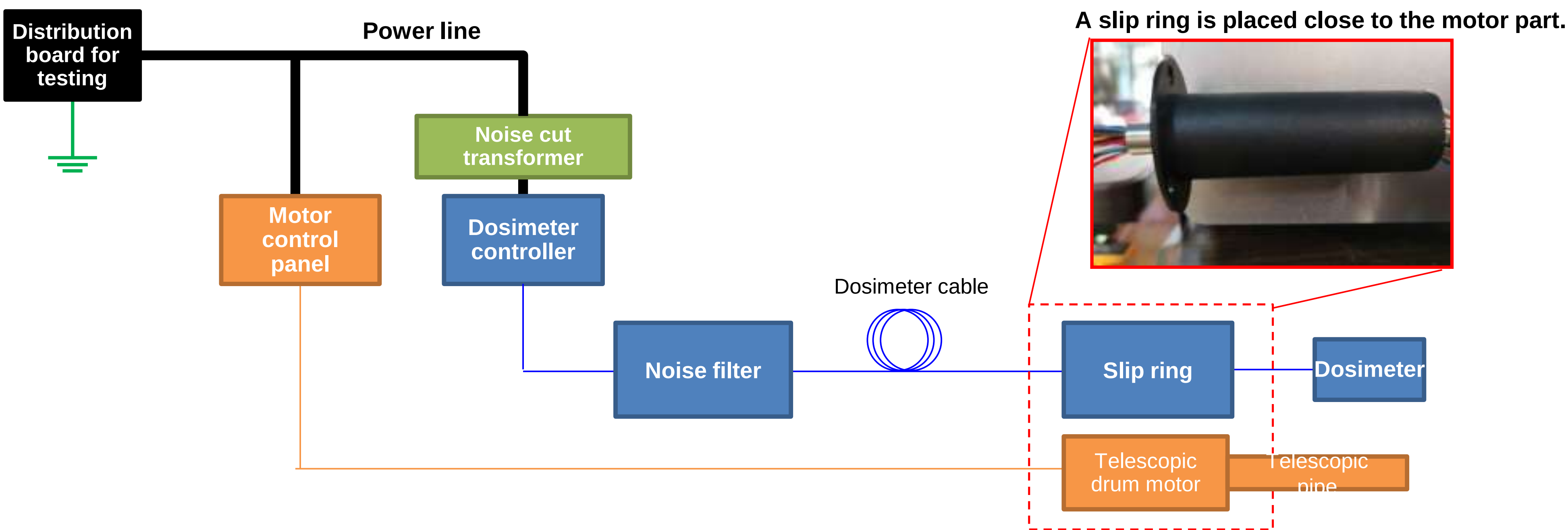
○ Purpose

Since the dosimeter to be used needs to transmit a very small current, it tends to generate noise and leakage current in areas with mechanical contacts such as connectors, where the electromagnetic shield is locally discontinuous. In particular, because slip rings contain rotating electrodes and are considered relatively vulnerable to noise, tests to verify noise effects will be conducted.

○ Test overview

① The effects on electromagnetic noise are verified when the cable drum drive motor operates near the slip ring

② The selected dosimeter element is connected through a slip ring and verify the effects of noise and leakage current.



6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues

<10. Noise reduction method: Evaluation of dosimeter noise using slip rings>

○ Test results

① Electromagnetic noise was effected when the cable drum drive motor operates near the slip ring.

- ◆ When acquiring data under conditions where the dosimeter does not output a measurement signal, the motor was driven at 100% load.
- ➢ Dosimeter controller output became unstable and an abnormal current value (instrument over-range) was recorded.
- ➢ It was verified that occurrence of an abnormal current value was suppressed by use of a noise filter in the dosimeter signal transmission line.

➡ It was verified that the effects on electromagnetic noise can be suppressed by using a noise filter.

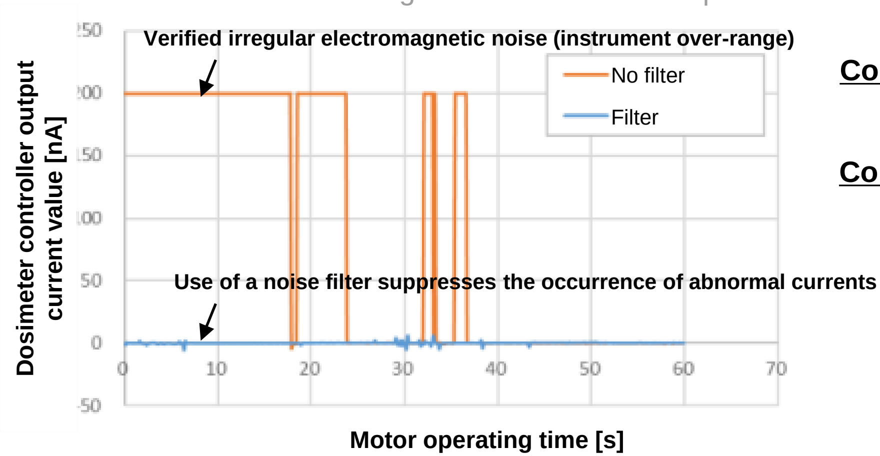
② The selected dosimeter element was connected through a slip ring to verify the effects of noise and leakage current.

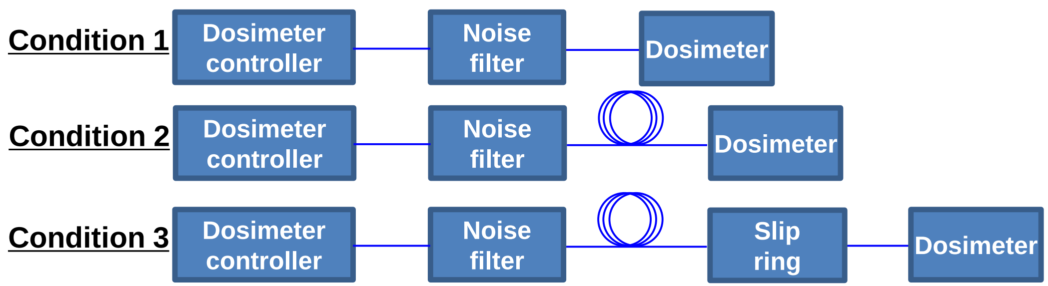
- ➢ With a simulated measurement signal (10 nA; equivalent to 20 [Gy/h]*) flowing through the dosimeter transmission line, the dosimeter cable and slip ring were inserted into the transmission line and the effects were verified.
- ➢ It was verified that the leakage current generated by the cable and slip ring is about 0.03 nA (equivalent to 0.06 Gy/h*).

*The conversion factor is diverted from the calibration data collected during the investigation inside the 1F-2 PCV

➡ It was verified there is no problem in the leakage current since it is a small amount compared to the expected environmental dose of 100 Gy/h.

Effects of electromagnetic noise on motor operation





Test conditions	Current value [nA]	Leakage current value [nA]
Condition 1	**10.055**	— (standard)
Condition 2	**10.035**	**0.020**
Condition 3	**10.028**	**0.027**

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

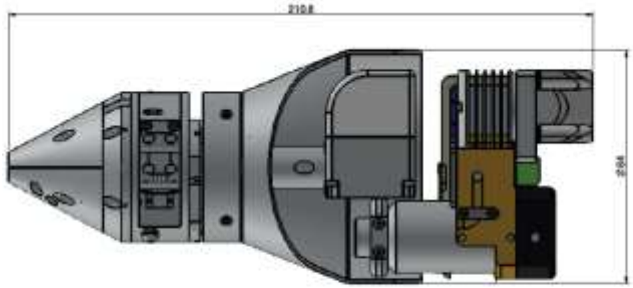
4) (d) Conceptual study and simplified test for development issues

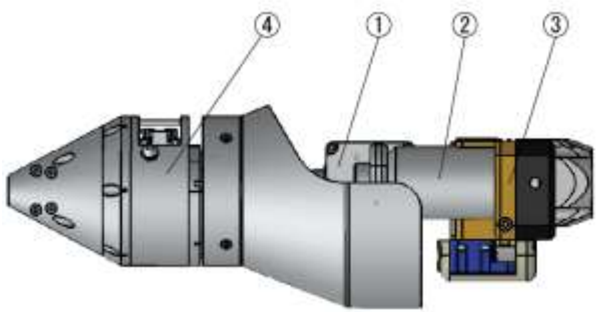
<11. Measures against adhering objects on cameras and lighting>

From results of previous investigations inside the PCV, it was verified that the surfaces of structures inside the PCV are covered with foreign substances such as mud and sand. Since the investigation equipment is mounted in an upward-pointed position on the telescopic access equipment to access into the inside of the RPV, foreign substances from structure surfaces may adhere to the camera and lighting when the investigation equipment is in motion, impairing visibility.

A new mechanism such as a wiper could be incorporated, but to drive the actuator, the number of cable cores for the investigation equipment needs to be increased. This would increase cable diameter, and the cable winder would not be able to wind the length of cable needed for telescopic guide pipe extension.

Therefore, as measures to remove adhered objects, the operational policy is to wash it away with cooling water that drips from the furnace, and if necessary, to tilt the investigation equipment so that the camera and lighting are at an angle that causes the objects to fall off.





① Tilt section
② Camera
③ LED lighting extension
④ Pan section

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues

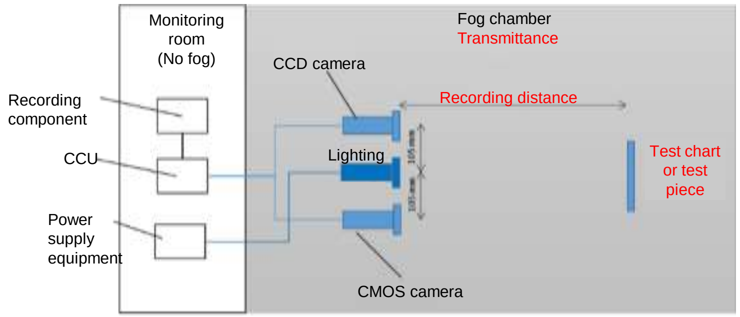
<12 Evaluation of camera visibility in consideration of CMOS camera adoption>

○ Purpose

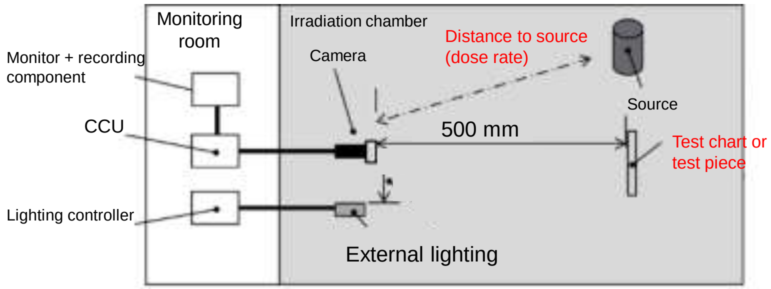
For the purpose of adopting CMOS cameras for thinner cables, the visibility is evaluated in foggy and radiated environments.

○ Test overview

In a foggy environment, visibility is evaluated when light transmittance varies due to changes in fog concentration. In addition, by radiation resistance testing, evaluate the effects of radiation noise on dose and the effects of cumulative doses of 1000 Gy or more.

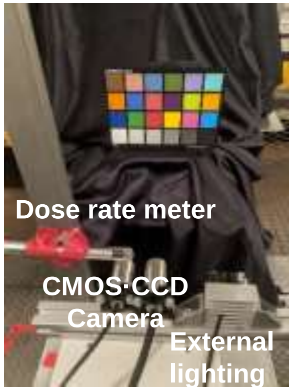


Proposed system for foggy environment testing



Proposed system for radiation resistance testing

Guiding system performance test



Guiding system performance test

6. Implementation details

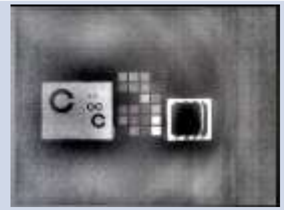
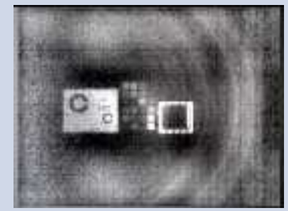
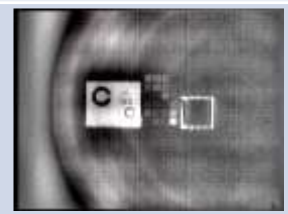
(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues

<12 Evaluation of camera visibility in consideration of CMOS camera adoption>

○ Foggy environment test results

Foggy environmental condition (estimated value at Unit 1 of Fukushima Daiichi Nuclear Power Station): Absorption coefficient 0.511
An absorption coefficient of 0.511 gives a transmittance of approx. 21.6% at a distance of 3000 mm. In this evaluation, a transmittance of 20%/3000 mm is evaluated as equivalent to a transmittance of 0.511

		Distance to object [mm]			
		1000	2000	3000	4000
CMOS	Before image processing				
	After image processing				
CCD	Before image processing				
	After image processing				

It was verified that that Landolt rings (20 mm opening) can be observed at up to 4000 mm, and simulated fuel rods (Φ10 mm) at up to 2000 mm by using both the CMOS and CCD cameras.

⇒ There was no difference of visibility between CMOS and CCD cameras in a foggy environment

6. Implementation details

Units 2 and 3

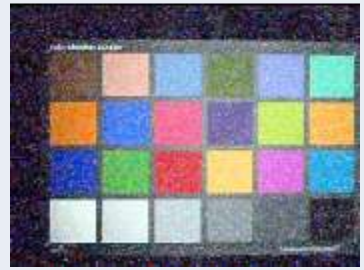
No.119

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues

<12 Evaluation of camera visibility in consideration of CMOS camera adoption>

○ Radiation resistance test results (effects of dose rate)

	Dose rate (Gy/h)			
	0 (unirradiated)	150	590	1850
CMOS				
CCD				

It was verified that video output was possible up to 1850 Gy/h, although both the CMOS and CCD cameras generated noise due to radiation.

⇒ There was no difference in visibility (dose rate effects) between CMOS and CCD cameras in a radiation environment.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues

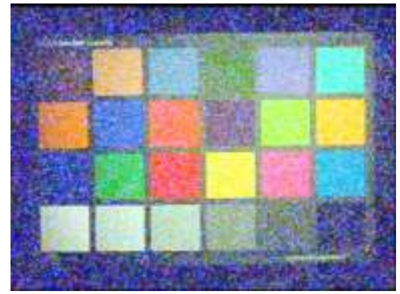
<12 Evaluation of camera visibility in consideration of CMOS camera adoption>

○ Radiation resistance test results (effects of cumulative dose, conducted only with CMOS cameras)

External lighting 1100lx

Before test
Unirradiated

During irradiation
Dose rate: approx. 1850 Gy/h

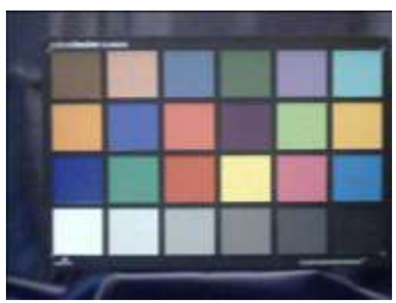


During irradiation (immediately before the end of the test)
Cumulative: 1600 Gy or more
Dose rate: approx. 340 Gy/h

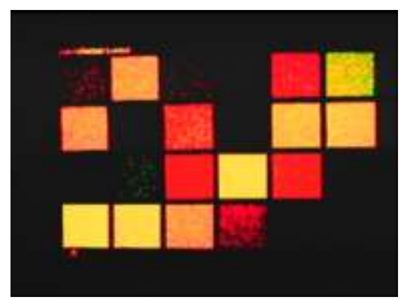
After test
Cumulative: 1600 Gy or more
Unirradiated

- ✓ After an irradiation test with a cumulative dose of at least 1600 Gy was conducted, and output of video images was verified. The CCD camera was tested in the same way as in the past investigation inside the PCV, and the contrast decreased after 1100 Gy irradiation
- ✓ After irradiation, an event that video images were distorted in low light intensity was verified. It is estimated that the gain control section of the camera was damaged due to the irradiation.
⇒ It is necessary to conduct an impact assessment on investigations of the cumulative dose that causes video distortions in low light intensity, and video alterations due to the cumulative dose

Laboratory lighting 36lx



Before test



After test

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

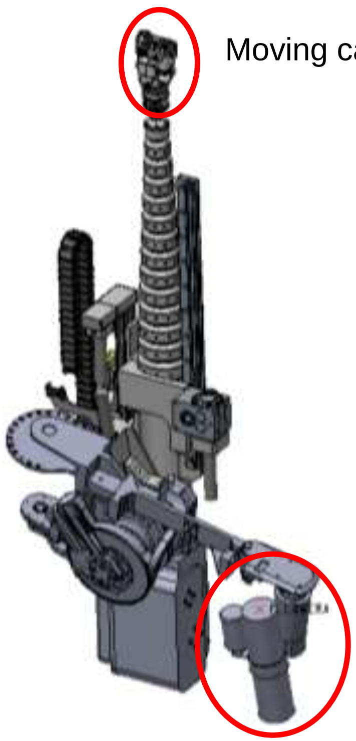
4) (d) Conceptual study and simplified test for development issues <12 Operability with camera>

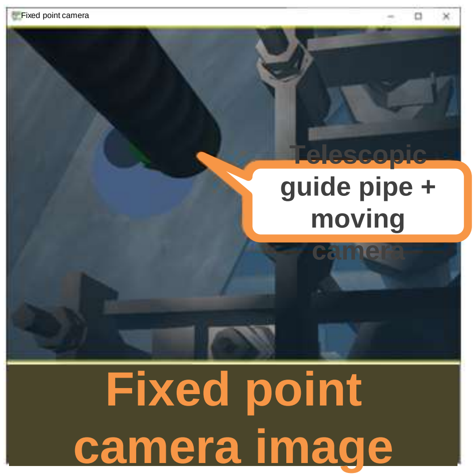
〇 Purpose

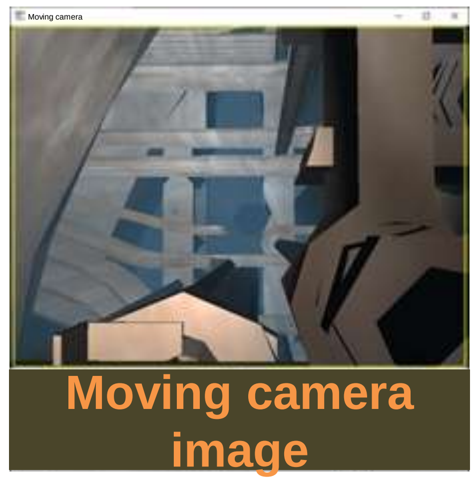
The purpose of investigating inside the RPV is to verify the visibility-ensuring camera mechanism and its operational method, by means of a simulator that allows to verify simulated reactor interior images.

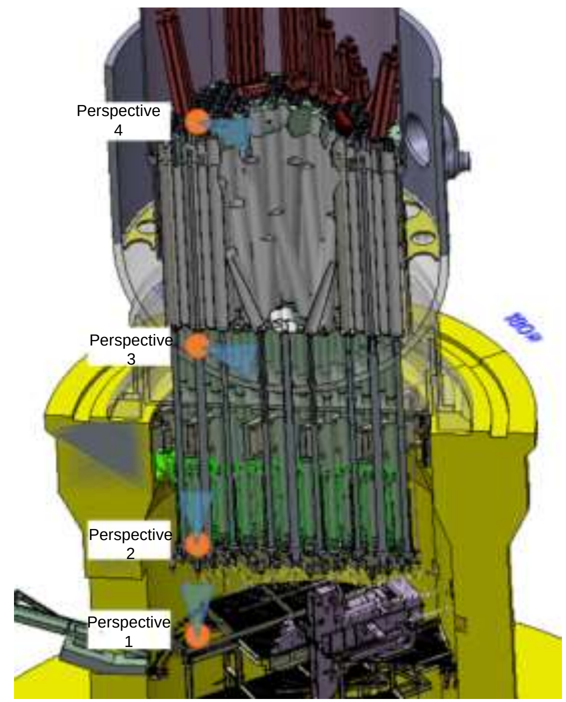
〇 Study outline

Two simulated video images (object display and overhead view from a fixed point) are acquired simultaneously from the camera mounted on the arm access equipment for retrieval (fixed point camera) and the camera mounted on the investigation equipment (moving camera).









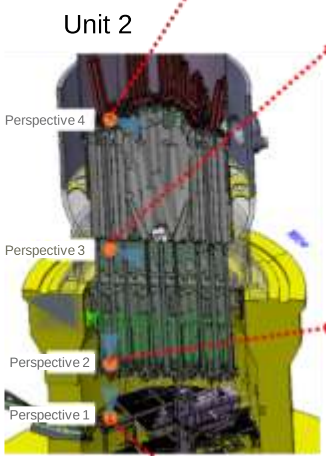
3D model of the structure used

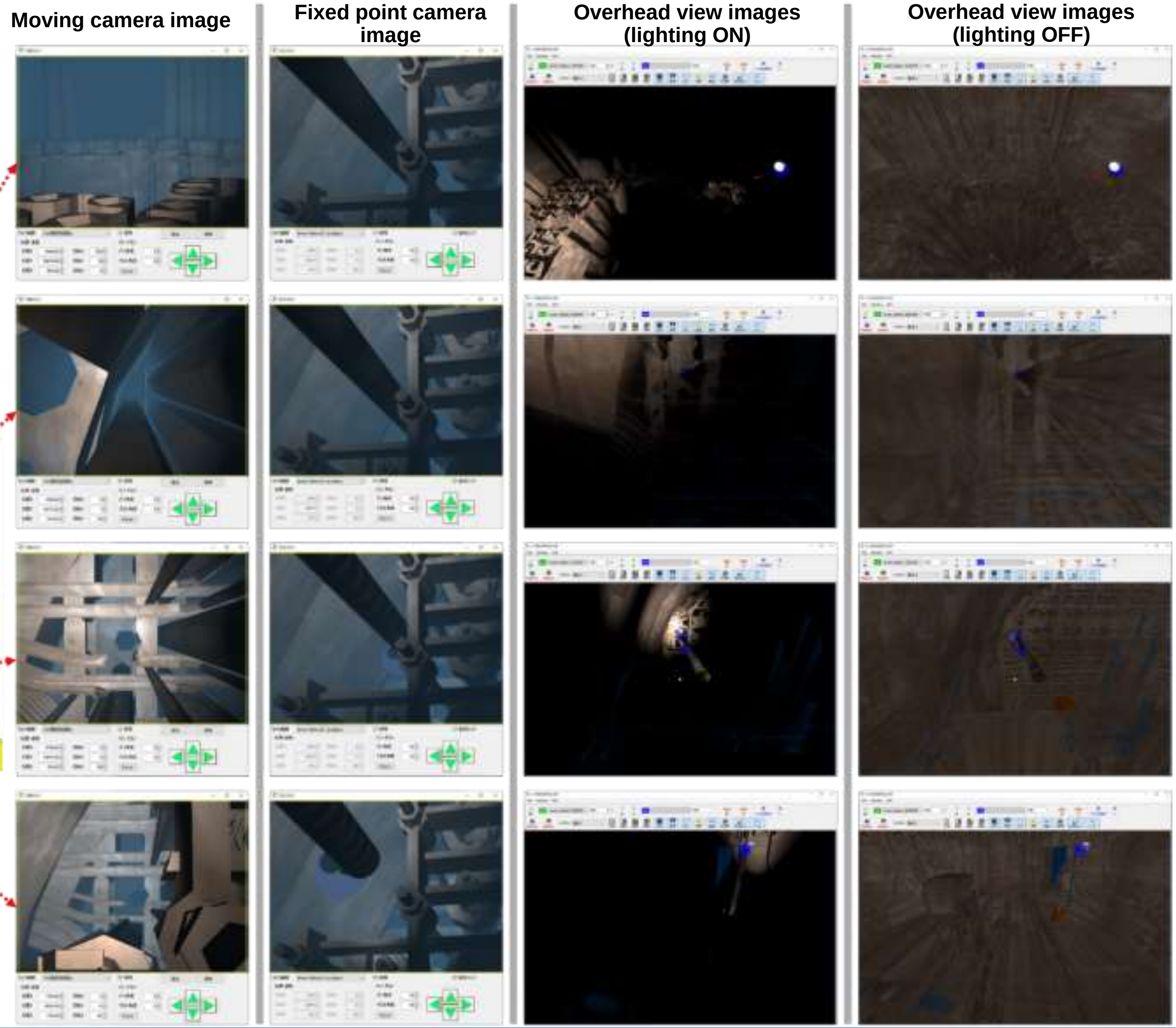
6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues <12 Operability with camera>

Simulated images and overhead view at each simulator perspective (Unit 2)



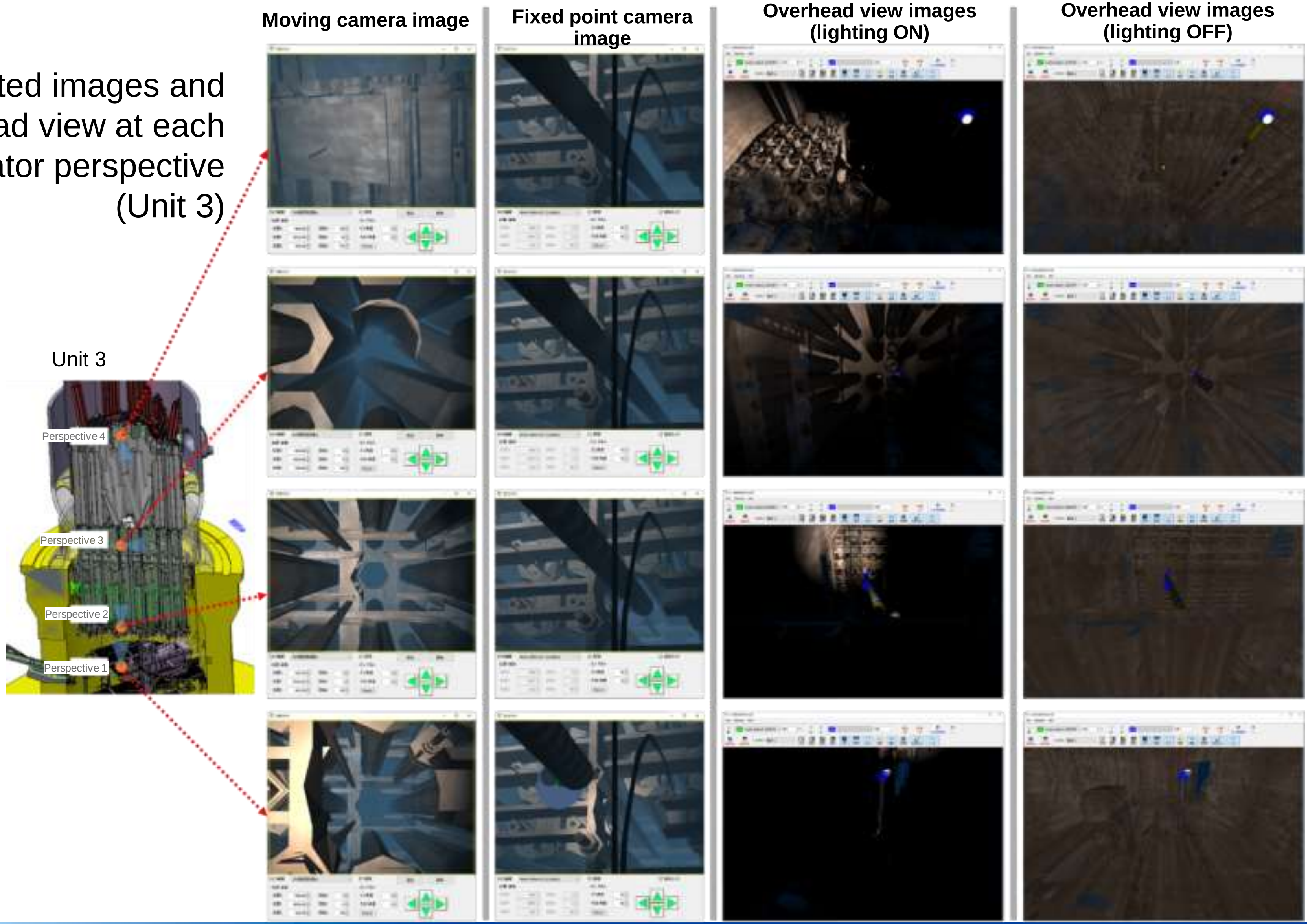


6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues <12 Operability with camera>

Simulated images and overhead view at each simulator perspective (Unit 3)



6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues

<13 Examination of items to be expected in case of emergency>

The equipment placed inside the PCV for the investigation should be collected in the enclosure after the investigation is completed in a way that ensures that the isolation valve installed between the enclosure and the PCV can be closed. How to collect or otherwise deal with the equipment that fails to operate properly during the investigation was examined.

Possible equipment problems that would make equipment collection difficult are listed below. Note that the problems with the arm-type access equipment for retrieval are not included here, since that equipment is being studied and developed in a separate project.

No.	Expected troubles	Basic response policy
1	The telescopic guide pipe is retracted by winding the cable through the inside of the investigation equipment, but the cable winder cannot be driven due to irregular winding or drive motor burnout, and the telescopic guide pipe cannot be retracted.	By creating negative pressure inside the telescopic guide pipe, it is retracted by air pressure. ⇒ (e) Feasibility verification test using the 14-stage telescopic guide pipe
2	The cable for investigation equipment inside the telescopic guide pipe broke, and the telescopic guide pipe can not be retracted. At this time, the telescopic pipe is fully extended.	By creating negative pressure inside the telescopic guide pipe, it is retracted by air pressure. ⇒ (e) Feasibility verification test using the 14-stage telescopic guide pipe
3	The cable installed on the exterior of the retrieval arm came into contact with a structure and broke, or the cable connector had poor contacts, and the cable winder does not function and can not be retracted.	By creating negative pressure inside the telescopic guide pipe, it is retracted by air pressure. ⇒ (e) Feasibility verification test using the 14-stage telescopic guide pipe
4	Due to a cable winder control software excursion, the telescopic guide pipe can not be extended or retracted as intended.	Stop the control of the cable winder, and by creating negative pressure in the pipe, it is retracted by air pressure. ⇒ (e) Feasibility verification test using the 14-stage telescopic guide pipe
5	Telescopic guide pipe and investigation equipment got caught on surrounding structures, and the telescopic guide pipe cannot be retracted.	Verify by testing to see if it actually causes a problem. ⇒ (e) Feasibility verification test using the 14-stage telescopic guide pipe
6	The structures inside the PCV are covered with powdery and muddy foreign substances, which adhere to the outer surface of the telescopic guide pipe, and it cannot be retracted.	Verify by testing to see if it actually causes a problem. ⇒ (e) Feasibility verification test using the 14-stage telescopic guide pipe
7	Camera failure or foreign substances adhering to the camera prevents the acquisition of images necessary for equipment operation.	Verify during the mockup test whether the collection can be performed using only one of the images from the investigation equipment camera and the overhead view camera (mounted at the end of the arm-type access equipment for retrieval).

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

4) (d) Conceptual study and simplified test for development issues

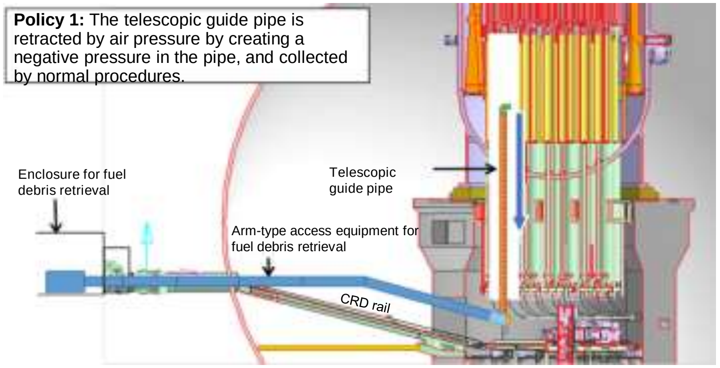
<13 Examination of items to be expected in case of emergency>

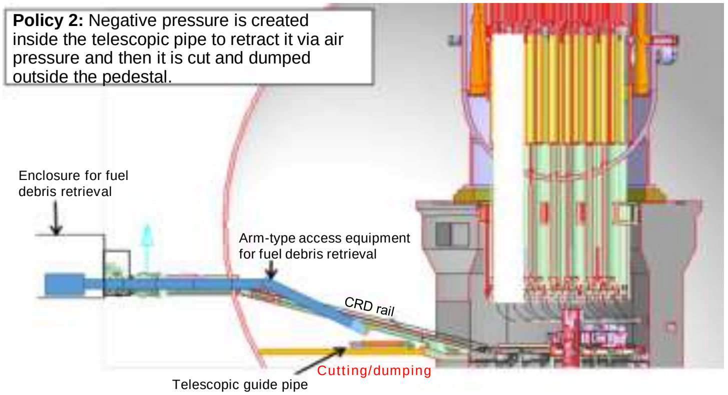
The following policies were adopted to deal with cases where retraction by cable winding is not possible, as in the cases of expected problems 1 to 4.

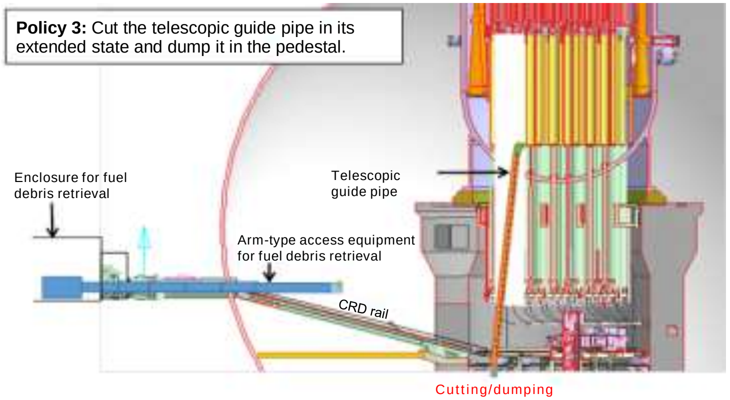
○ Policy 1: By creating a negative pressure inside the telescopic guide pipe, it is fully retracted by air pressure and is collected inside the enclosure by the normal procedures.

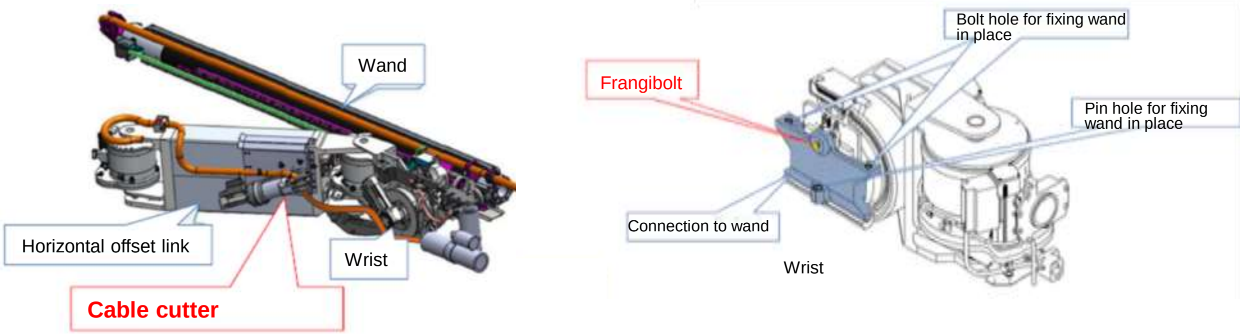
○ Policy 2: If total retraction cannot be achieved via Policy 1 and the isolation valve cannot be closed even after collected in the enclosure, the telescopic access equipment should be cut off and discarded inside the PCV using the cutting mechanism on the arm tip of the arm-type access equipment for retrieval, and only the arm-type access equipment for retrieval should be collected in the enclosure. At this time, the equipment should be moved to a location outside the pedestal (where it would not interfere with future operations) by the arm-type access equipment for retrieval, and then be cut and discarded.

○ Policy 3: If the telescopic guide pipe interior cannot be negatively pressurized due to an air tube rupture, etc., and the telescopic guide pipe cannot be pulled out below the lower end of the CRD, it should be cut and discarded on the spot. This means that the telescopic access equipment will remain inside the pedestal.









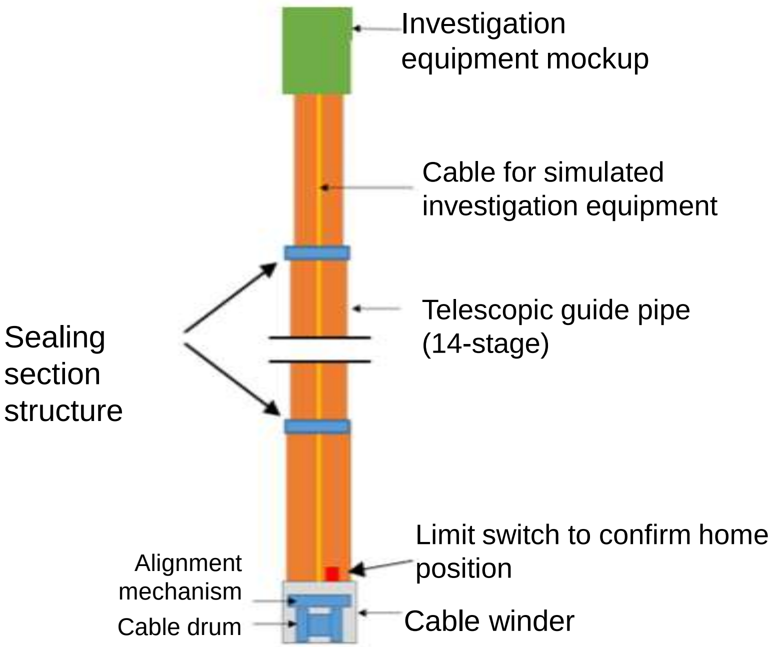
Overview of the cutting mechanism

6. Implementation details

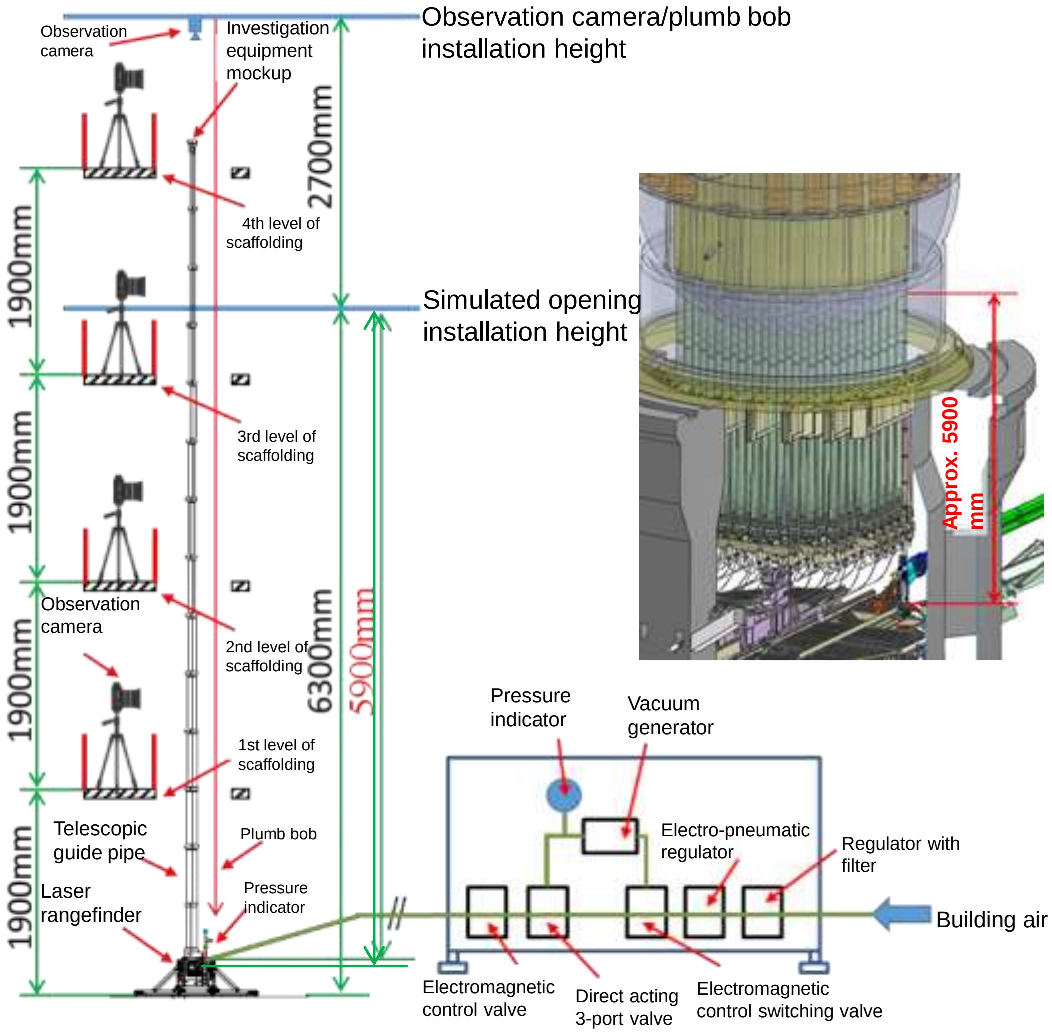
(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

○ Test system



Test piece for verifying telescopic guide pipe extension/retraction operations



Test system

6. Implementation details

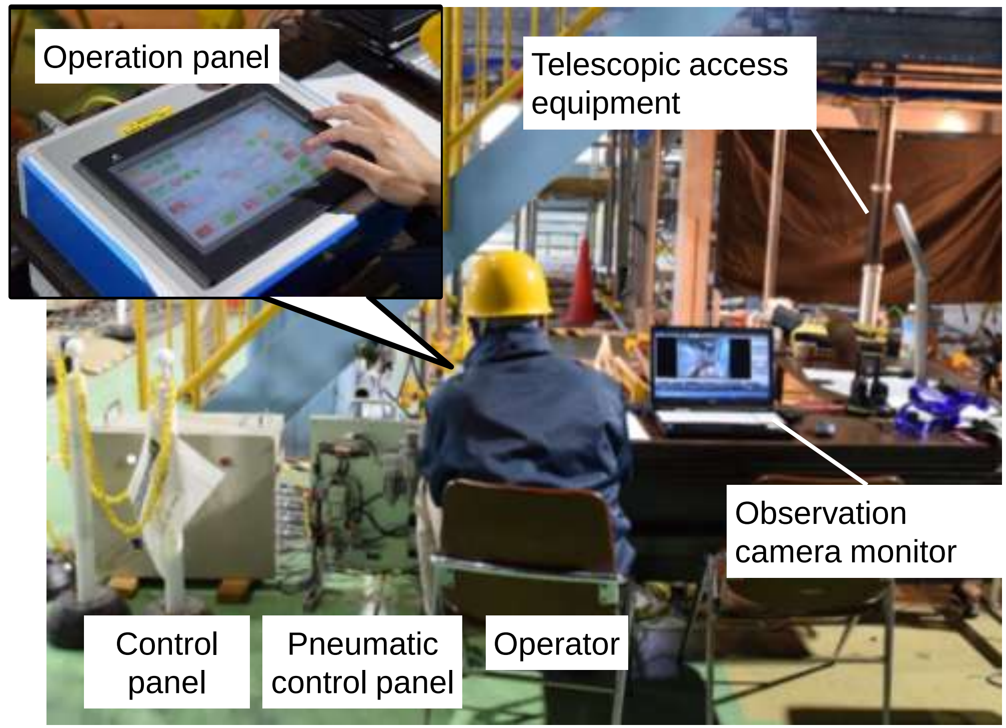
(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

○ Test environment

The operator checks the telescopic guide pipe extension status by direct visual observation as well as observation camera video footage, and then operates the equipment under the direction of the observer and conductor.
(Remote operation performance is not evaluated in this test)

Exterior view of the test site



Operating condition

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

○ Testing status

During retraction

2nd stage pipe extension

Full extension

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

○ Test items

No.	Test items/outline	Confirmation items	Evaluation items	Objective (evaluation criteria)	Rationale of objectives
1	Test item: Verification of extension/retraction operations Test overview: Verify if the telescopic guide pipe can be vertically extended and retracted, and understand the characteristics of vertical operation	Tensile force required from maximum extension	Cable tension required during retraction	319 N or less	Because it must be able to retract at or below 319 N (design value), the tension force obtained when the cable winder motor output torque is 100%
		Supplied pressure required for extension	Air pressure required during extension	0.1 MPa or less	Normal pressure of telescopic guide pipe: because it must be able to expand and retract at 0.1 MPa or less
		Amount of swaying during telescopic guide pipe extension	Whether the telescopic guide pipe sways (if there is swaying, the time it takes for swaying to stop after extension has stopped)	No large amplitude (qualitative evaluation)	—
		Whether the pressure in the pipe can be adjusted to the target value	Difference between supplied pressure and the pressure inside the telescopic guide pipe	Capable of adjusting the pressure in the pipe to the desired pressure	—
		Accuracy of measurement of telescopic guide pipe extended length	Value converted from the amount of drum rotation of the cable winder	Verify the actual performance	—
2	Test item: Verification of rigidity when horizontal load is applied Test overview: In a fully extended telescopic guide pipe, a horizontal load is applied to each pipe joint and the tip of the telescopic guide pipe, in sequence from the base, to verify the amount of tip misalignment of the telescopic guide pipe. (Measurement of misalignment is performed only when a load is applied to the tip of the 14th stage pipe).	Tilt control of each sealing section structure during extension (load applied: 15 points)	Amount of misalignment at height of reactor bottom opening	50 mm or less	Because ideally, even if the investigation equipment with Φ84 mm is misaligned in the horizontal direction, it should not touch the Φ187 mm opening
3	Test item: Verification of extension/retraction operations when the telescopic guide pipe is inclined Test overview: The telescopic guide pipe is installed at an angle to verify the maximum inclined angle at which it can be extended and retracted (while the design limit angle is 5 degrees, the maximum angle is set at 3.5 degrees in terms of margin)	Tensile force required from maximum extension	Cable tension required during retraction	319 N or less	Rated tension force of the cable winder: Because it must be able to retract the pipe at 319 N or less
		Supplied pressure required for extension	Air pressure required during extension	0.1 MPa or less	Normal pressure of telescopic guide pipe: because it must be able to expand and retract at 0.1 MPa or less
		Amount of swaying during telescopic guide pipe extension	Whether the telescopic guide pipe sways (if there is swaying, the time it takes for swaying to stop)	No large amplitude (qualitative evaluation)	—
		Whether the pressure in the pipe can be adjusted to the target value	Difference between supplied pressure and the pressure inside the telescopic guide pipe	The pressure in the pipe should be equal to the desired pressure	—
		Accuracy of measurement of telescopic guide pipe extended length	Value converted from the amount of drum rotation of the cable winder	Verify the actual performance	—

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

○ Test items

No.	Test items/outline	Confirmation items	Evaluation items	Objective (evaluation criteria)	Rationale of objectives
4	Test item: Verification of pressure resistance (0.2 MPa supply) Test overview: The telescopic guide pipe is fully extended and subjected to pneumatic pressure of 0.2 MPa, which is the design pressure resistance value of the telescopic guide pipe, for 3 hours (= 2 hour round trip for telescopic pipe operation + 1 hour of survey time). Disassemble and visually inspect for damage to the pipe and deformation of the pipe end stopper ring, scraper, scraper retaining bolt, and collar	Must be able to withstand a pressure of 0.2 MPa	Whether there is deformation of main components 3 hours after supplying 0.2 MPa	No deformation before or after supplying 0.2 MPa	—
		Whether the pressure in the pipe can be adjusted to the target value	Difference between supplied pressure and the pressure inside the telescopic guide pipe	Verify the actual performance	—
5	Test item: Verification of behavior of simulated structure and telescopic pipe when snagged Test overview: A simulated opening is placed at the bottom of the RPV at a height of about 5.9 m from the end face of the cable winder, and the scraper of the telescopic guide pipe is snagged. Verify whether the telescopic guide pipe can extend/retract following the tapered shape of the scraper Target scraper: Because the larger diameter pipes are easier to catch on the opening, when the pipe is fully extended, of the scrapers that have passed through the opening, the one closest to the opening (12th stage pipe scraper)	Capable of being pulled out even if caught on the opening	Possibility of passing through an opening	Capable of passing through following the tapered shape of the scraper	—
6	Test item: Verification of emergency retraction behavior Test overview: The 14-stage telescopic guide pipe is extended to verify if it can be retracted without using a cable winder, either by reducing the interior pressure or by creating a negative pressure using a vacuum generator.	Whether the negative pressure generated by a vacuum generator can retract the telescopic pipe	Negative pressure during telescopic pipe retraction	-0.092 MPa or less	Maximum negative pressure that can be generated by the selected vacuum generator: Because it must be able to retract at -0.092 MPa or less
7	Test item: Verification of extension/retraction operations when there is adhesion of foreign substances Test overview: Foreign substances are adhered to the outer surface of the 2nd stage pipe, which has the largest diameter, greatest sliding resistance, and easily accumulates foreign matter and thus is likely susceptible to adhesion effects. Verify whether telescopic guide pipe extension/retraction operations are possible. The foreign substances to be used are soil with a 15 µm grain size and alumina with a 75 to 100 µm grain size	Tensile force required from maximum extension	Cable tension required during retraction	319 N or less	Rated tension force of the cable winder: Because it must be able to retract the pipe at 319 N or less
		Supplied pressure required for extension	Air pressure required during extension	0.1 MPa or less	Normal pressure of telescopic guide pipe: because it must be able to expand and retract at 0.1 MPa or less
		Whether it is possible to supply the desired pressure to inside the pipe	Difference between supplied pressure and the pressure inside the telescopic guide pipe	Capable of adjusting the pressure in the pipe to the desired pressure	—
8	Test item: Verification of change in leakage volume when pipe is tilted Test overview: The telescopic guide pipe is placed in a vertical/inclined and fully extended state, the compressed air supply is turned off. Verify any difference in internal pressure change due to leakage. Measurement time of 30 minutes.	Whether the leakage volume increases even if the telescopic guide pipe is tilted	Difference in leakage volume between vertical and tilted states	Even if the telescopic guide pipe is tilted, the leakage volume should be the same as in the vertical state	Because even if the telescopic pipe is tilted, extension/retraction operations (pressure adjustment) should be the same as when the pipe is in the vertical position

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

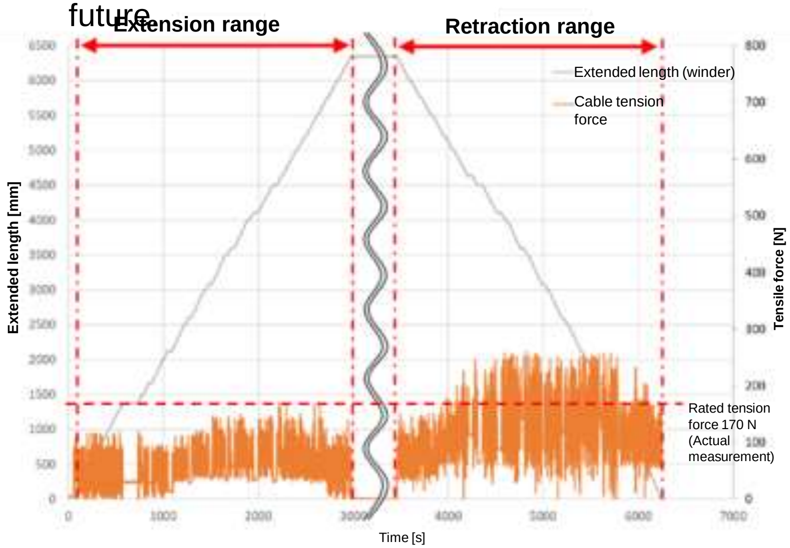
<1 Verification of extension/retraction operations>

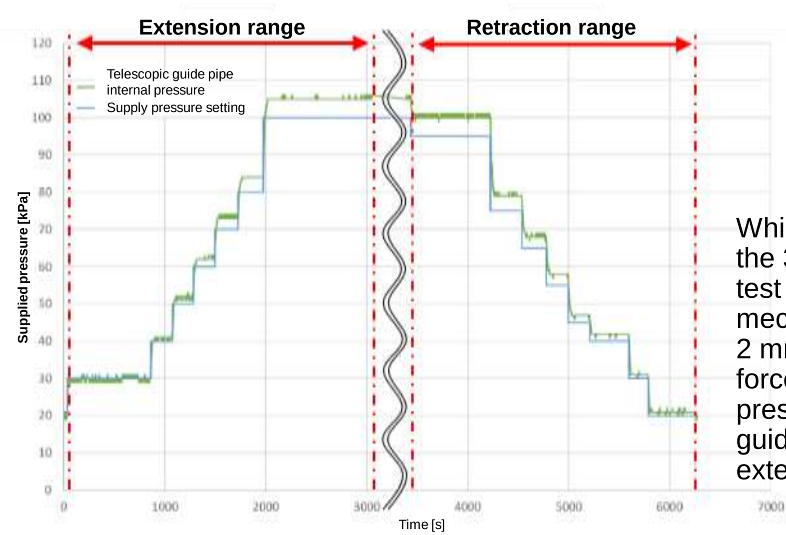
○ Test overview

Vertical motions and characteristics of vertical motions are verified when the telescopic pipe is vertically extended.

○ Test results (Part 1)

- Fundamentally, the pipe was extended from the base, and the diameter and the pressure-receiving area become smaller toward the tip. It was verified that by increasing the internal pipe pressure, all stage pipes can be extended with 0.1 MPa, the upper limit of the operational design pressure. It was also verified that via decompression and cable winding, by retracting starting from the tip piece, all stage pipes can be retracted. During retraction, the cable tension force (measured value) at 100% motor output torque was exceeded, but not constantly, and since no motor overload error occurred, it was determined that there was no problem.
- The cable tends to incline toward the anti-rotation rail on the side of the telescopic guide pipe (see No. 97) as it is extended, but the degree of inclination was improved when the cable was fed out without tension force being applied after full extension. If the pipe is inclined and the cable is in contact with the pipe inner surface, tension force will be applied to the cable, which may push the pipe horizontally, so countermeasures are required.
- Cable tension force (motor drive torque) fluctuates greatly in a short time, but the drive load may not be uniform due to imprecise assembly of gears and drive shafts. This results in a loss of cable tension force and needs to be inspected and improved in the future.





While the extension speed during the 3-stage telescopic guide pipe test was 20 mm/s, the mechanism was slowed down to 2 mm/s to increase the tension force of the cable winder, so the pressure inside the telescopic guide pipe did not decrease with extension.

Changes in the extended length, cable tension force, and internal pressure during telescopic guide pipe extension/retraction operations

6. Implementation details

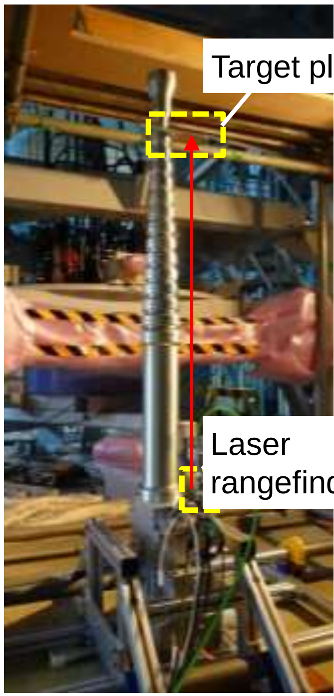
(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

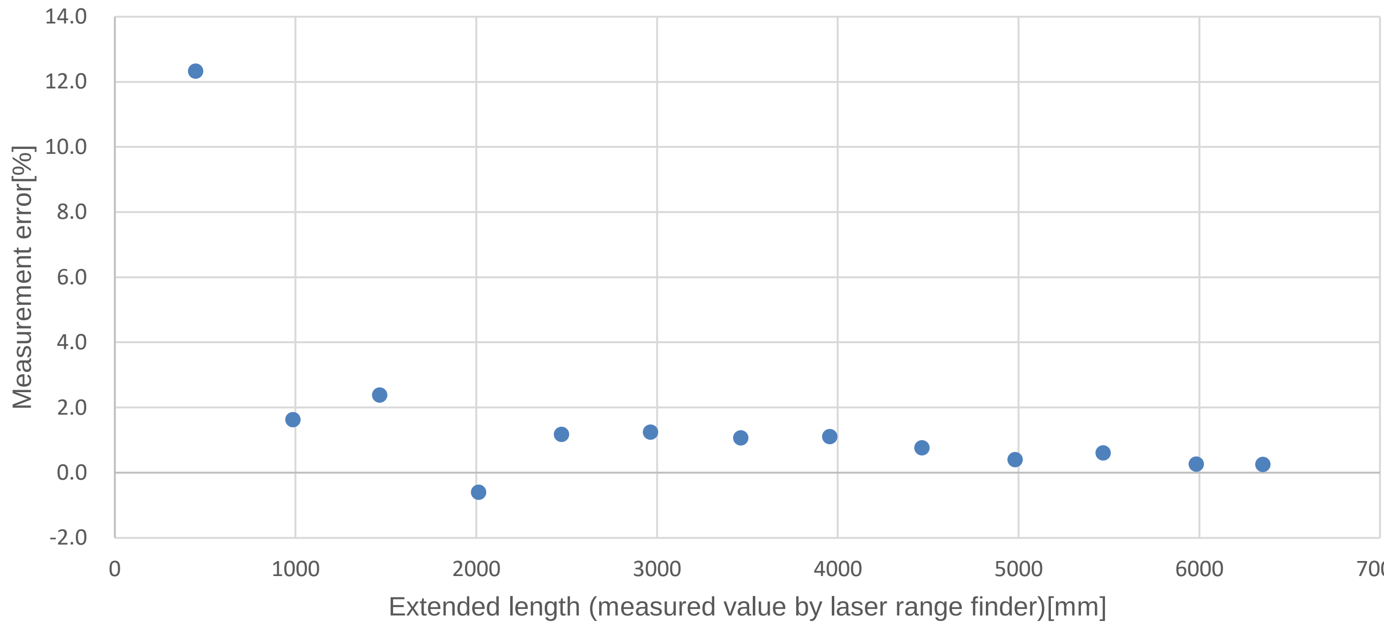
<1. Verification of extension/retraction operations>

○ Test results (Part 2)

- It was verified that after extending each stage pipe, or at the start of retraction, the telescopic guide pipe tip sways with an amplitude of about ±10 mm, but extension/retraction is possible without more swaying than that. In addition, even when there was swaying, it stopped in approx. 2 seconds, verifying that there are no extension/retraction problems.
- The extended length of the telescopic guide pipe was determined by the cable feed rate (the amount of rotation of the winding drum), but a comparative evaluation with the actual extension length using a laser rangefinder verified that the full extension length (6282 mm) can be measured with a 2% error.



Method of measuring extended length by laser rangefinder



Telescopic guide pipe extended length and the measurement error

It was verified that the 14-stage telescopic guide pipe and cable winder studied in FY2021 can be used for full extension and retraction. It is necessary to modify for fixing the inclination in the direction of the anti-rotation rail during extension and for improving the accuracy of cable winder drive shaft assembly.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

<2. Verification of rigidity when horizontal load is applied>

○ Test overview

In a fully extended telescopic guide pipe, apply a horizontal load to each pipe joint and the tip, starting from the base, and verify the amount of tip misalignment. (Misalignment is measured only when a load is applied to the 14th stage pipe tip)

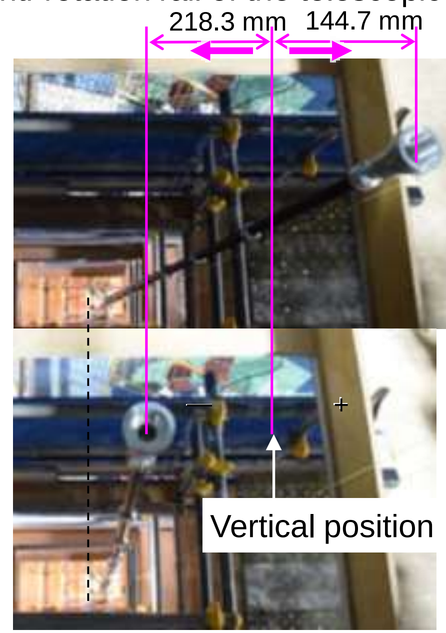
○ Test results

When a horizontal load was applied to the pipe tip, it applied a large bending moment on the base, and since sufficient force could not be applied to the tip to counteract the looseness, bending force was manually applied to each stage pipe starting from the tip. After that, the amount of the tip misalignment of the 14th stage pipe due to looseness in a state of no load was checked, and it was verified that there was a looseness of +144.7 to -218.3 mm. (The direction in which the anti-rotation rail of the telescopic guide pipe is attached is negative)

The bending direction force is being applied to the pipe so that the third stage pipe is inclined

Plumb bob

Measuring the distance from the plumb bob



Amount of tip misalignment caused by inclination due to looseness

It was verified that if the looseness due to the gap between each stage pipe is biased in one direction, the telescopic guide pipe cannot pass through the expected opening (Φ187 mm), even if it is extended vertically from directly under the opening. Looseness must be suppressed.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

<3. Verification of extension/retraction operations when the telescopic guide pipe is inclined>

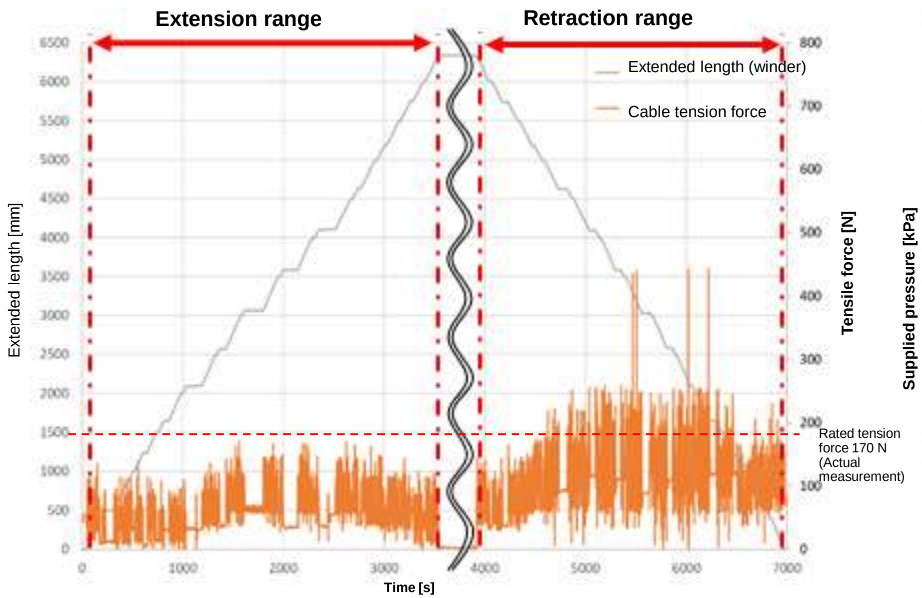
○ Test overview

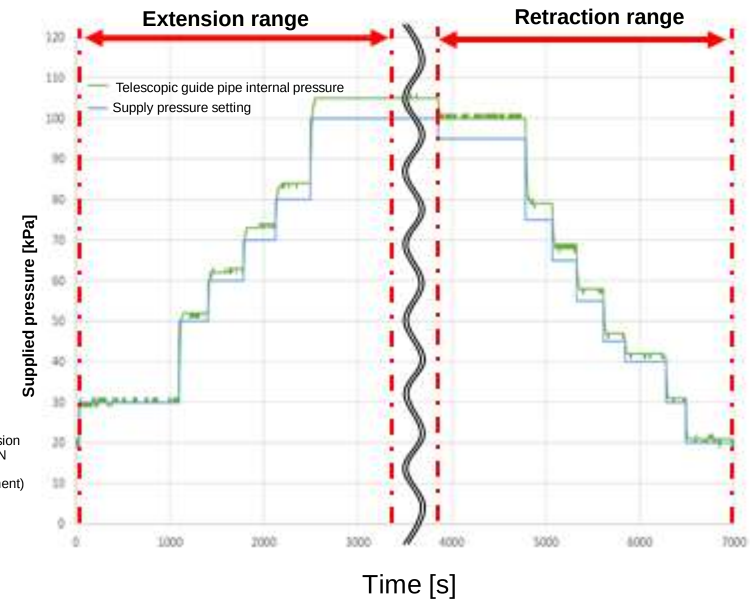
Install the telescopic pipe at an angle and verify the maximum inclined angle at which extension/retraction operations are possible (maximum 3.5 degrees)

○ Test results

- It was verified that all stage pipes can be extended and retracted at a 3.5-degree angle, in the same way as when vertically installed.
- There was no significant change in cable tension force compared to vertical installation. In addition, the telescopic guide pipe could be operated with an internal pressure equivalent to the source pressure used for extension/retraction operations in the vertical state.

Installation at a 3.5 degree angle





Changes in the extended length, cable tension force, and internal pressure during telescopic guide pipe extension/retraction operations

No significant change in supply pressure during extension or required tension force during retraction was observed when the telescopic guide pipe was inclined compared to when it was installed vertically, verifying that extension/retraction operations are possible at an angle of up to 3.5 degrees.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

<4 Verification of pressure resistance (0.2 MPa supply)>

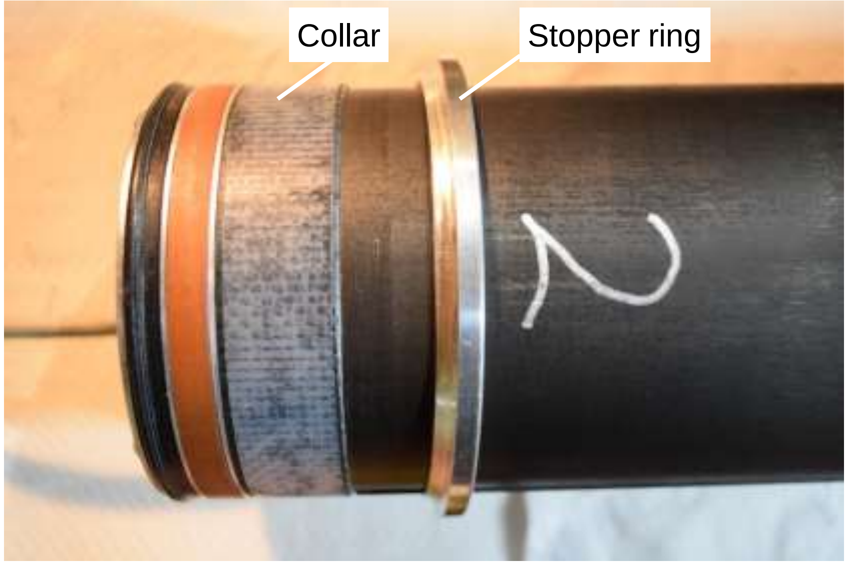
○ Test overview

With the telescopic guide pipe fully extended, air pressure of 0.2 MPa (the design pressure resistance value) is applied for 3 hours (= 2 hour round trip for telescopic guide pipe operation + 1 hour of survey time). Disassemble and visually inspect for damage to the pipe and deformation of the pipe end stopper ring, scraper, scraper retaining bolt, and collar.

○ Test results

- No abnormal behavior or anomalies were observed when the pipe internal pressure was set to 0.2 MPa.
- After retracting the telescopic pipe, the stopper ring, scraper, scraper retaining bolt, and collar were visually inspected at the joints between the 1st/2nd, 7th/8th, and 13th/14th stage pipes and no deformation or other abnormalities were observed.

Appearance of scraper at the tip of the 1st stage pipe after pressure resistance test (disassembled state)



Stopper ring and collar of the 2nd stage pipe after pressure resistance test (disassembled state)

It was verified that the test manufacturing of FY2021 telescopic guide pipe has pressure-resistant strength that satisfies required specifications.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

<5 Verification of behavior of simulated structure and telescopic guide pipe when snagged>

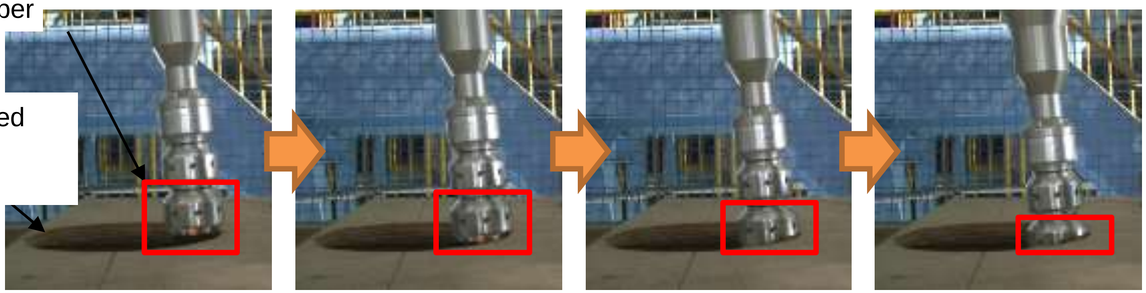
○ Test overview

A simulated opening at the bottom of the RPV is placed at a height of approx. 5.9 m from the end face of the cable winder, and the telescopic guide pipe scraper is placed on the opening. Verify that the telescopic guide pipe can be extended and retracted following the tapered shape of the scraper

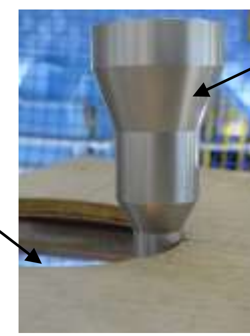
Target scraper: Because the larger diameter pipes are easier to catch on the opening, when the pipe is fully extended, of the scrapers that have passed through the opening, the one closest to the opening (12th stage pipe scraper)

○ Test results

- When the taper of the lower side of the 12th stage pipe scraper was brought into contact with the simulated opening, the entire telescopic guide pipe inclined, allowing it to pass through and retract.
- Since the scraper upper taper of the 12th stage pipe could not structurally be brought into contact with the simulated opening, extension was performed after bringing the narrow part of the telescopic guide pipe connector into contact with the investigation equipment. The telescopic guide similarly inclined to allow extension after passing the scraper through.
- The pressure in the pipe during extension was the same as during non-contact, and no significant change was observed in the cable tension force during retraction.
- The taper of the investigation equipment was also brought into contact with the simulated opening and then retraction was performed. The telescopic guide pipe similarly inclined, allowing it to pass through and retract.



Retracting through the simulated opening following the taper



The taper of the investigation equipment is in contact with the simulated opening

It was verified that even if the telescopic guide pipe gets caught on the structure, the telescopic guide pipe inclines along the scraper's tapered surface, thereby eliminating the snag and allowing extension/retraction to continue.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

<6. Verification of emergency retraction behavior>

○ Test overview

With the 14-stage telescopic guide pipe extended, reduce the internal pressure or create a negative pressure using a vacuum generator. Verify that the telescopic guide pipe can be retracted without using a cable winder.

○ Test results

- When the pipe internal pressure was reduced during the fully extended state, the telescopic guide pipe gradually tilted, and the test was stopped when the tip of the 14th stage pipe tilted more than 5.5 degrees. The test was resumed with the tip of the telescopic guide pipe lightly suspended by a rope to prevent it from tilting too much.
- The pipe retracted irregularly as the pressure was reduced, and at an internal pressure of 0 kPaG (atmospheric pressure), the 2nd stage pipe and the 5th to 9th stage pipes retracted completely.
- As a result of creating a vacuum inside the pipe and reducing the pressure to -74 kPaG (maximum negative pressure value), the 10th to 12th stage pipes further retracted, and the pipe retracted to the extended length of 250 mm. Since in this state the pipe did not move even when retraction was attempted by manually pushing in the tip, it is assumed that the cable was jammed inside the pipe.
- It is expected that even at this retracted length, the telescopic access equipment can be collected in the enclosure by adjusting the posture of the arm-type access equipment for retrieval, but it is necessary to evaluate whether the telescopic access equipment can be subsequently isolated and collected via the maintenance arm in the enclosure.

The stage on the tip side does not retract completely

Retracted by negative pressure (most retracted state)

Since the telescopic guide pipe cannot be completely retracted from the fully extended state even when the pipe interior is negatively pressurized, future evaluation is required to determine whether the pipe can be collected in the enclosure while in said state, or whether it can be isolated and collected by a maintenance arm.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

<7 Verification of extension/retraction operations when there is adhesion of foreign substances>

○ Test overview

Among the 14 stage pipes, the 2nd stage pipe has the largest diameter, the highest sliding resistance, and is believed to be most impacted by adhesion of foreign substances. Foreign substances are applied to the outer surface of the 2nd stage pipe to verify whether extension/retraction operations are possible. The foreign substances to be used are soil with a grain size of 15 μm and alumina with a grain size of 75 to 100 μm.

○ Test results

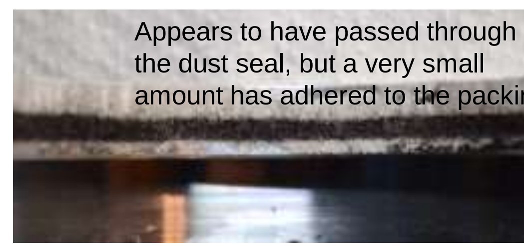
- It was verified that the 2nd stage pipe, which was covered in soil and alumina, could be re-extended after retraction.
- The telescopic guide pipe internal pressure during extension was the same as in the normal condition, and the cable tension force during winding was not significantly different from that in the normal condition.
- After the test, the scraper was disassembled and visually inspected for wrapping around the dust seal and the packing. Although the dirt was caught by the dust seal and did not appear to adhere to the packing, there were traces of larger alumina particles that had passed through the dust seal and also adhered to the packing in minute amounts.


(a) Soil (b) Alumina
Powder adhered to the entire outer surface of the pipe


(a) Soil There are wiping streaks (b) Alumina
Condition of pipe outer surface after retraction and re-extension

There are no signs that a large amount passed through the dust seal

(a) Soil



(b) Alumina
Dust seal condition

Compared to the case where no powder is adhered, there is no significant difference in the internal pressure during extension or in the cable tension force during retraction, so it is determined that the telescopic guide pipe can be extended and retracted without any problem even in the case of adhesion of powdery foreign substances.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

<8. Verification of change in leakage volume when pipe is tilted>

〇 Test overview

Set the telescopic guide pipe in a vertical/inclined position and then in a fully extended position, shut off the compressed air supply, and verify for any difference in internal pressure changes due to leakage. Measurement time of 30 minutes.

〇 Test results

It was verified that there is no pressure change difference in the telescopic guide pipe due to leakage when vertical vs. when inclined (3.5 degrees). Even if the posture of the telescopic guide pipe changes, the internal pressure of the telescopic guide pipe can be adjusted with the same amount of air supply as is used during vertical operation. Therefore, the equipment design will be proceeded using the air supply required for vertical operation.

Result of change in telescopic guide pipe pressure

	Telescopic guide pipe internal pressure [MPa]		
	At the start of the test	30 minutes after the test	Pressure drop due to leakage
Vertical	0.105	0.082	0.023
Inclined angle: 3.5°	0.106	0.081	0.025

It was verified that there is no significant change in leakage volume compared to vertical installation, even if the telescopic pipe is inclined.

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

○ Test results: Summary

No.	Test item	Confirmation items	Evaluation items	Objective (evaluation criteria)	Results
1	Verification of extension/retraction operations	Tensile force required from maximum extension	Cable tension required during retraction	319 N or less	Achieved (No motor overload error)
		Supplied pressure required for extension	Air pressure required during extension	0.1 MPa or less	Achieved (Maximum 0.1 MPa)
		Amount of swaying during telescopic guide pipe extension	Whether the telescopic guide pipe sways (if there is swaying, the time it takes for swaying to stop after extension has stopped)	No large amplitude (qualitative evaluation)	Achieved (No large amplitude)
		Whether the pressure in the pipe can be adjusted to the target value	Difference between supplied pressure and the pressure inside the telescopic guide pipe	There should be no significant difference between the supply pressure and the telescopic guide pipe internal pressure	Achieved (No significant difference)
		Accuracy of measurement of telescopic guide pipe extended length	Value converted from the amount of drum rotation of the cable winder	Verify the actual performance	Average error 2%
2	Verification of rigidity when horizontal load is applied	Tilt control of each sealing section structure during extension (load applied: 15 points)	Amount of misalignment at height of reactor bottom opening	50 mm or less	Not achieved (misalignment of approx. 220 mm)
3	Verification of extension/retraction operations when telescopic guide pipe is inclined	Tensile force required from maximum extension	Cable tension required during retraction	319 N or less	Achieved (No motor overload error)
		Supplied pressure required for extension	Air pressure required during extension	0.1 MPa or less	Achieved (Maximum 0.1 MPa)
		Amount of swaying during telescopic guide pipe extension	Whether the telescopic guide pipe sways (if there is swaying, the time it takes for swaying to stop)	No large amplitude (qualitative evaluation)	Achieved
		Whether the pressure in the pipe can be adjusted to the target value	Difference between supplied pressure and the pressure inside the telescopic guide pipe	There should be no significant difference between the supply pressure and the telescopic guide pipe internal pressure	Achieved (No significant difference)
		Accuracy of measurement of telescopic guide pipe extended length	Value converted from the amount of drum rotation of the cable winder	Verify the actual performance	- (The true value could not be measured by the laser rangefinder because the telescopic guide pipe inclined beyond the installation angle)
4	Verification of pressure resistance (0.2 MPa supply)	Must be able to withstand a pressure of 0.2 MPa	Whether there is deformation of main components 3 hours after supplying 0.2 MPa	No deformation before or after supplying 0.2 MPa	Achieved (No deformation)
		Whether the pressure in the pipe can be adjusted to the target value	Difference between supplied pressure and the pressure inside the telescopic guide pipe	There should be no significant difference between the supply pressure and the telescopic guide pipe internal pressure	Achieved (No significant difference)
5	Verification of behavior of simulated structure and telescopic pipe when snagged	Capable of being pulled out even if caught on the opening	Opening passability	Capable of passing through following the tapered shape of the scraper	Achieved (Passable)

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

5) (e) Feasibility verification test using the 14-stage telescopic guide pipe

○ Test results: Summary

No.	Test item	Confirmation items	Evaluation items	Objective (evaluation criteria)	Results
6	Verification of emergency retraction behavior	Whether the negative pressure generated by a vacuum generator can retract the telescopic pipe	Negative pressure during telescopic pipe retraction	-0.092 MPa or less	Not achieved (Could be reduced to -0.074 MPa, but the telescopic guide pipe was not be retracted completely and was not also be retracted by hand.)
7	Verification of extension/retraction operations when there is adhesion of foreign substances	Tensile force required from maximum extension	Cable tension required during retraction	319 N or less	Achieved (No motor overload error)
		Supplied pressure required for extension	Air pressure required during extension	0.1 MPa or less	Achieved (Maximum 0.1 MPa)
		Whether it is possible to supply the desired pressure to inside the pipe	Difference between supplied pressure and the pressure inside the telescopic guide pipe	Capable of adjusting the pressure in the pipe to the desired pressure	Achieved (No significant difference)
8	Verification of change in leakage volume when pipe is tilted	Whether the leakage volume increases even if the telescopic guide pipe is tilted	Difference in leakage volume between vertical and tilted states	Even if the telescopic guide pipe is tilted, the leakage volume should be the same as in the vertical state	Achieved (No significant difference)

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

(6) (f) Feasibility evaluation

○ Purpose

Based on the results of “(e) Feasibility verification test using the 14-stage telescopic guide pipe,” evaluate whether the 14-stage telescopic access equipment can be driven under the conditions of the reactor environment (high-temperature, high-humidity, radiation).

○ Evaluation

Among the 14-stage telescopic access equipment, the site of the drive that is affected by the environment is thought to be the sealing section of the telescopic guide pipe. Therefore, based on the results of the sealing functions verification test which simulates the reactor environment (see Sheet No. 92), evaluate whether the equipment can be driven.

[Predicted reactor environment]
Temperature: 50℃
Humidity: 100%
Cumulative dose: 7200 Gy
(assuming a 3-day investigation under 100 Gy/h environment)

[Results of the sealing functions verification test]
Sliding resistance: Increased by approx. 10 N compared to normal environment
Leakage volume: Leakage volume was reduced compared to normal environment

Summary of the sealing functions verification test results (environmental simulation test)

Environmental conditions			Normal environment		Simulated reactor environment 1		Simulated reactor environment 2	
Temperature			Room temperature		50℃		50℃	
Cumulative dose rate			0 Gy (unirradiated)		7200 Gy		7200 Gy	
Temperature			Normal humidity		100% (immersed in room temperature water for 3 days)		100% (immersed in room temperature water for 3 days)	
Wetting inside the pipe			None		None		Yes	
Sliding resistance	Sliding resistance [N]	Transport frequency	Max. value	While sliding	Max. value	While sliding	Max. value	While sliding
Sliding resistance	Sliding resistance [N]	1	15.4	approx. 5 to 7	14.2	approx. 5 to 7	22.6	approx. 5 to 7
Sliding resistance	Sliding resistance [N]	2	13.4		16.7		22.1	
Sliding resistance	Sliding resistance [N]	3	13.5		13.4		23.3	
Sliding resistance	Sliding resistance [N]	4	13.0		14.3		24.2	
Sliding resistance	Sliding resistance [N]	5	13.4		15.9		23.6	
Sliding resistance	Average		13.7	—	14.9	—	23.2	—
Leakage volume	Piston direction		Front-facing	Rear-facing	Front-facing	Rear-facing	Front-facing	Rear-facing
Leakage volume	Time taken from 0.01 MPa to 0.09 MPa		113 min. 58 sec.	5 min. 16 sec.	132 min. 47 sec.	11 min. 26 sec.	—	—
Leakage volume	Leakage volume from 2nd stage pipe		0.006 L/min	0.140 L/min	0.005 L/min	0.063 L/min	—	—
Leakage volume	Leakage volume when converted to the 14-stage telescopic guide pipe		0.06 L/min	1.22 L/min	0.05 L/min	0.56 L/min	—	—

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

(6) (f) Feasibility evaluation

(1) Effects of change in leakage:
The leakage does not increase in the reactor environment, and it is determined that the telescopic guide pipe can be operated by adjusting the internal pressure to the desired level

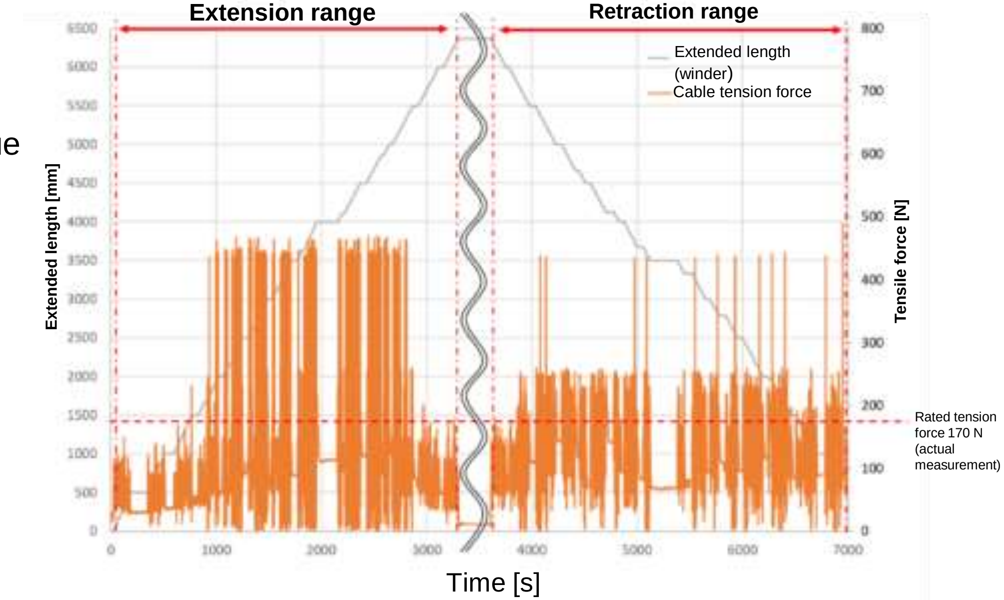
(2) Effects of change in sliding resistance:

① Extension effects

- The difference in the pressure required for pipe extension due to the increase in sliding resistance was calculated to be small enough that there is no problem.

(2) Retraction effects

- Even when the tension force is close to 500 N during extension, the motor does not shutdown (from an overload error in the motor driver), and operates without issues, so a maximum increase of 10 N in tension force, compared to approx. 250 N during retraction, is not a problem.



Changes in the amount of extension/retraction and the cable tension force during extension/retraction operations of the vertically installed 14-stage telescopic guide pipe

Difference in thrust required for extension

Target pipe	Increased sliding resistance in reactor environment [N]	Difference in thrust required for extension [MPa]
2nd stage pipe	10 *1	0.002
14th stage pipe	3.7	0.006

Small differences

It was verified that there are no operational problems in the reactor environment, and that the feasibility of investigation by using the telescopic access equipment was evaluated.

*1: Calculated by multiplying the result of the 2nd stage pipe packing by the circumference ratio

6. Implementation details

(2) Development of the bottom access investigation method (telescopic pipe)

(7) Summary and remaining issues

Summary

- Conceptual design and element tests were conducted to address development issues, including the study of connections on the arm-type access equipment for retrieval.
- Reflecting the measures taken to address issues from last fiscal year (leakage and large sliding resistance at the sealing section of the telescopic guide pipe), a prototype of the 14-stage telescopic guide pipe was manufactured and the function verification test was conducted. The feasibility of the equipment for telescopic access operations was verified.

Remaining issues

New issues obtained from the FY2021 study and test results are listed below.

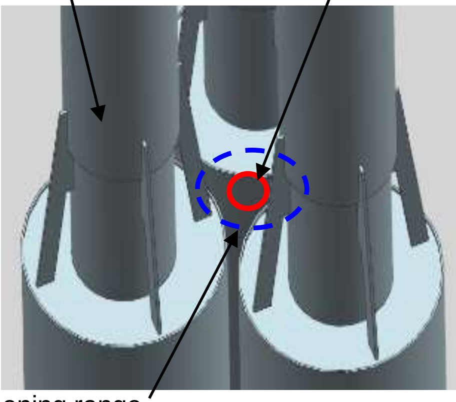
① Verification of adhesive strength assuming cylindrical pipe shape
② Verification of aluminum pipe operability, an alternative structural proposal for telescopic guide pipe
③ Control of inclination in the direction of the anti-rotation rail during telescopic guide pipe extension
④ Control of looseness due to the gap between each stage pipe, and prevention of the inclination during emergency retraction (when depressurizing) due to the gap
⑤ Evaluation of telescopic guide pipe behavior when the arm-type access equipment for retrieval sways
⑥ Uniform drive torque for cable winding drum (reduction of the loss of a cable tension force)
⑦ Test manufacturing and evaluation of posture control mechanism
⑧ Noise evaluation of the investigation equipment to dosimeters
⑨ Impact assessment of the cumulative dose on video due to CMOS camera irradiation
⑩ Evaluation of the possibility of determining telescopic guide pipe passage clearance and extension length via the fixed-point camera at the tip of an arm-type access equipment for retrieval
⑪ Evaluation of the possibility of determining the passage of an opening and the directional correction of telescopic guide pipe posture by the camera of investigation equipment

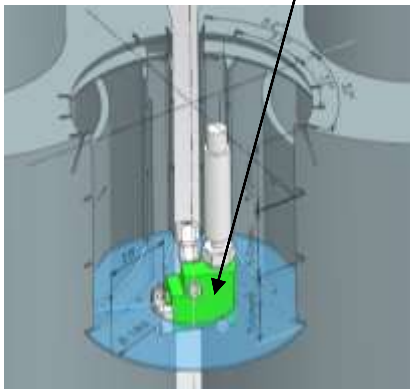
7. Summary

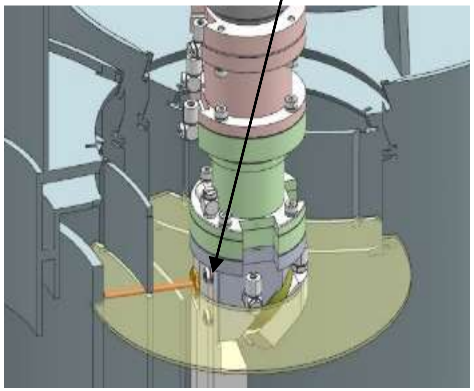
(1) Upgrading of processing technology for the top access investigation method

- Nozzle downsizing in FY2020 enabled a significant reduction in abrasive consumption when cutting the main body of the steam separator by AWJ (Abrasive Water Jet). In this fiscal year, study of further reduction of abrasive consumption including for cutting targets other than the main body of the steam separator was conducted. Due to reduction and optimization of the abrasive feed rate and use of the smaller FY2020 nozzles on cutting targets other than the main body of the steam separator, **<u>the prospect of achieving the target abrasive consumption of 500 kg or less was verified through element tests.</u>**

- Laser cutting was not applicable in FY2020 and a nozzle applicable for horizontal cutting of the steam separator main body was examined. By combining the nozzle studied in FY2020, **<u>the operational conditions were verified to allow cutting of all targeted reactor internals.</u>**







<u>Illustration of cutting of steam separator body (AWJ cutting, laser cutting)</u>

7. Summary

(2) Development of the bottom access investigation method

○ Development of drone access equipment for Unit 1

- In the simplified FY2020 test, the wired drone failed to reach its target flight height due to a voltage drop in the power cable, and the wireless drone failed to extend flight time. Issues common to both drone types included drone monitoring methods and difficulty in investigating the RPV bottom due to turning movements of a drone. In response to these issues, countermeasures were examined and a drone was test-manufactured.

- Other than that, proposed measures for issues such as response to real environments (darkness, dripping water, etc.) were included, and element tests were conducted to verify the effect.

- From the results of the element tests, the wired drone achieved the target flight height by revising the power supply method, and the wireless drone was able to remain in flight longer than the target time by revising the battery configuration.

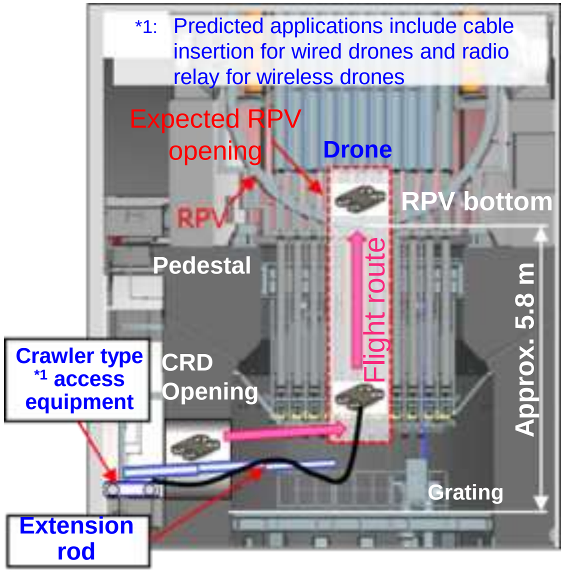
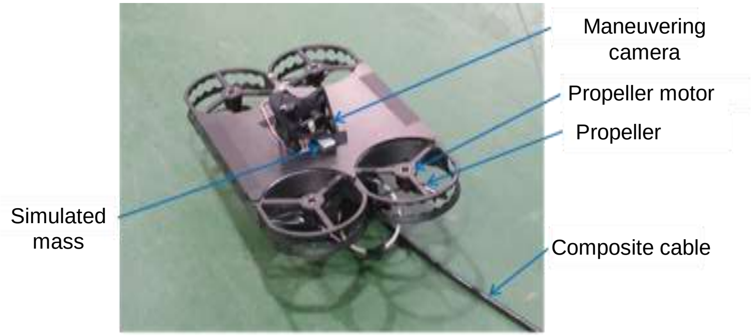
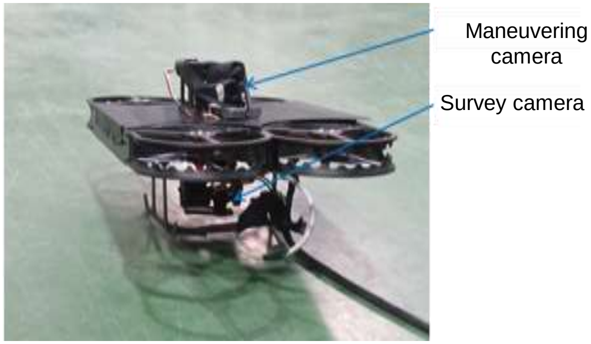


Illustration of accessing by drone





Wired drone prototype

Test-manufactured wireless drone

Exterior view of test-manufactured drones

7. Summary

(2) Development of the bottom access investigation method

○ Development of telescopic access equipment for Units 2 and 3

- Conceptual design and element tests were conducted to address development issues, including the study of connections on arm-type access equipment for retrieval operations.

- Simplified tests for using a 3-stage telescopic guide pipe were conducted in FY2020 to respond to issues of leakage from the sealing section and high sliding resistance. Improvement of pipe inner surface roughness, etc., was applied to equipment specifications. Another simplified test using a 3-stage telescopic guide pipe was conducted to verify the effect of the proposed response.

- Element tests were conducted to evaluate the feasibility of access equipment for all 14 stage pipes. The feasibility of a unit of telescopic access equipment was evaluated.

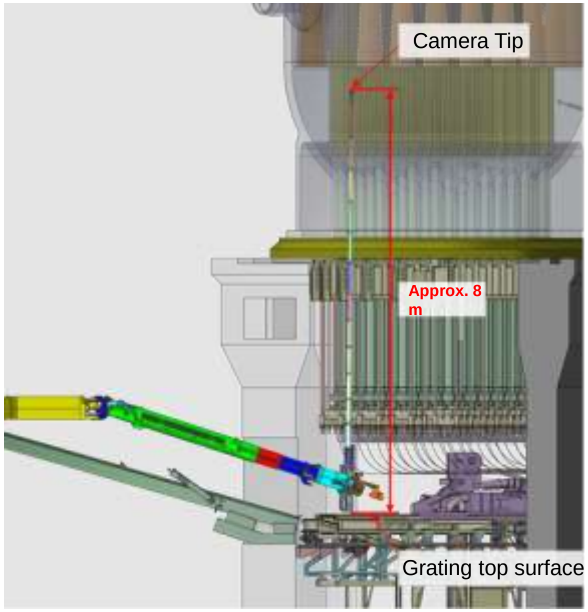


Illustration of access by telescopic guide pipe

Full retraction Full extension

Simplified test using a 3-stage telescopic guide pipe

Element test for the 14-stage telescopic guide pipe