Subsidy Project of Decommissioning and Contaminated Water Management
in the FY2017 Supplementary Budgets

Development of Technology for Investigation inside the reactor pressure vessel (RPV)

Final Report

August 2020

International Research Institute for Nuclear Decommissioning (IRID)

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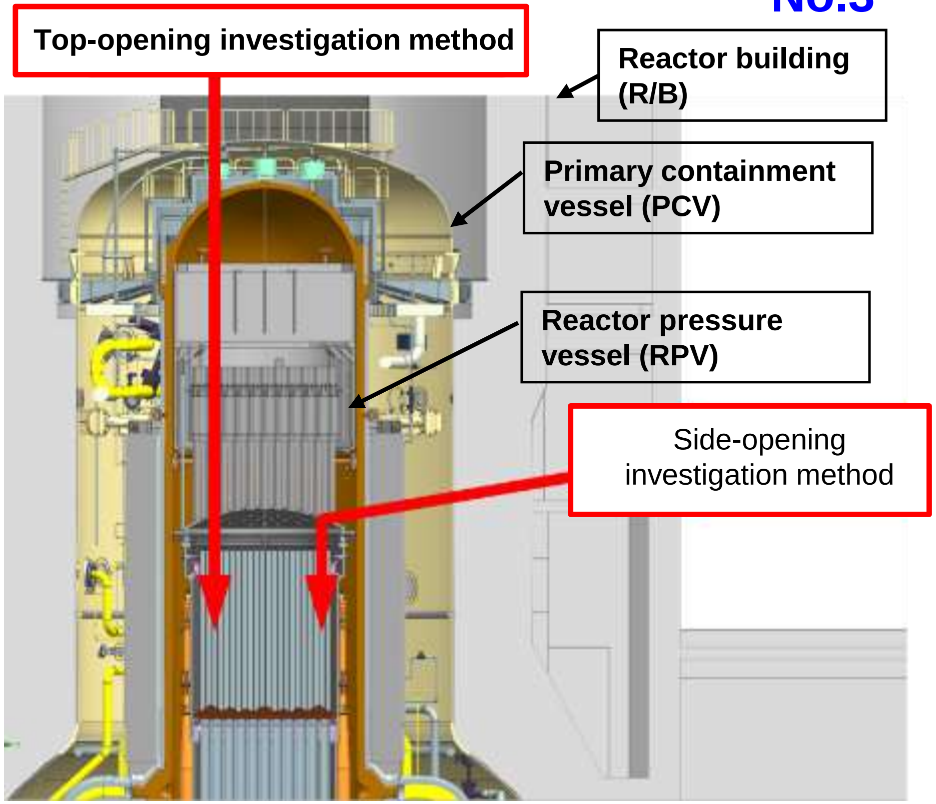
1. Research Background and Purposes

[Purpose of investigating the inside of the RPV]
Basic information regarding the inside of the reactor pressure vessel (RPV) is obtained toward fuel debris retrieval (fuel debris distribution, dose, conditions of the structures, etc.).

[Purpose of the technical development]
Information inside the RPV required for fuel debris retrieval (Investigation needs) is examined to clarify investigation targets, and technology that enables the investigation is developed.

[Implementation items conducted in FY2016–2017]
Investigation inside the RPV and technological plans developed until FY2015 were established and updated, and technological development of the side-opening investigation method started. Remote-operated investigation equipment and system were developed based on the investigation and development plans to confirm environmental conditions including the fuel debris conditions and doses. Equipment to access the reactor core from the top was developed, and an investigation method for accessing the reactor core was selected. Moreover, work steps for both of the top-opening and side-opening investigation methods, from preparations for prior investigation and treatment after investigation, were planned for the entire investigation equipment design and the method planning.



【Contribution of project achievements】
Because of this project development, actual investigation can be performed, and the obtained information that would contribute detailed study of criticality control will be provided.

Development of Technology for Investigation inside the RPV → Actual investigation → Study on the method and equipment design for fuel debris retrieval

Information on inside the RPV (Visual information, dose rate, etc.)

2. Project goals (FY2018 to FY2019)

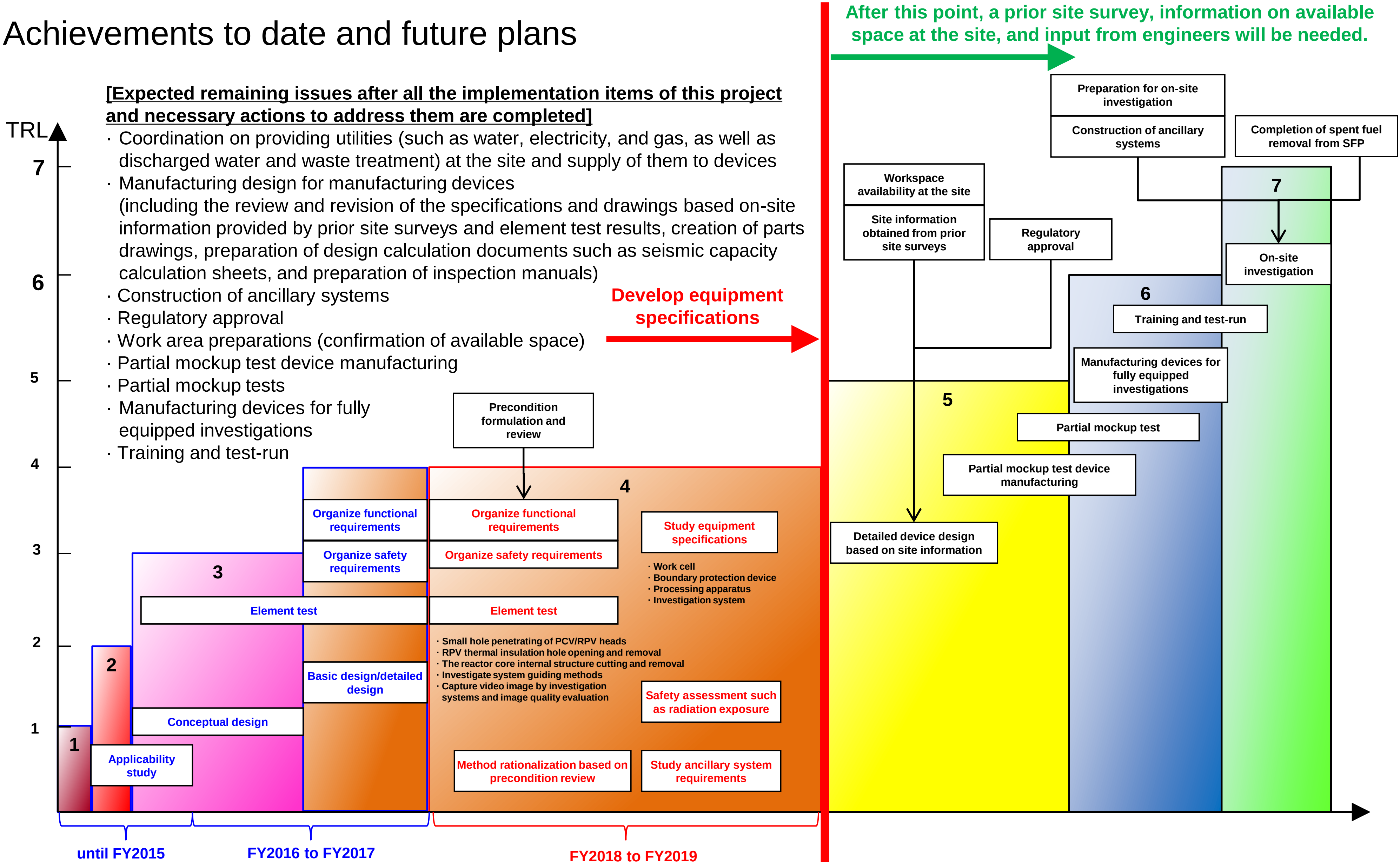
Implementation Items	Goal indicator
(1) Investigation and development Planning	Information required to plan and implement fuel debris retrieval shall have been collected and organized. An investigation plan shall have been formulated based on a clear understanding of preconditions for on-site investigation, such as implementation timing. In addition, the development plan shall have been updated as needed. (No target is set for technology readiness level (TRL) as it's an information organizing task)
(2) Investigation method planning	Work steps, procedures, and safety requirements shall have been made clear and specific. In addition, the investigation work's impact on the surrounding environment shall have been evaluated through exposure assessment based on the clearly defined work steps and procedures. (No target is set for technology readiness level (TRL) as it's an information organizing task)
(3) Study of investigation auxiliary system	The system's specifications for investigating and configuring the exposure assessment systems shall have been studied. (Target TRL upon completion: Level 2)
(4) Development of access and investigation equipment ① Development of investigation equipment for the top access method	The following shall have been achieved for the top-opening investigation method: drawings of the devices with specifications, element tests if necessary, and verification of the devices' on-site applicability based on the correct understanding of the actual site conditions and the devices' use conditions. (Target TRL upon completion: Level 4)
② Development of investigation equipment for side access method	The following shall have been achieved for the side-opening investigation method: drawings of the devices with specifications, element tests if necessary, and verification of the devices' on-site applicability based on the correct understanding of the actual site conditions and the devices' use conditions. (Target TRL upon completion: Level 4)

2.1 Roadmap of the top-opening investigation method

Achievements to date and future plans

[Expected remaining issues after all the implementation items of this project and necessary actions to address them are completed]

- Coordination on providing utilities (such as water, electricity, and gas, as well as discharged water and waste treatment) at the site and supply of them to devices
- Manufacturing design for manufacturing devices (including the review and revision of the specifications and drawings based on-site information provided by prior site surveys and element test results, creation of parts drawings, preparation of design calculation documents such as seismic capacity calculation sheets, and preparation of inspection manuals)
- Construction of ancillary systems
- Regulatory approval
- Work area preparations (confirmation of available space)
- Partial mockup test device manufacturing
- Partial mockup tests
- Manufacturing devices for fully equipped investigations
- Training and test-run



2.2 Roadmap of the side-opening investigation method

Achievements to date and future plans

[Expected remaining issues after all the implementation items of this project and necessary actions to address them are completed]

- Coordination on providing utilities (such as water, electricity, and gas, as well as discharged water and waste treatment) at the site and supply of them to devices
- Manufacturing design for manufacturing devices (including the review and revision of the specifications and drawings based on-site information provided by prior site surveys and element test results, creation of parts drawings, preparation of design calculation documents such as seismic capacity calculation sheets, and preparation of inspection manuals)
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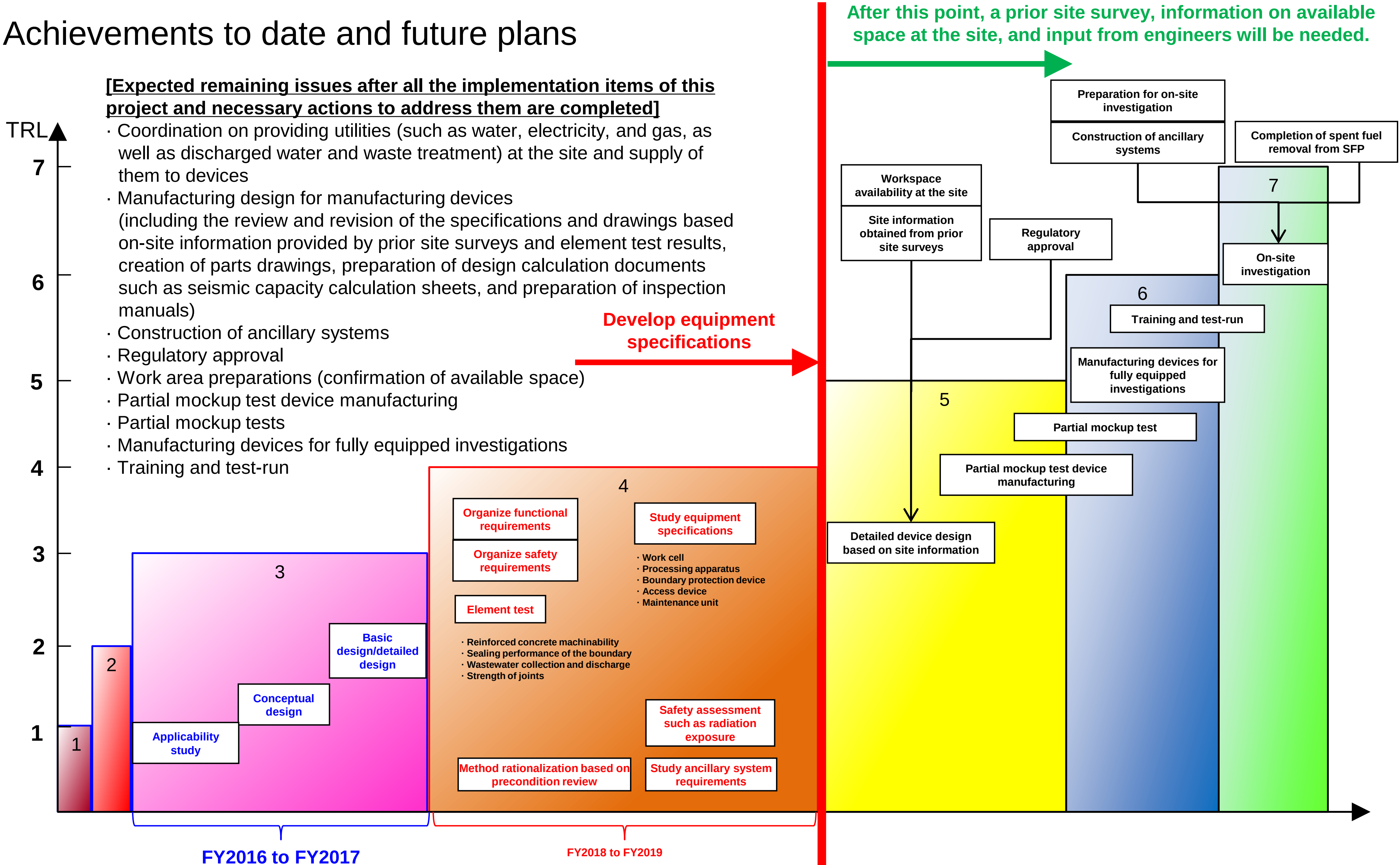
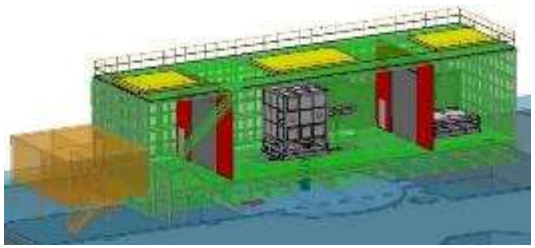


3.1 Implementation items of the project (FY2018-2019)

Implementation items	Outlines of items
(1) Investigation and development plans (See 6.1) ① Organization of fuel debris retrieval information (See 6.1.1)	Organize and update the list of items to be investigated about RPV inside conditions.
② Investigation update and development plans (See 6.1.2)	Update investigation and development plans based on the organized and updated list of investigation needs. In addition, review preconditions required for the investigation.
(2) Investigation method planning (See 6.2) ① Detailed design of work steps and rationalization of construction procedures (See 6.2.1)	Design detailed work steps based on the work steps outlined in the FY2017 project and clarify and rationalize procedures for each work step.
② Clarification of safety requirements and exposure assessment (See 6.2.2)	Clarify safety requirements for investigation, perform exposure assessment, and assess the impact of investigations on the surrounding environment.
(3) Study of ancillary systems required for investigations (See 6.3)	Clarify the timing of ancillary systems required for investigations and safety assurance, such as gas and negative pressure control system, nitrogen supply system, and criticality control system, and required specifications for them from the investigation team to prevent contaminated dust from spreading.
(4) Development of access and investigation equipment (See 6.4) ① Development of investigation equipment for top access method (See 6.4.1)	Develop technologies that can solve issues to realize investigation works at the site, design devices and systems in detail, and rationalize them based on element tests performed in the FY2017 project. In addition, consider the necessity of elements tests for device development and perform them if necessary in FY2018 to verify the devices' on-site applicability to investigation works based on the correct understanding of the actual site conditions.
② Development of investigation equipment for side access method (See 6.4.2)	Develop technologies that can solve issues to realize investigation works at the site, design devices and systems in detail, and rationalize them based on the FY2017 project's outcomes. In addition, consider the necessity of elements tests for device development and perform them if necessary in FY2018 to verify the devices' on-site applicability to investigation works based on actual site conditions.

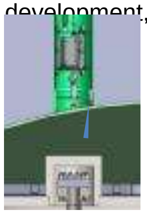
3.2 Correlation among implementation items: Top-opening investigation method

- Development of a negative pressure control system for contamination spread prevention
- Study on the method/carrier to carry in/out the equipment



- Hole opening machine development for each location
- Small diameter hole-penetrating machine development, etc.

Processing apparatus ⇒ 6.4.1.3



PCV head processing apparatus

RPV insulation hole opening machine

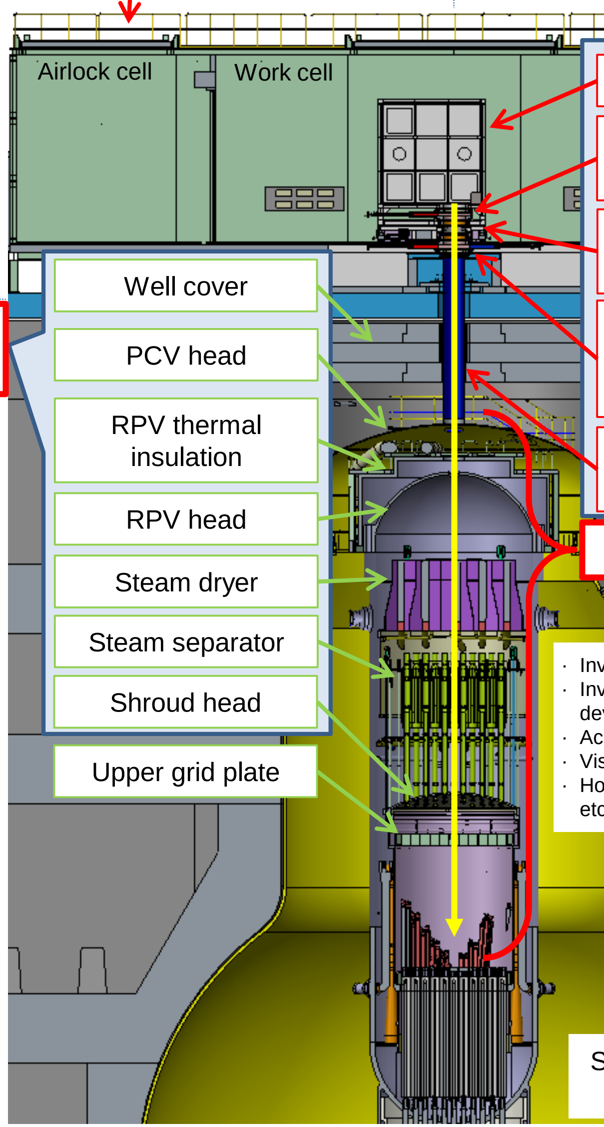
RPV head spare nozzle flange hole-opening machine

Machines to reach and cut reactor internals

AWJ tool head

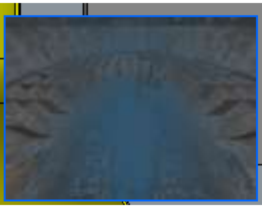
Work cell ⇒ 6.4.1.1

Boundary function maintenance system ⇒ 6.4.1.2



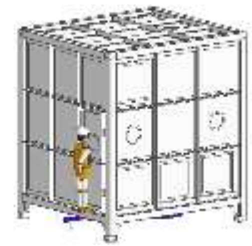
Investigation system ⇒ 6.4.1.4

- Investigation system development
- Investigation equipment development
- Access device development
- Visibility simulation
- Horizontal extension arm design, etc.

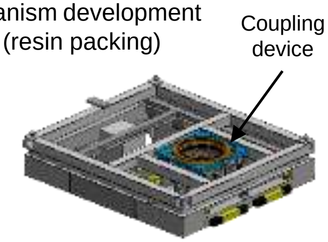


Simulation of overlaying captured images

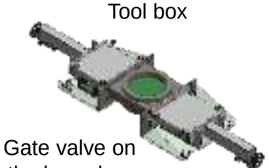
- Tool box design
- Gate valve development
- Seal mechanism development and design (resin packing)



Tool box



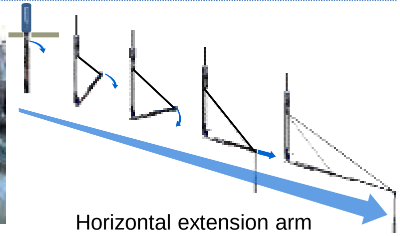
Tool box transfer carrier



Gate valve on the boundary guide pipe side

Boundary guide pipe (section to run through PCV head)

Suspension device



Horizontal extension arm

Access device

For preliminary verification

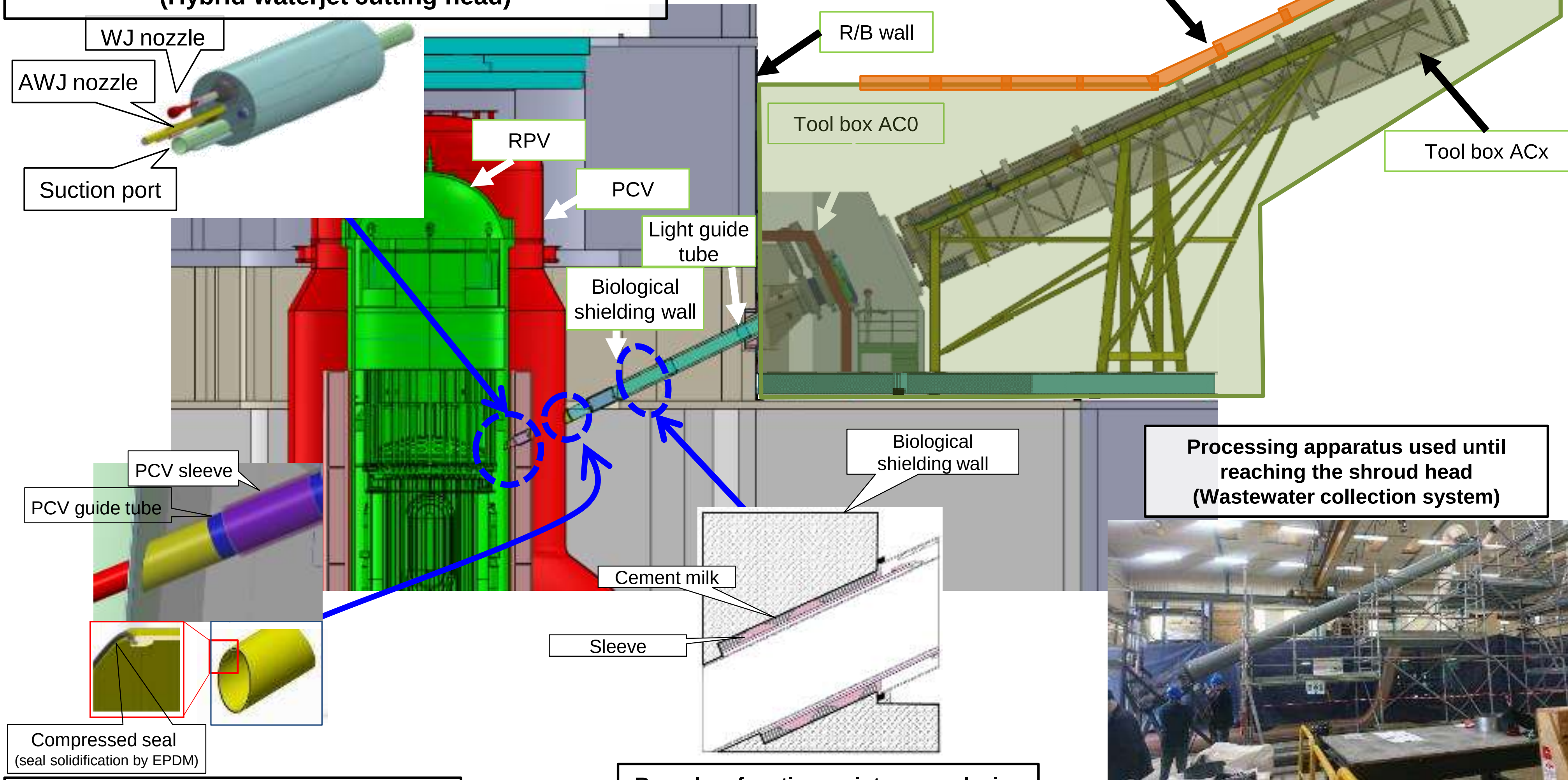
For full investigation

Investigation equipment

* AWJ: Abrasive Waterjet

3.2 Correlation among implementation items: Side-opening investigation method No.9

Processing apparatus used until reaching the shroud head (Hybrid waterjet cutting head) ⇒ 6.4.2.2

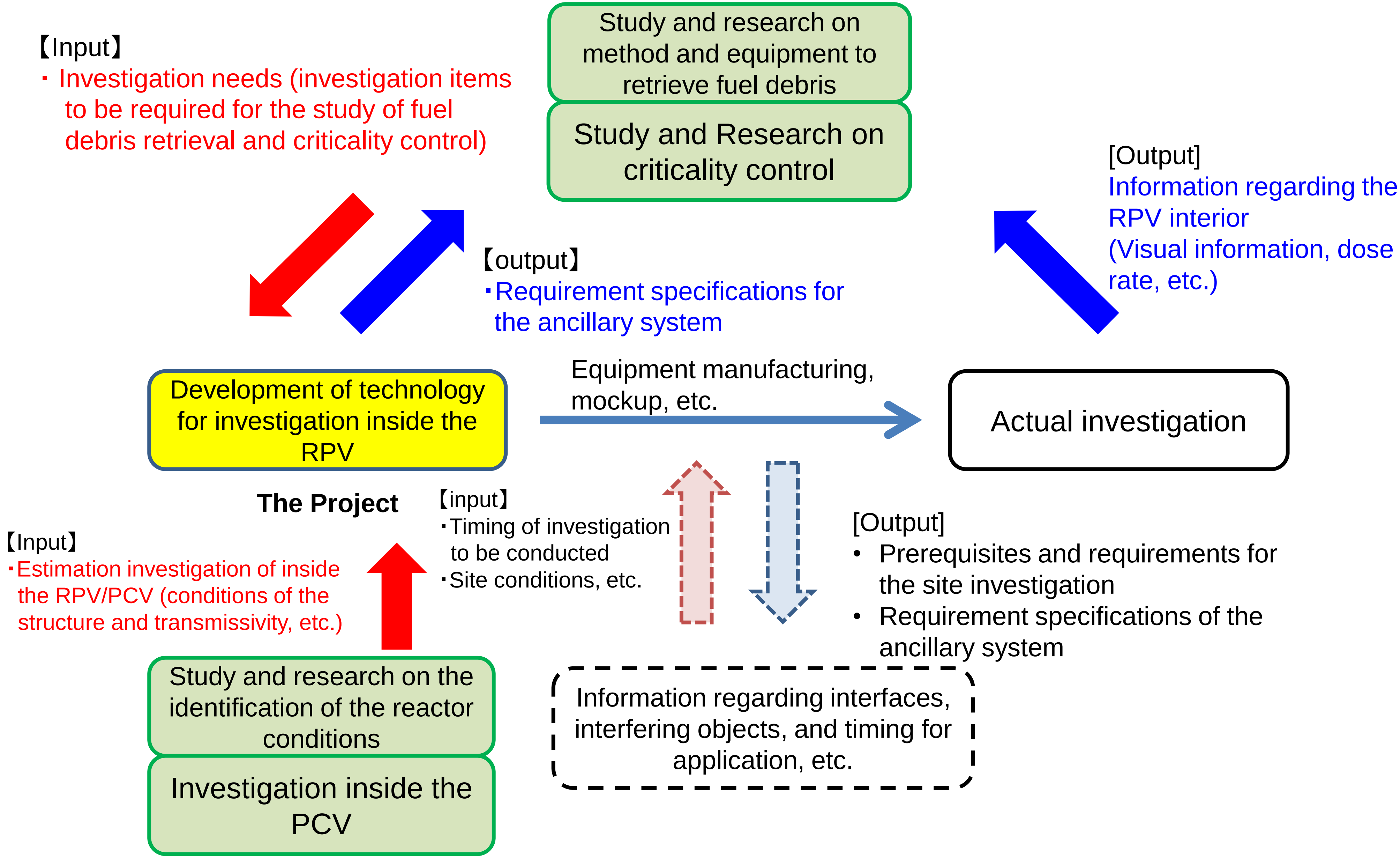


Processing apparatus used until reaching the shroud head (Wastewater collection system) ⇒ 6.4.2.2

Boundary function maintenance device (Sealing performance around the guide tube) ⇒ 6.4.2.3

Boundary function maintenance device (Guide tube fixation to the hole of the biological shielding wall) ⇒ 6.4.2.3

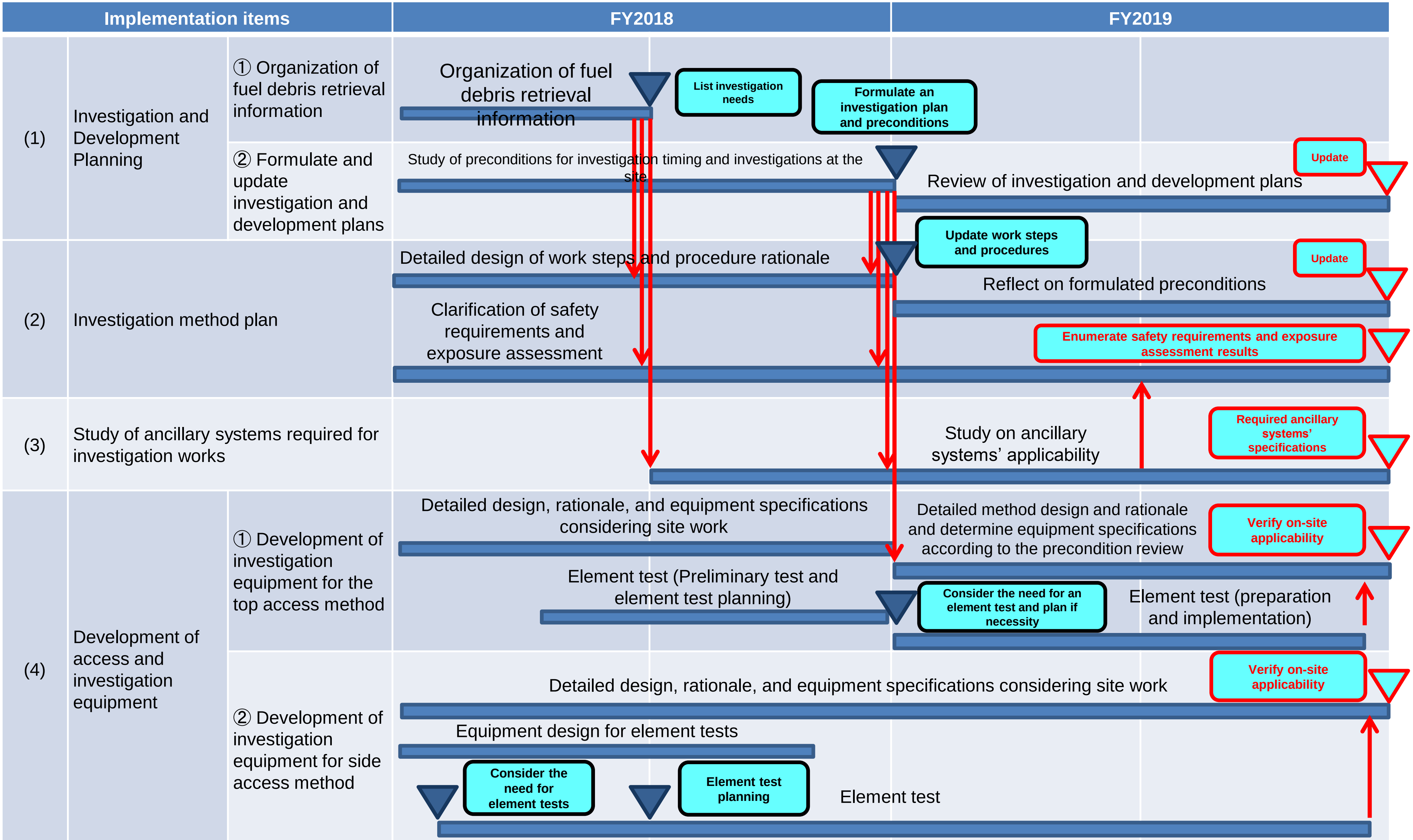
3.3 Relations with other research



4. Schedule

* Preliminary test: a test to examine the feasibility of an element technology and formulate an element test plan
Element test: a test to validate device specifications or obtain information to determine specifications

No.11



5. Project organization chart

International Research Institute for Nuclear Decommissioning (IRID Head Office)

- ○ Integral planning and technical supervision
- ○ Management of technical development and its progress

Tokyo Electric Power Company Holdings, Inc.

Cooperating development project teams

Development of Investigation for Further Increasing the Scale of Retravel Debris and Internal Structures

Toshiba Energy Systems and Solutions Corporation

(1) Investigation and development planning
①Organization of information required for fuel debris retrieval
②Planning and updates of investigation and development
(2) Creation of method planning
(3) Study of the ancillary system for investigation
(4) Development of access and investigation equipment
①Development of equipment for the top-opening investigation method

- IHI Corporation
  - ・(4)①Study and test of opening device for accessing the RPV head
- IHI Corporation
  - ・(4)①Study and test for boundary function maintenance equipment
- KIMURA CHEMICAL PLANTS CO., LTD.
  - ・(4)①Study on a work cell

Hitachi-GE Nuclear Energy, Ltd.

(1) Investigation and development planning
①Organization of information required for fuel debris retrieval
②Planning and updates of investigation and development
(2) Creation of method planning
(3) Study of the ancillary system for investigation
(4) Development of access and investigation equipment
①Development of equipment for the top-opening investigation method

- Sugino Machine Limited
  - ・(4)①Structural design of processing equipment for the reactor internals to develop opening equipment of the upper grid plate.
- Hitachi Power Solutions Co., Ltd.
  - ・(4)①Test production and test of processing equipment for the reactor internals to develop opening equipment of the upper grid plate.

Mitsubishi Heavy Industries, Ltd.

(1) Investigation and development planning
①Organization of information required for fuel debris retrieval
②Planning and updates of investigation and development
(2) Creation of method planning
(3) Study of the ancillary system for investigation
(4) Development of access and investigation equipment
①Development of equipment for the side-opening method

- Orano ATOX D&D Solutions (ANADEC)
  - ・(4)②Development of access and investigation equipment
- Kajima Corporation
  - ・(4)②Concretization of the structure for accessing the reactor core from the side, such as a work cell and maintenance unit.

6. Implementation details
(1) Preconditions (including outcomes in previous fiscal years)

Items	Preconditions
Investigation needs	· Collect information and data about reactor inside conditions by accessing it can accelerate the detailed design of fuel debris retrieval devices. · Data to be collected are two types: visual images and dose.
Implementation policy	Do not cut or touch any structures under the upper grid plate unless necessary as defined by fuel debris Cutting will be allowed only for the shroud head and structures above it.
Reactors to be investigated (Achievements through FY2017)	· Top opening: Unit3 · Side opening: Unit2
Access route (Achievements through FY2017)	· Top opening: From right above RPV spare nozzle to the reactor core · Side opening: From the air conditioning room roof on the east side of R/B to the reactor core
Preconditions of work areas	· Top opening: Interfering objects on the operation floor should have been removed, and shielding should have been installed on the floor. An environment with a dose rate of 1 mSv/h or less should have been established in work areas. · Side opening: Exhaust ducts and chillers should have been removed. An environment with a dose rate of 1 mSv/h or less should have been established in work areas.
Estimated air dose rate (Max)	· Drywell: 16 Sv/h · Inside the reactor (near steam dryer/steam separator): 800 Sv/h · Inside the reactor (near reactor core): 5,000 Sv/h
Estimated conditions of each structure	· From well cover to shroud head: Not damaged · Upper grid plate and below: Seriously damaged Note that access to the reactor core's deepest part must be based on the assumption that all the fuel and structures in the reactor core should have melted down to the bottom.
Light transmission (in a foggy condition)	· 46% at 1.5 m distance (from Unit1 PCV inside investigation result): Absorption coefficient of 0.511 · 72% at 1.5 m distance (from Unit2 PCV inside investigation result): Absorption coefficient of 0.223 ⇒ Used as design conditions
Workplace and remote operability	· Top opening: Operation floor In addition, the work area height should be 1.3 m from the operation floor. · Side opening: The air conditioning room roof on the east side of R/B
Use of remote operation	As a basic policy, equipment and devices should be installed by a direct operation. Cutting and investigation work should be done remotely.
Handling of processed materials generated by cutting	The possibility of a criticality accident is considered low even if the possibly largest processed materials(about 16 kg) falls to the reactor core. Falling processed materials are considered acceptable as long as they are within this size.
Boundary (Achievements through FY2017)	The boundary should be established by PCV. As a basic policy, a work cell should be prepared on the operation floor and/or the air conditioning room roof. Maintain negative pressure inside to prevent radioactive material spread in case of leakage through holes made for the investigation.

6.1 Investigation and development planning
6.1.1 Organization of fuel debris retrieval information

Investigation needs that contribute to the fuel debris retrieval are collected, organized, and updated based on the latest information, such as that on the lower part of PCV obtained from PCV inside investigation.

	Item	Outlines	Progress status	FY2018	FY2019
1	Organization of fuel debris retrieval information	Collect information for required fuel debris retrieval from each PJ and update it.	Investigation needs listed in FY2016 were updated. There was no change in investigation items. (Reported)	Listing investigation needs	Result of investigation needs

The investigation needs listed in FY2018

- The early collection of information and data about reactor inside conditions by accessing it can accelerate the detailed design of fuel debris retrieval devices.
  - ✓ Essential for detailed design The sooner investigation is performed, the more useful the investigation results.
  - ✓ Information about the reactor core and bottom is the most important, followed by information about the upper part of RPV inside, such as the steam dryer and steam separator.
- The following information is considered effective for risk reduction:
  - ✓ Visual information: can help determine the deformation and damage of structures, distribution of fuel debris, and tree stump shape fuel. An investigation that provides information about overall conditions such as the distribution of fuel debris and inclination and deformation of structures is more useful than detailed investigations, including dimensional measurement. Imaging data resolution should be on the order of several cm.
  - ✓ Dose rate: Estimation of the order of dose rate (1 to 10^3 Gy/h)

6.1.2 Investigation update and development plans

An investigation plan is formulated in FY2018 to rationalize each action item about the investigation needs listed in Section 6.1.1. The site's latest conditions, including the planning of fuel removal from the fuel pool, should be reflected for a more practical updated investigation plan. Simultaneously, the implementation timing and preconditions of the on-site investigation (on-site validation), such as necessary preparations, should be clarified. Additionally, the development plan of access and investigation equipment should be updated as needed.

	Implementation items	Outlines	Progress status	FY2018	FY2019
1	Development of an RPV inside investigation implementation plan based on the entire plan	Develop an overall schedule of RPV inside based on the SFP fuel removal and fuel debris retrieval plans.	Update the investigation and development plans based on the updated investigation needs list. (Reported) Update the investigation plan based on the latest information, such as that about the site condition.	Determination of investigation implementation timing and environmental conditions Investigation plan and preconditions formulation	Investigation plan and preconditions review Update
2	Evaluation of the structure condition	Estimate the structures' conditions based on the PCV inside investigation result and the Reactor Inside Condition Investigation Project outputs in 2017.	Analyze the temperature change in the reactor core internal structures based on the result of the accident progression analysis performed by the Reactor Inside Condition Investigation Project in FY2017. Estimate the structures' condition. (Reported)	Temperature change estimation Study of the influence of structures	
	Air dose rate estimation	Verify the estimated air dose rate of 5,000 Sv/h based on PCV inside investigation results and the outputs of the Reactor Inside Condition Investigation Project in 2017.	Estimate the dose rates to determine the device design preconditions. (Reported)	Estimation of the contamination level of structures Air dose rate estimation	
	Risk assessment for the occurrence of a criticality accident by processed materials falling*	The maximum weight of processed materials is determined in terms of not causing a criticality accident even if it falls to the reactor core.	The possibility of a criticality accident is considered low even if processed materials falls as long as its weight is within an expected range. The public and workers' exposure outside R/B would remain within a permissible level even if a criticality accident occurs. (Reported)	Study of evaluation policies Risk assessment for a criticality accident in case of a heavy object fall	

* Use the same basic evaluation method as the other project teams. Evaluations expected to be performed in RPV inside investigation and modeling are performed in this project.

6.1.2.1 Update of the investigation plan

No.16

Expected work steps for Unit 2 and Unit 3 in consideration of overall processes (draft)

[Preconditions]
- Only implement the side-opening investigation before the top-opening investigation.
- Plan to implement the top-opening after removing the SFP fuel and establishing a negative pressure environment.

Work area		Expected work steps (time scale not considered)
Unit2	Operation floor (Top floor)	**Preparation for SFP fuel removal (Shield installation, exhaust ventilation system installation, etc.)** → **SFP fuel removal** → **Preliminary site survey** → **Upper R/B dismantlement** → Work area setup → **Top-opening investigation** → **Fuel debris removal (Top entry)**
	The air conditioning room roof (Side)	Blow-out panel duct removal → Interfering object removal from the roof of the air conditioning room → Support structure construction → **Side-opening investigation**
	R/B 3rd floor	**Preliminary site survey** → Interfering object removal
	R/B 1st floor	**PCV inside detailed investigation and fuel debris retrieval tests** → Establish a negative pressure environment in PCV → **Gradually scaled up fuel debris retrieval tests (Side entry)** → **Fuel debris removal (Side entry)**
	Yard around R/B	Preparation for SFP fuel removal (Platform construction, etc) → Platform removal → Extension building construction
Unit3	Operation floor (Top floor)	**SFP fuel removal** → **Preliminary site survey** → SFP condition control → SFP fuel removal Equipment removal → Upper dome removal → Shielding removal → Work area setup → **Top-opening investigation** → **Fuel debris removal (Top entry)**
	The air conditioning room roof (Side)	Interfering object removal from the roof of the air conditioning room → Support structure construction → **Side-opening investigation**
	R/B 3rd floor	**Preliminary site survey** → Interfering object removal
	R/B 1st floor	Establish a negative pressure environment in PCV → **Fuel debris removal (Side entry)**
	Yard around R/B	Platform removal → Extension building construction

Remarks

<Considerations and preparations>

o Common to both units
- Implementation of preliminary site surveys
- Decision on the priority order of each work
- Determination of the implementation period of each item
- Determination of negative pressure activation timing

o For Unit2
- Time when interfering objects can be removed from the air conditioning room roof
- Dismantle the upper part of R/B and coordinate space available on the operation floor for fuel debris retrieval works after completing fuel removal from SFP and on-site investigation

o For Unit3
- Coordinate space allocation of the operation floor for fuel debris retrieval work after completing fuel removal from SFP and on-site investigation
- Investigate the well cover damage

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(Yellow box): Relevant to RPV inside investigation

6.2 Investigation method planning

6.2.1 Crystallization of work steps and rationalization of work procedures

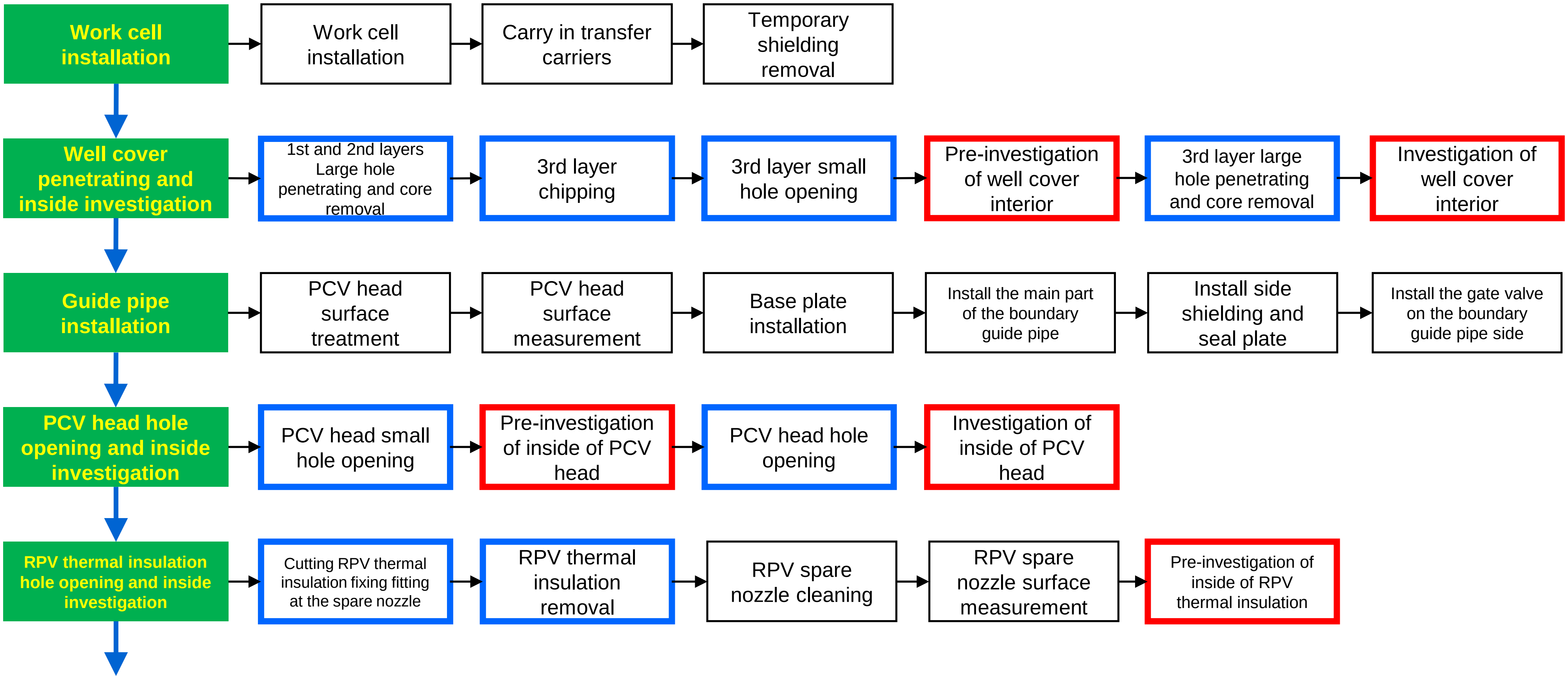
Design of detailed work steps based on the series of work steps outlined in the FY2017 project.
Clarification and rationalization of work step procedures.

	Implementation items	Outlines	Progress status	FY2018	FY2019
1	Detailed design and rationalization of work steps and procedures (Creation of a step diagram)	Detailed design and rationalization of construction procedures after STEP 2 based on the results of the projects until FY2017	Update of work procedures based on the progress of design work, including element test results.	List of investigation needs Detailed design and rationalization of work steps and procedures	Update work steps and procedures Plan of preconditions Reflection of results Update
2*	Preliminary site survey (STEP 1) planning	Study of access routes to the inside of the reactor well and determination of penetrating locations	Study of the access route for investigation equipment to the inside of the reactor and penetrating locations. A specific plan, including implementation timing, needs to be discussed with the Tokyo Electric Power Company (TOPECO).	Planning On-site work planning	Within the project scope Outside the project scope
	Study of preliminary site investigation methods (STEP 1) for penetrating	Study of penetrating methods	Conceptual study for a method applicable to the penetrating of the well cover and the shielding installed on it. (Reported)	Conceptual study Detailed study	
	Study of preliminary site investigation methods (STEP 1) for investigation	Study of investigation methods	Study of equipment used for the investigation and suggestion of outputs obtained by the investigation. (Reported)	Conceptual study Detailed study	

* These items are necessary only for the top-opening investigation method because preliminary site investigations for the side-opening investigation method will be implemented using existing technologies and devices. Thus, there are no elements to develop.

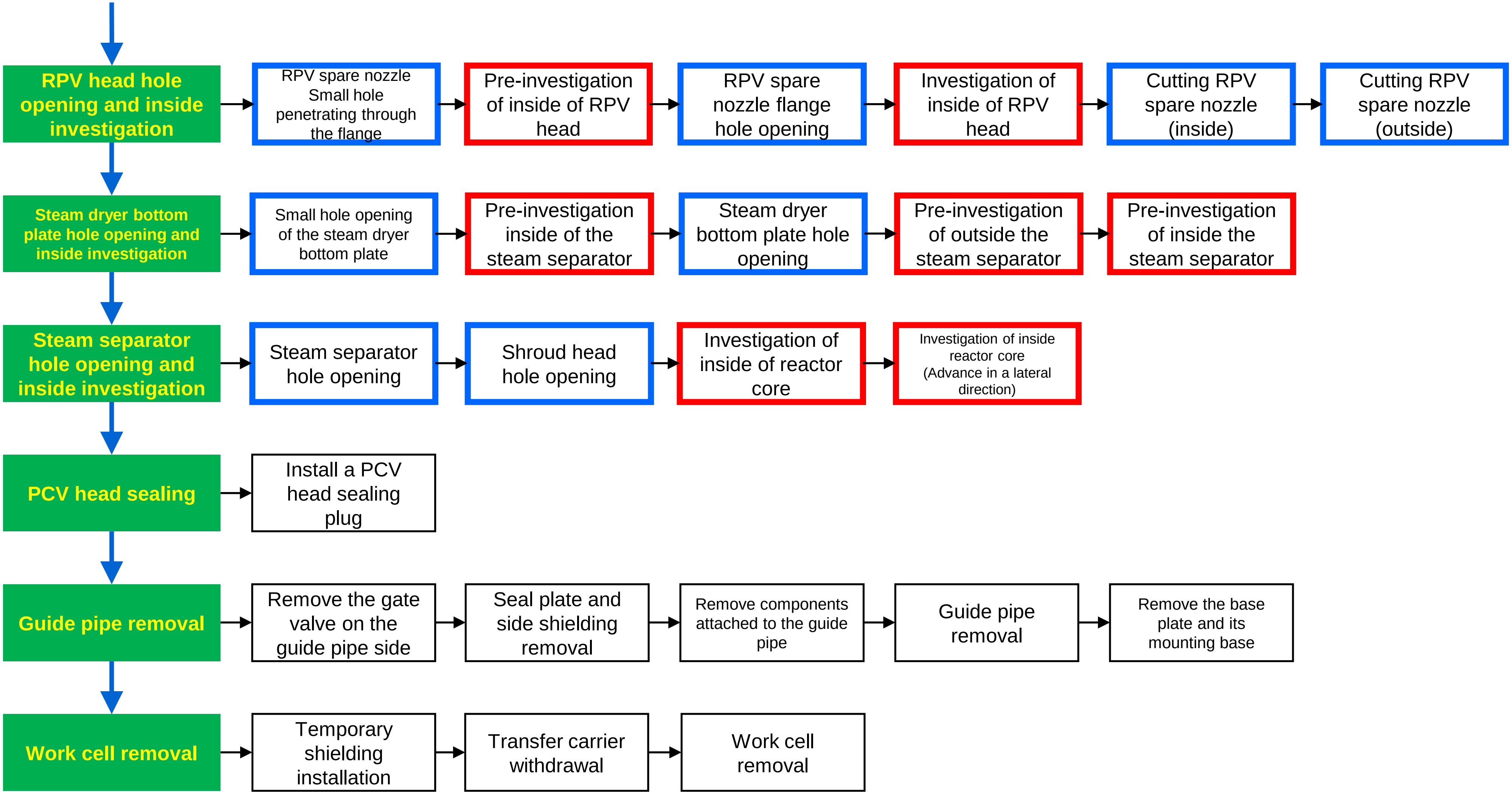
6.2.1.1 Work step: Top-opening investigation method (1/2)

Main step | Sub-step (Others) | Sub-step (Investigation) | Sub-step (Cutting)



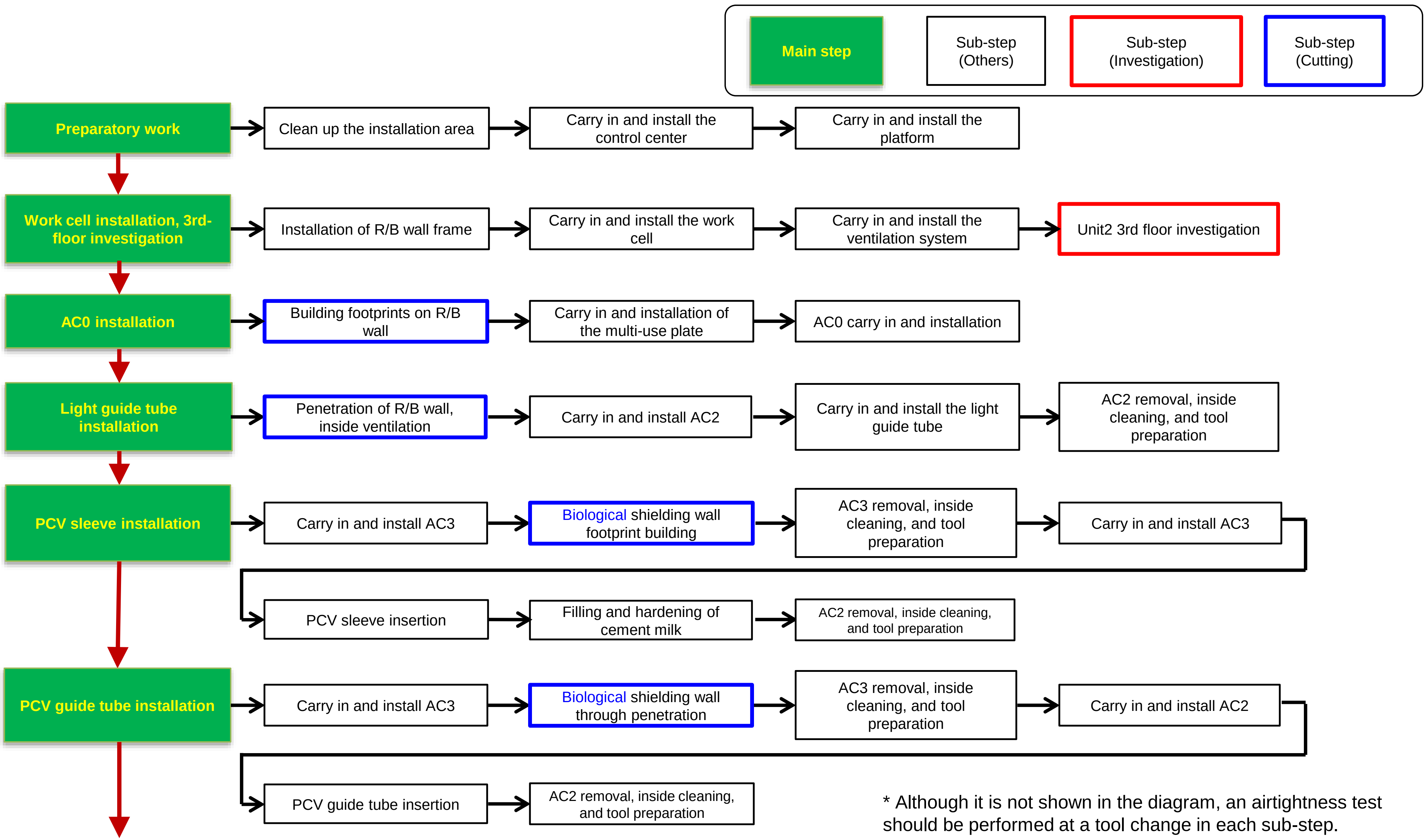
* Although it is not shown in the diagram, an airtightness test should be performed at a tool change in each sub-step.

6.2.1.1 Work step: Top-opening investigation method (2/2)



* Although it is not shown in the diagram, an airtightness test should be performed at a tool change in each sub-step.

6.2.1.2 Work step: Side-opening investigation method (1/2)



* Although it is not shown in the diagram, an airtightness test should be performed at a tool change in each sub-step.

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* See Equipment and device specifications No. 75 and No. 77 for toolboxes AC2, AC3, and AC5.

6.2.1.2 Work step: Side-opening investigation method (2/2)

Work step	Step 1	Step 2	Step 3	Step 4	Step 5
RPV guide tube installation	Carry in and install AC3	Reactor shielding wall through penetration	AC3 removal, inside cleaning, and tool preparation	Carry in and install AC2	
	RPV guide tube insertion	AC2 removal, inside cleaning, and tool preparation			
Hole opening through RPV and shroud head (small hole)	Carry in and install AC3	Penetration through RPV and shroud head	Change investigation equipment	Implement investigation 1	
Hole opening through RPV (large hole) Penetrating through the shroud head	Change investigation equipment	Hole opening through RPV (large hole) Penetrating through the shroud head	AC3 removal and inside cleaning		
Implement investigation 2	AC5 transportation and installation	Implement investigation 2	AC5 removal and inside cleaning		
RPV guide tube removal	Carry in and install AC2	RPV guide tube removal	AC2 removal and inside cleaning		
PCV plug installation and PCV guide tube removal	Carry in and install AC2	PCV plug installation	PCV guide tube removal	AC2 removal and inside cleaning	
Light guide tube removal	Carry in and install AC2	Light guide tube removal	AC2 removal and inside cleaning		
Work cell/attached equipment removal	Multi-use plate Plug	Work cell removal	AC0/platform removal	Attached equipment removal	

* See Equipment and device specifications No. 75 and No. 77 for toolboxes AC2, AC3, and AC5.

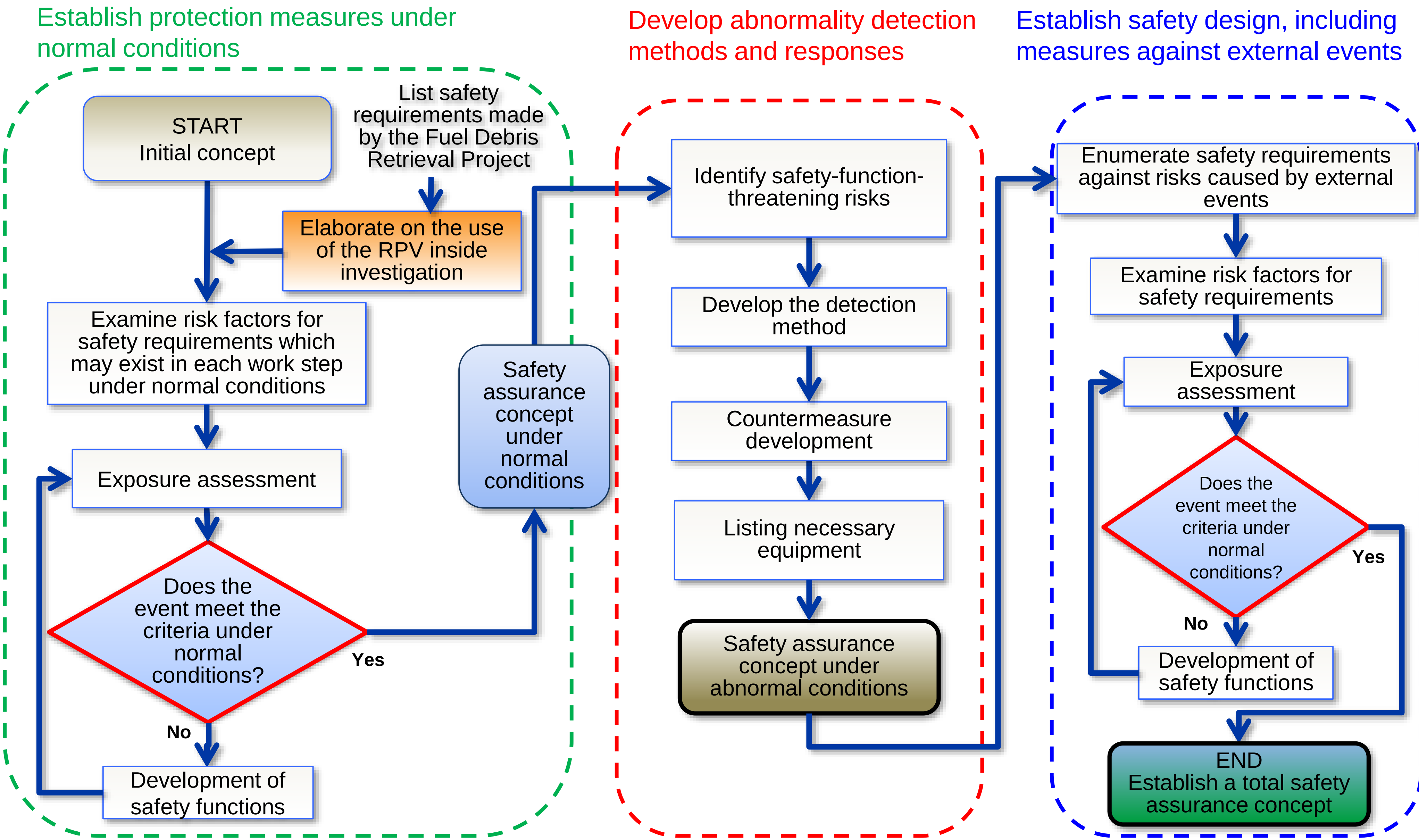
6.2.2 Clarification of safety requirements and exposure assessment

Safety requirements are listed and classified as related to an accident event, single failure, and seismic category. At the same time, exposure assessment is performed based on the device design and detailed investigation planning. Through those actions, the investigation works' impact on the surrounding environment is evaluated.

	Implementation items	Outlines	Implementation Items and Results	FY2018	FY2019
1	Clarification of safety requirements	Organize concepts of safety requirements for investigations. ⇒ Related projects: Fuel Debris Retrieval Methods and Systems	Formulate safety design process and clarify safety requirements. Based on the work organization results, identify the required safety functions under normal and abnormal conditions. In addition, consider and list safety requirements against external events.	List of investigation needs Consider the assessment methods	Update work steps and procedures Safety requirements list Clarification of safety requirements
2	Estimation of the contamination level of structures	Estimate the amount of radioactivity that spreads during cutting and reflect the result in the assessment model.	Estimate the amount of adhered Cs based on the result of the accident progression analysis performed by the Reactor Inside Condition Investigation Project team in FY2017. (Reported)	Estimation of the contamination level of structures	
	Scrutiny of the exposure assessment model (airflow analysis) *	Analyze airflow in PCV to concretize the exposure assessment model and reflect results in it.	Analyze the exposure assessment model and the airflow. Evaluate the radioactive dust reduction effect by gravity settling.	Study the assessment models	Modeling and analysis
	Exposure assessment*	Assess exposure levels (of workers and at the border of the premise) caused by investigation works.	The exposure levels estimated in previous years were reexamined with updated conditions and found to be safe.		Exposure assessment result Exposure assessment

* Use the same basic evaluation method as the other project teams. Perform the evaluations appropriate for the RPV inside investigation and modeling.

6.2.2.1 Clarification of safety requirements(Safety design process)



6.2.2.1 Clarification of safety requirements

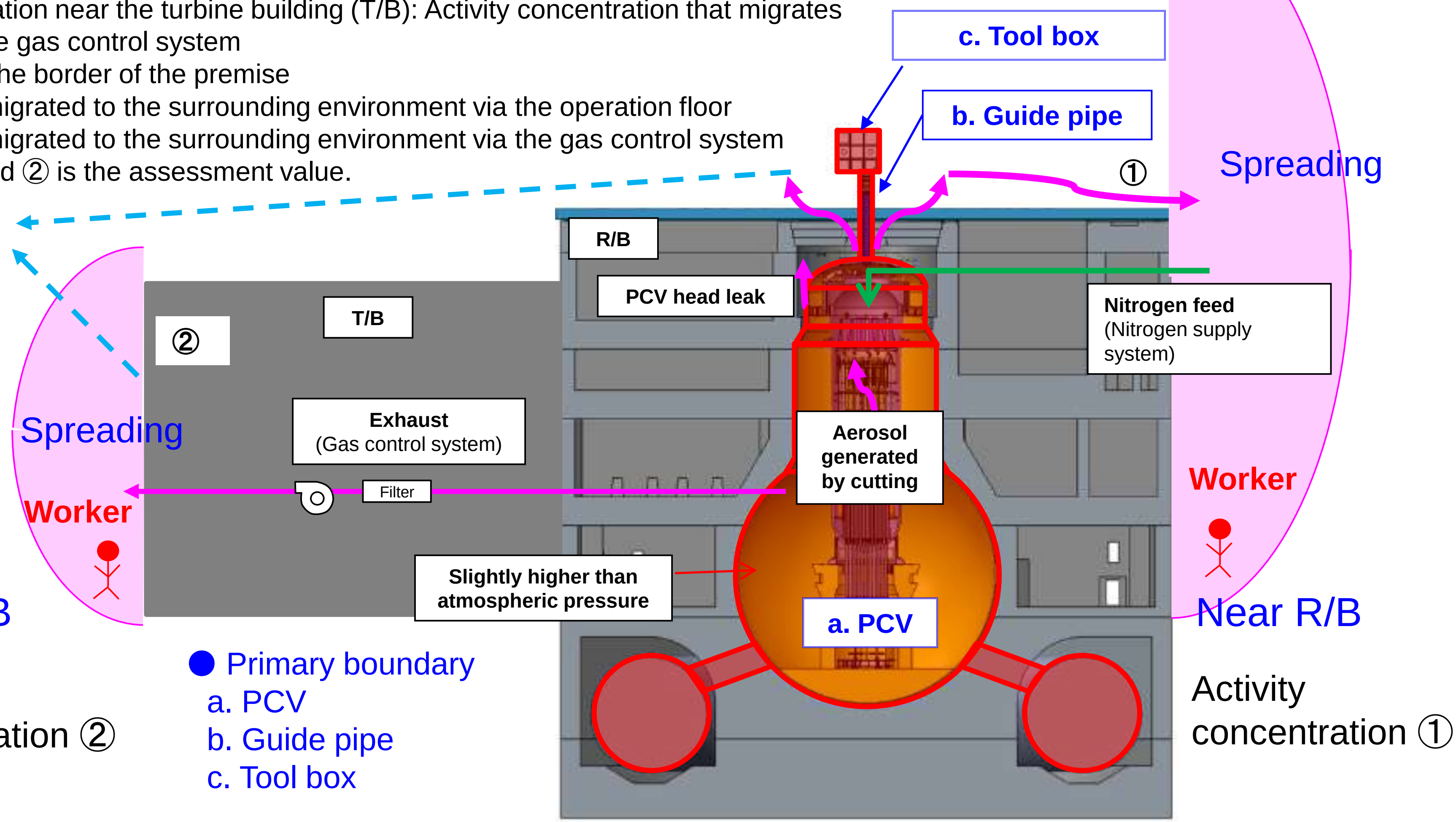
Safety requirements	Internal event			External event	
	Safety functions under normal conditions	Abnormal conditions		Earthquake	Others
		Detection	Countermeasures		
Confinement of radioactive materials in the gas phase	Confinement of airborne radioactive materials by the primary boundary	Gas control system breakdown alarm, radiation and radioactive duct monitoring in the reactor well, operation floor, and work cells	Activate the backup gas control system, shut off the nitrogen supply system if the backup system fails to function, shut off the migration of radioactive materials to the tool boxes by isolation valves, reduce the amount of radioactive material leakage to the operation floor by installing a work cell, and reduce the spread of radioactive materials by installing a ventilation system (with filters) in the work cell.	Confirm no additional safety functions are required.	Equipment installed for RPV inside investigation shall be designed so that it won't degrade the environmental conditions of the 1st floor.
Confinement of radioactive materials in the liquid phase	In accordance with the methods to confine airborne radioactive materials by the primary boundary	—	—	—	
Criticality control	Use of a criticality monitoring system and prevention of tools and materials from falling The weight of processed materials pieces needs to be controlled if they are allowed to scatter.	—	—	—	
Overheating prevention	Use a temperature monitoring system and prevent tools and materials from falling	—	—	—	
Prevention of the excessive spread of radioactive materials due to abnormal cutting	Monitor the appropriate process control of cutting work	—	—	—	
Reduction of workers' radiation exposure (External exposure)	Provision of shielding	—	—	—	
Reduction of workers' radiation exposure (Internal exposure)	In accordance with the methods to confine airborne radioactive materials by the primary boundary	—	—	—	
Prevention of fire and explosion	Work conditions should be properly managed to avoid explosion due to locally accumulated hydrogen.	—	—	—	

6.2.2.2 Exposure assessment: Details of the assessment

- Exposure assessment under the PCV condition of a slight positive pressure (assessment conditions changed from those used in FY2017)

Assessment for the top-opening investigation method

1. Concentration of airborne radioactive material (under normal conditions)
   ① Activity concentration near R/B: Activity concentration that migrates to near R/B via the operation floor
   ② Activity concentration near the turbine building (T/B): Activity concentration that migrates to near T/B via the gas control system
2. Radiation dose at the border of the premise
   ① Exposure dose migrated to the surrounding environment via the operation floor
   ② Exposure dose migrated to the surrounding environment via the gas control system
   The sum of ① and ② is the assessment value.



- Primary boundary
  a. PCV
  b. Guide pipe
  c. Tool box

6.2.2.2 Exposure assessment results for the top-opening investigation (compared to those in FY2017)

Numbers in ( ) are margins (if meeting the criteria: Pass) or insufficiencies (if not meeting: Fail) expressed in the number of digits

Evaluation item	Results of the previous assessment	Results of the assessment in this project	Effects of review	Target values
Activity concentration near R/B (Cs-137) [Bq/m3]	1.7E+00 (*1) **Pass (3-digit)**	2.6E-02 (*1) **Pass (5-digit)**	2-digit	3.0E+03 (Outdoor, without mask)
Activity concentration near R/B (Pu-238) [Bq/m3]	2.7E-5 (*1) **Pass (4-digit)**	2.6E-07 (*1) **Pass (6-digit)**	2-digit	7.0E-01 (Outdoor, without mask)
2. Radiation dose at the border of the premise [μSv/y]	1.9E+01 (*2) **Pass (1-digit)**	1.6E-01 **Pass (3-digit)**	2-digit	1.0E+02

(*1) These values of the activity concentration near R/B were obtained during the cutting of the steam separator, which showed the maximum activity concentration in the assessment in FY2017 (except for the activity concentration near T/B via the gas control system).

(*2) The radiation dose at the border of the premise was the sum of the radiation doses at the same location caused by the cutting of the PCV head, RPV thermal insulator, steam dryer, steam separator, and shroud head (including that originated from the exhaust of the gas control system with a filter DF of 1,000).

The exposure assessment results had shown that investigation for the inside of RPV can be conducted by the top-opening investigation method under the PCV condition of a slight positive pressure from a perspective of a safety assessment. It is the same conclusion as the FY2017 assessment.

6.2.2.2 Exposure assessment: Activity concentration in R/B

Item	① FY2017 top-opening investigation method	② FY2019 top-opening investigation method	The difference in number of digits [① minus ②]	Target values
Maximum activity concentration (Cs137) in R/B (Bq/m^3)	1.1E+06	1.9E+07	- 1-digit	3.0E+03 (Outdoor, without mask)
Maximum activity concentration (Pu238) in R/B (Bq/m^3)	1.8E+01	8.6E+01	0-digit	7.0E-01 (Outdoor, without mask)

On the other hand, the exposure assessment result had shown that the top-opening investigation for the inside of RPV cannot be conducted under the PCV condition of a slight positive pressure, because radioactivity concentration in R/B is higher than target levels same as the result in FY2017.

The following changes in assessment conditions affected the result of FY2019 assessment greatly:

- More structures were added as an assessment target. ⇒ All conceivable structures were considered to be a cutting target.
- The stagnation and sedimentation in PCV and R/B was taken into consideration. ⇒ The result of airflow analysis using GOTHIC code was reflected.
- Radiation dilution effect by the volume of R/B ⇒ The volume of R/B used to calculate the dilution effect was decreased.

Note that exposure assessment conditions (including contamination level setting using MAAP code, setting of the percent of airborne spreading dust during cutting, leakage from PCV including leak locations and leak rate) are accompanied with uncertainty. Additional information, such as site information, is needed to improve the accuracy of the assessment.

There may still be a possibility to establish a safe environment by maintaining a slight positive pressure in PCV and negative pressure in R/B. Further, there is also a possibility to establish a negative pressure environment in PCV with the advancement of fuel debris retrieval method development and scaling up that will take place in parallel to this project.

6.3 Study on investigation auxiliary system

The use timing of ancillary systems required for investigation works and safety assurance, such as the nitrogen supply system, dust monitoring system, and criticality control system as well as gas and negative pressure control system, and required specifications for them from the investigation team are clarified to prevent contaminated dust from spreading. Especially, the top-opening investigation method will be used under the PCV environment of negative pressure before fuel debris retrieval from the PCV bottom is started. Therefore, specifications need to be clarified for the gas control system and a negative pressure control system that will be required for negative pressure control. In addition, operation instructions will need to be considered for a dust monitoring system if used constantly to prevent contaminated dust.

	Implementation items	Outlines	Implementation Items and Results	FY2018	FY2019
1	Formulation of required specifications of the systems needed for investigation works	The investigation team clarifies the use timing of ancillary systems required for investigations, safety assurance, and required specifications. ⇒ Related projects: Fuel Debris Retrieval Methods and Systems, Criticality Control	Required specifications were considered based on the created safety requirement list.	Update work steps and procedures Study on ancillary systems' applicability	Formulation of required specifications for ancillary systems

No.	Ancillary systems considered to be necessary for investigation works	Outlines
1	Gas control system	System to reduce the concentration and amount of radioactive materials spreading out from PCV to the surrounding environment as much as possible by the ventilation and filtration of gas in PCV
2	Nitrogen supply system	System to keep the inside of RPV and PCV in an inert condition to prevent hydrogen explosion by feeding nitrogen
3	Negative pressure control system (Only for top-opening investigation method)	System to keep the inside of PCV in a negative pressure environment to prevent airborne radioactive particles generated by the cutting of structures from spreading out of PCV
4	Criticality control system	System to monitor the occurrence of a criticality accident caused by fuel and fuel debris lying in the reactor during structure cutting work and to keep the accident under control even if it occurs ⇒ Use existing equipment.
5	Dust monitoring system	System to monitor the concentration of airborne radiation during structure cutting work
6	Water treatment system	System to reduce the concentration and amount of radioactive materials that are generated by structure cutting, mixed into wastewater circulation, and spread out from PCV to the surrounding environment by filtration

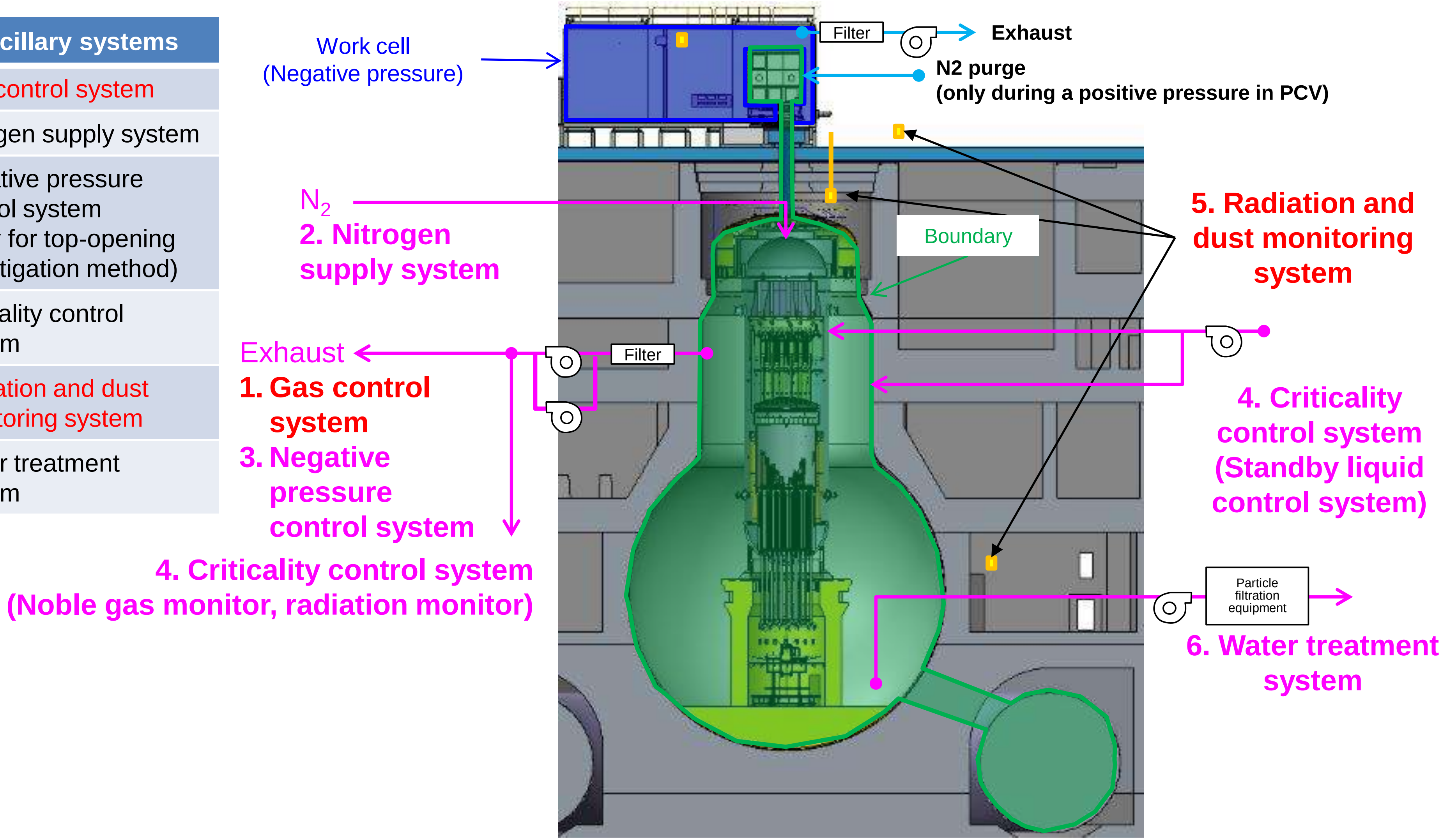
6.3.1 Requirements for ancillary systems

Possible abnormal events were listed along with necessary responses to them based on the created safety requirement list.

Detection and response		Necessary equipment
Detection	Detection by the gas control system breakdown alarm	**Gas control system breakdown alarm**
	Radiation leak detection by the radiation monitor and dust monitor of the reactor well	**Radiation monitor and dust monitor of the reactor well**
	Radiation leak detection by the radiation monitor and dust monitor of the operation floor	**Radiation monitor and dust monitor of the operation floor**
	Radiation leak detection by the radiation monitor and dust monitor installed in the work cell	Radiation monitor and dust monitor in the work cell (to be developed in this project)
Countermeasures	Activation of the backup system of the gas control system, shutting off the nitrogen supply system if the backup system fails to function	**Backup gas control system**
	Mitigation of the migration of radioactive materials to the toolboxes by isolation valves	Isolation valve (to be developed in this project)
	Reduction of radioactive material leakage to the operation floor by installing a work cell	Work cell (to be developed in this project)
	Reduction of radioactive material spread by installing a ventilation system (filter) in the work cell	Work cell ventilation system (filter) (to be developed in this project)

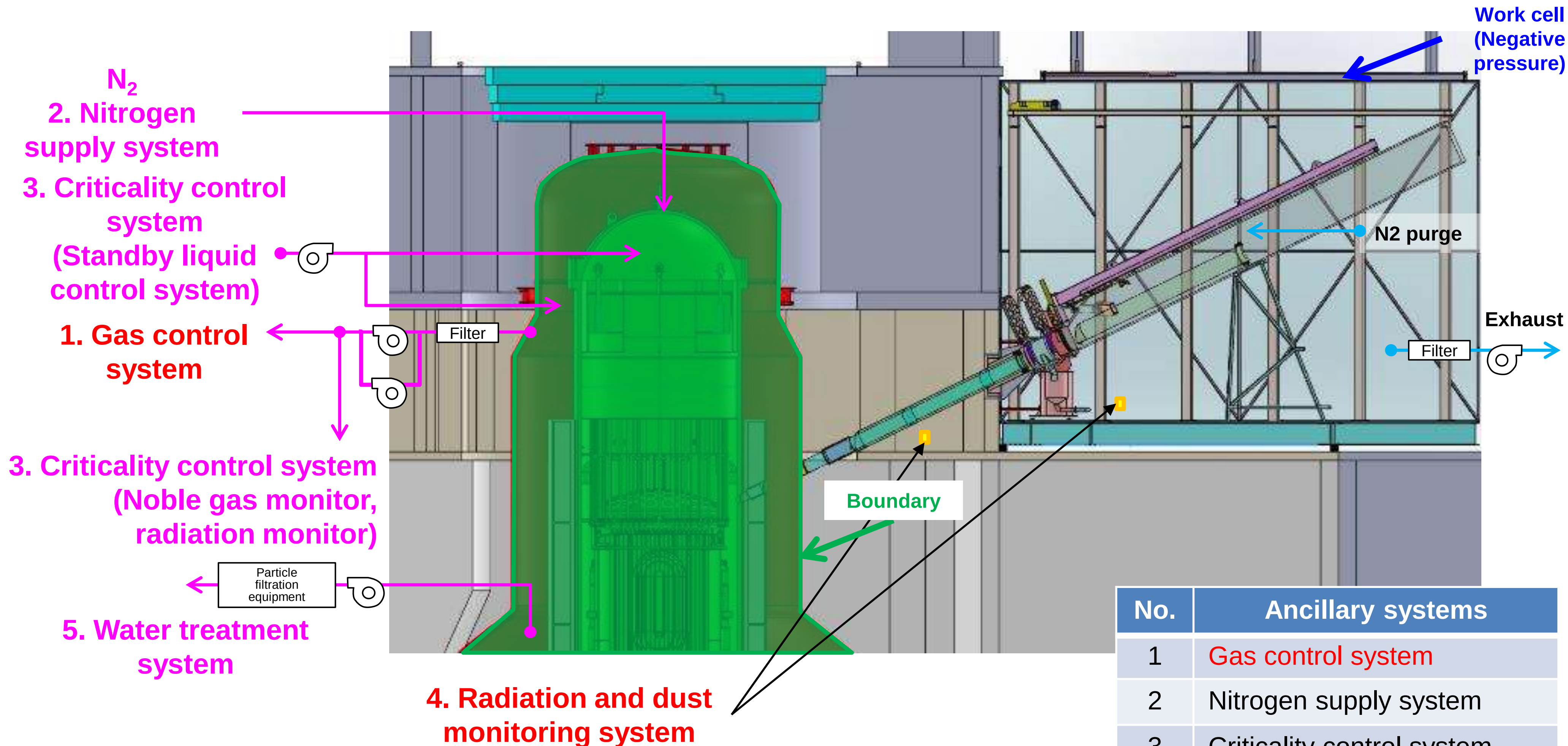
6.3.2 Ancillary systems for the top-opening investigation

No.	Ancillary systems
1	Gas control system
2	Nitrogen supply system
3	Negative pressure control system (Only for top-opening investigation method)
4	Criticality control system
5	Radiation and dust monitoring system
6	Water treatment system



Update ancillary systems necessary for the top-opening investigation method based on the created safety requirement list (items written in red letters).

6.3.3 Ancillary systems for the side-opening investigation



No.	Ancillary systems
1	Gas control system
2	Nitrogen supply system
3	Criticality control system
4	Radiation and dust monitoring system
5	Water treatment system

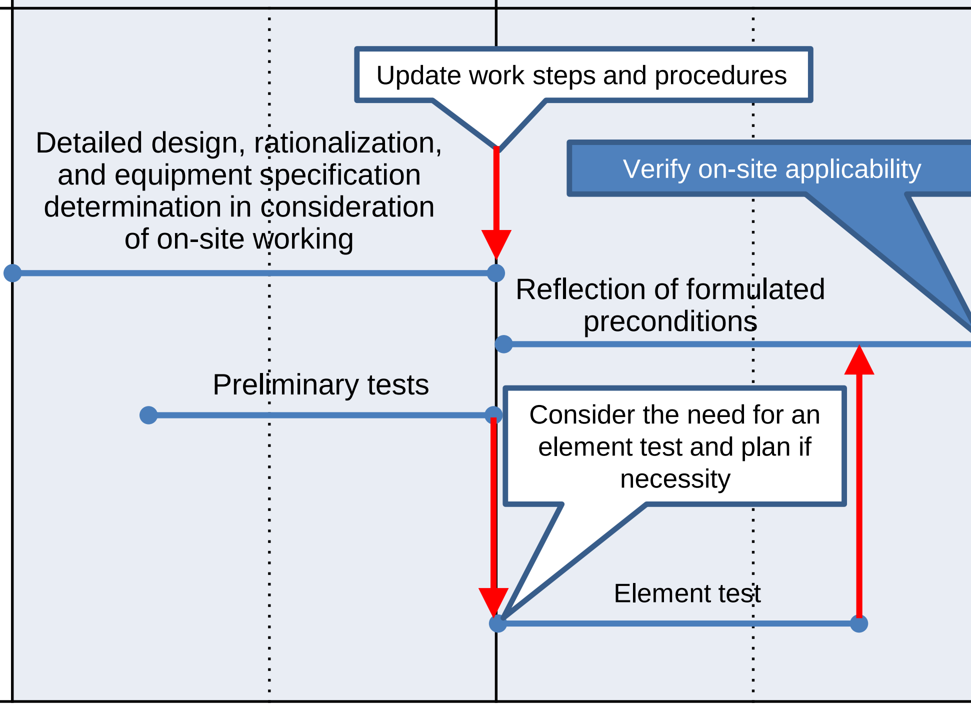
Improvement of ancillary systems necessary for the side-opening investigation method based on the created safety requirement list (items written in red letters).

6.4 Development of access and investigation equipment

6.4.1 Development of investigation equipment for the top access method

Machines used for penetrating from the top of the operation floor to the shroud head, equipment to prevent dust spread, and investigation equipment applicable to different investigation targets. Specifically, develop technologies that can solve issues to realize investigation works at the site. Design and rationalize necessary devices and systems in detail based on the outcomes of the projects until FY2017. In addition, consider the necessity of elements tests for device development and perform tests if necessary in FY 2018 to verify the devices' applicability to site investigation works based on the correct understanding of the site conditions.

	Implementation items	Outlines	Progress status	FY2018	FY2019
1	Work cell development	Develop technologies that can solve issues to realize investigations at the site. Design and rationalize necessary devices and systems in detail based on the outcomes of the FY2017 project. Perform large-scale element tests, like a combination test, as needed.	See the following pages.		
2	Development of a boundary function maintenance device				
3	Development of processing apparatus				
4	Development of investigation systems				



6.4.1 Development of investigation equipment for the top access method

Item	Implementation plan	Implementation Items and Results
Work cell	· Rationalization of structures and methods in consideration of the operability of each device · Rationalize device and equipment layout plans in and around the work cell. · Clarify installation methods and interface conditions · Detailed design of the negative pressure control system	· Preparation for on-site works including penetrating and investigation work and the organization of work procedures for each operation such as toolbox change · Study ancillary systems required for the work cell (negative pressure control and monitoring systems). · Organize required utilities and peripherals as well as interface information for each device · Examine layout plans in detail. · Redundant design (dual system design) of the exhaust system in preparation for a failure
Boundary protection equipment	· Rationalize structures and methods in consideration of ease of construction · Improvement of the reliability of the guide pipe sealing mechanism for negative pressure · Verification of the sealing performance (confinement performance) of the joint between the guide pipe and toolbox	· Operating procedures and necessary functions were reviewed and organized for the transfer carrier, connection mechanism, and gate valves in connection with toolbox replacement. · Determine a sealing mechanism applicable to negative pressure through a preliminary test. · Verify a temporary clamping method and necessary clamp force through the gate valve and joint preliminary tests. · Perform preliminary tests on the connection mechanism in terms of the up/down movement of its bellows, forced separation, and sealing performance, and confirm that the targeted functions and performance can be achieved.
Processing apparatus used until reaching RPV head	· Rationalization of structures and methods · Study of other access routes than the one via RPV spare nozzle (RPV thermal insulation and RPV head cutting method)	· Regarding small hole opening of PCV and RPV head, perform element tests to assess the feasibility of carrying out hydrogen degassing and cutting for prior check in a single work process. · Perform preliminary tests to assess the applicability of AWJ to well cover hole opening as an alternative. · Perform element tests to study RPV thermal insulation hole opening and removal methods.
Processing apparatus for the reactor core internal structure	· Size reduction of the tool head device · Guide pipe vibration suppression · Improvement of cutting performance, positioning accuracy, and workability · Study methods to maneuver around interfering objects in the reactor and to locate hole opening positions · Design and develop devices based on the estimated condition inside the reactor vessel · Development and design of devices and systems, and verification of their on-site workability	· Install an injection reaction force receiving jig to reduce the deviation of the injection head from the target position due to the injection reaction force during cutting. Test the effect of the receiver with element tests. · Plan element tests for the hole opening of the steam separator and shroud head. Verify the connected guide pipe linearity. · Reexamine AWJ operation parameters. Confirm that the amount of abrasive could be reduced from about 20 t to about 9 t by adjusting cutting speed and other parameters. · In response to changes made in shroud head cutting parameters as the result of element tests, design a new tool head. Attach an injection reaction force receiving jig, which concurrently serves as a jig for processed materials collection.
Investigation system	· Improvement of the reachable range and maneuverability of investigation equipment · Measures to improve visibility (image processing) · Develop investigation methods and devices that fit estimated conditions in the reactor · Reflect on the outcomes of device development and design for reactor inside investigation in designing assess devices used for the side-opening investigation	· Perform an accessibility evaluation test as an element test and indicate the test result in the design of the investigation and access devices to complete the design work. · Suspend the investigation equipment at a simulated height and test to capture a celestial-sphere image (B2) and an around-view image B3). They were confirmed to be able to output a seamless composite image without any problematic blurring.

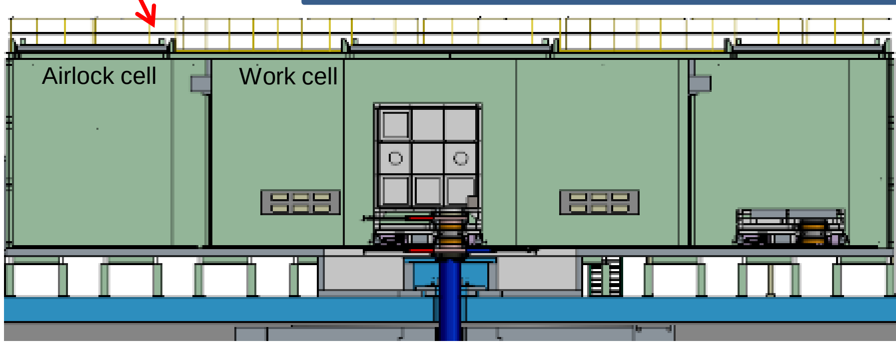
* See Equipment and Device List (No. 57) for investigation equipment B2 and B3.

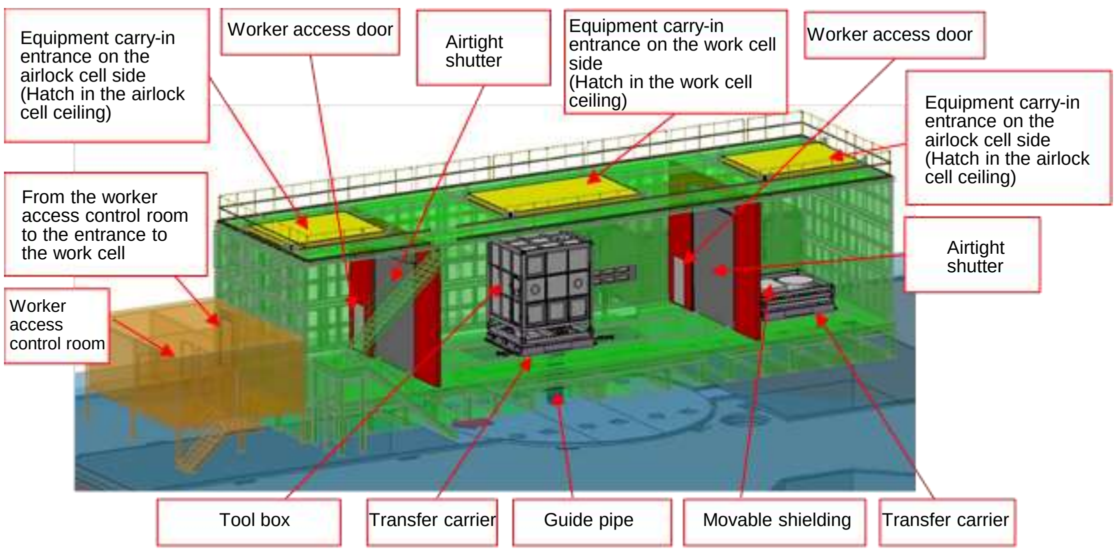
6.4.1.1 Top-opening investigation method: Work cell

Implementation items	Implementation plan	Implementation Items and Results	Remarks
Rationalization of structures and construction methods considering operability of each equipment	· Rationalize the work cell's design by reexamining its structure and method from the viewpoint of minimizing work time and radiation exposure to protect workers and the surrounding environment from exposure during the installation of the work cell, processing apparatus, and investigation equipment.	· Preparation for on-site works including penetrating and investigation work and the organization of work procedures for each operation such as toolbox change (Reported) · Study ancillary systems required for the work cell (negative pressure control and monitoring systems).	
Rationalization of device and equipment layout plans in and around the work cell	· Plan device and equipment layouts taking into account workers' traffic lines around the work cell, and plan the layout of utility supply systems according to the above-mentioned method rationalization effort.	· Organize required utilities and peripherals as well as interface information for each device · Examine layout plans in detail.	
Clarification of installation methods and interface conditions	· Determine the available space for the installation of the work cell and seismic design conditions.	· Use the same target seismic strength as that for PCV inside investigation for seismic design. (Reported)	
Detailed design of a negative pressure control system for the work cell	· Study functional requirements for the work cell negative pressure control system from a safety point of view and reflect the system specifications.	· Redundant design (dual system design) of the exhaust system in preparation for a failure (Reported)	

A temporary facility to prevent contaminated materials from spreading to the surrounding environment, protect workers from radiation exposure and provide devices with a safe environment if by any possibility the PCV boundary fails to function *

Work cell





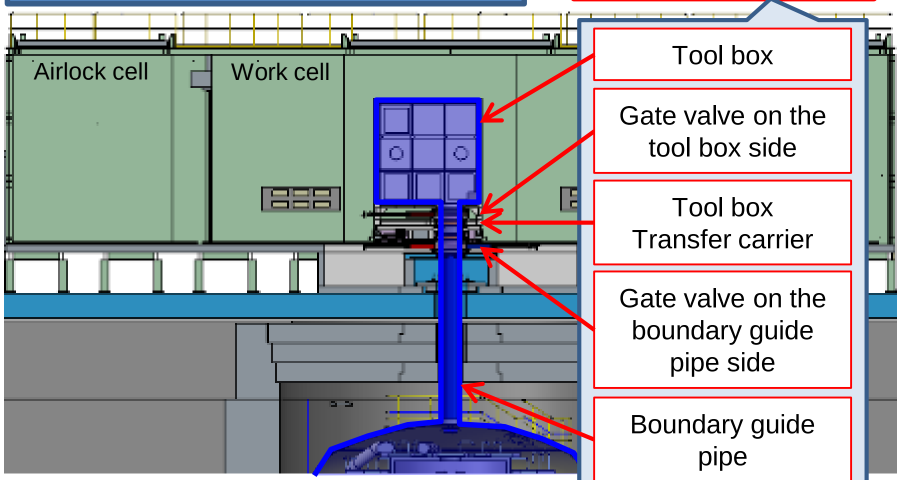
* This is not a cell constructed to establish the primary boundary planned for fuel debris retrieval and other works.

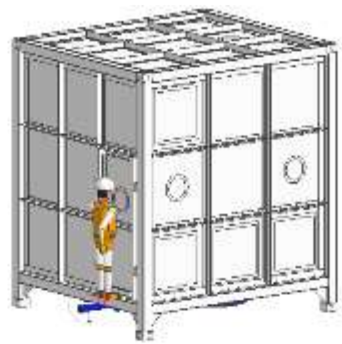
6.4.1.2 Top-opening investigation method: Equipment for maintaining boundary function

Implementation items	Implementation plan	Implementation Items and Results	Remarks
Rationalization of structures and construction methods in consideration of ease of construction	· Rationalize the design of the boundary protection equipment by reexamining its structure and method from the viewpoint of minimizing work time and radiation exposure to protect workers and the surrounding environment from exposure during the installation of the boundary guide pipe and toolboxes.	· Operating procedures and necessary functions were reviewed and organized for the transfer carrier, connection mechanism, and gate valves in connection with toolbox replacement. (Reported)	
· Improvement of the reliability of the boundary guide pipe sealing mechanism for negative pressure	· Evaluate the reliability of the improved boundary guide pipe sealing mechanism for negative pressure.	· Determine a sealing mechanism applicable to negative pressure through a preliminary test. (Reported)	Including preliminary tests
Verify the sealing performance (confinement performance) of the joint between the boundary guide pipe and toolbox	· Feasibility verification of the gate valve · Evaluate the sealing performance of the connection mechanism between the boundary guide pipe and toolbox	· Verify a temporary clamping method and necessary clamp force through the gate valve and joint preliminary tests. (Reported) · Perform preliminary tests on the connection mechanism in terms of the up/down movement of its bellows, forced separation, and sealing performance, and confirm that the targeted functions and performance can be achieved.	Including preliminary tests

A temporary facility that allows the transfer of processing apparatus and investigation equipment into the PCV by extending the PCV boundary

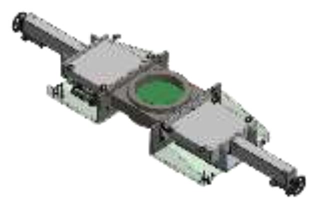
Boundary protection equipment





Tool box

Tool box transfer carrier



Gate valve on the boundary guide pipe side

Connection part of PCV head (Test in FY2017)

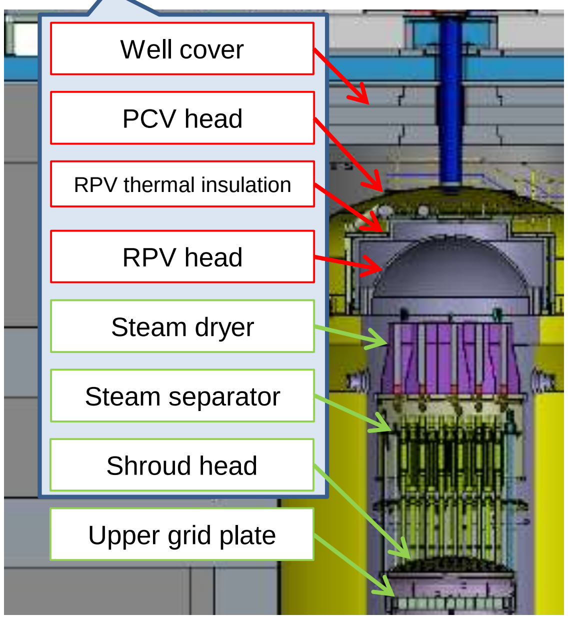
Boundary guide pipe

6.4.1.3 Top-opening investigation method: Processing apparatus (1) for opening of RPV head and upper structures

Implementation items	Implementation plan	Implementation Items and Results	Remarks
Rationalization of structures and construction methods	· Rationalize the work cell's design by reexamining its structure and method from the viewpoint of minimizing work time and radiation exposure to protect workers and the surrounding environment from exposure during the installation of the work cell, processing apparatus, and investigation equipment.	· Regarding small hole opening of PCV and RPV head, perform element tests to assess the feasibility of carrying out hydrogen degassing and cutting for preliminary survey in a single work process. (Reported)	Including element tests
Technology design to address issues arose in the previous years and feasibility study	· Perform preliminary tests and element tests for technology design and feasibility study to address issues that arose in the element tests and design work in the previous years and reflect device design results.	· Perform preliminary tests to assess the applicability of AWJ to well cover hole opening as an alternative. (Reported) · Perform element tests to study RPV thermal insulation hole opening and removal methods.	Including preliminary tests and element tests

Processing apparatus

Hole-opening machines used to construct an access route into the reactor for investigation equipment



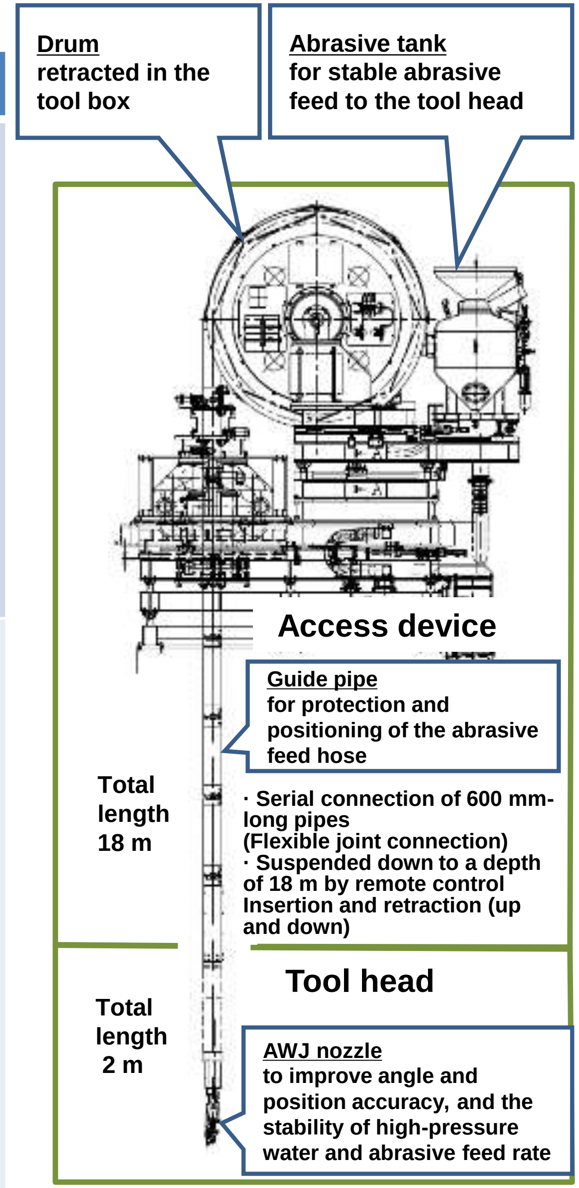
[Outlines of the penetrating of RPV head and structures above it]

Structures to be processed	Specifications of the structures	Processing methods	Required hole diameter
Well cover	Material: Reinforced concrete Thickness: 618 mm (top), 610 mm (middle and bottom)	Core boring AWJ (alternative)	≥ φ750 mm
PCV head	Material: Carbon steel Thickness: 30 mm Curvature: 8,347 mm	Small hole opening: Mechanical cutting* Large hole opening: AWJ	Small hole: ≥ φ40 Large hole: ≥ φ550
RPV thermal insulation	Material: SUS304, A3004P-0 Thickness: 0.7 mm/1.5 mm	AWJ	≥ φ600
RPV head (Spare nozzle section)	Material: ASTM A 533 Gr.B CL.1 Thickness: Min. 75 mm	Small hole opening: Mechanical cutting* Large hole opening: AWJ	Small hole: ≥ φ40 Large hole: ≥ φ300

* Pay attention to accumulated hydrogen when selecting a method.

6.4.1.3 Top-opening investigation method: Processing apparatus (2) for processing the reactor core internal structures

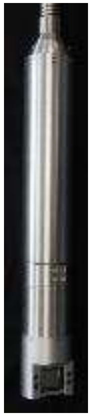
	Implementation items	Implementation plan	Implementation Items and Results	Remarks
Structural design of devices	Tool head Size reduction	· Reduce the tool head's size by making it foldable (using 600 mm-long pipes serially connected with flexible joints) to retract it in the work cell (tentative height of 4 m or less).	• Redesign the size and layout of the tool head. • Compare the new tool head design with the current design, and examine its feasibility.	Completed in FY2018 Including preliminary tests
	Suppression of the guide pipe vibration	· Take the following measures to suppress the tool head vibration: making the flexible joints rigid, adjusting mechanism review, and detailed design for accuracy improvement.	• Investigate guide pipe vibration factors and study measures for improvement. • Design parts based on the devised measures and perform preliminary tests.	
	Improvement of cutting performance, positioning accuracy, and workability	· Review AWJ cutting parameters (combination angle, position, etc.), upgrade the machine, and stabilize the abrasive feed rate (increase abrasive feed rate from 200 to max. 500 g/min) to improve the accuracy of the diameter of bored holes made by remote operation and to reduce re-do work.	• AWJ cutting parameters were reviewed. • Investigate factors to improve the abrasive feed rate stability. • AWJ cutting parameters were optimized, and parts were reselected or added to improve abrasive feed rate stability.	
Sample production for element tests and testing	Methods to maneuver around interfering objects in the reactor and locate hole opening positions	· Rationalization of remote operation and monitoring tailored to the design of devices (the type of structure to be cut and method of locating hole opening position)	• Install an injection reaction force receiving jig to reduce the deviation of the injection head from the target position due to injection reaction force during cutting. Test the effect of the receiver with element tests.	Completed in FY2019 Including element tests
	On-site workability of devices and systems	· Prototype the combined system of the tool head and the access device and perform partial mockup tests to evaluate the remote operation, monitoring, and utility facility management.	• Plan element tests for the hole opening of the steam separator and shroud head. Verify the connected guide pipe linearity. • AWJ operation parameters were reexamined. Confirm that the amount of abrasive could be reduced from about 20 t to about 9 t by adjusting cutting speed and other parameters.	
	Rationalization of devices based on the estimated condition inside the reactor vessel	· Design cutting and investigation work steps (such as the location of structures to be cut and hole opening locations and diameters), and rationalize methods and devices according to the ease of restriction on the processed materials that is produced and falls in the reactor during cutting	• In response to changes made in shroud head cutting parameters as the result of element tests, a new tool head was designed. An injection reaction force receiving jig, which concurrently serves as a jig for processed materials collection, was attached to it.	



6.4.1.4 Top-opening investigation method: Investigation system

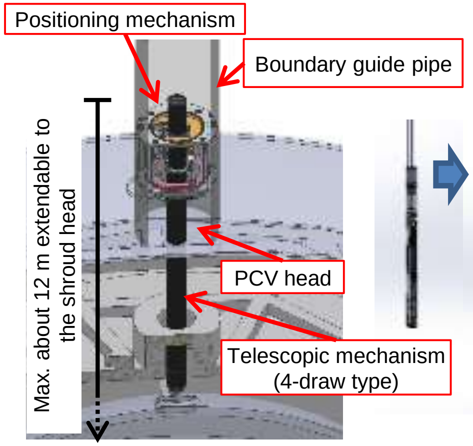
Item	Implementation plan	Implementation Items and Results	Remarks
Investigation equipment prototyping, improvement of outreach range and maneuverability of them	· Test the prototype samples to address issues that were found in designed devices and preliminary tests in FY2017. · Set the investigation equipment in the guide pipe dispensing and retracting equipment and evaluate the accessibility to the reactor core internal structures.	· Design change was made to the whole part of the investigation equipment based on the results of tests on the partial prototypes of the full investigation equipment B2 and B3, and prototypes were built. The accessibility to the reactor bottom (equivalent reaching a depth of about 26 m) and the prototypes' ability to capture a celestial-sphere image and around-view image were tested in the site-simulated environment with structure mockups. · The configuration of the components of the guide pipe dispensing and retracting equipment (cable drum) was designed based on the result of noise tests with the use of slip rings, and a single cable-drum style unit was prototyped. Noise tests were performed with it. The influence of drum driving noise on the operation of the equipment was negligible though the noise was mixed in image data. Ethernet signals required special slip rings. · The design verification of the investigation and access devices was completed.	Including preliminary tests and element tests
Development of investigation methods and devices that fit estimated conditions in the reactor	· Conceptual design was conducted in FY2018 to develop a horizontal extension arm with increased extension range and a telescopic guide pipe mechanism used to guide the new arm to expand the range of investigation in the reactor core section. Design these two mechanisms in detail, build their prototypes, and evaluate their performance. · Perform accessibility evaluation tests to the reactor core internal structures.	· A new horizontal extension arm with increased extension range was prototyped to expand the range of investigation in the reactor core section. At the same time, a telescopic guide pipe and positioning mechanism suitable for the guiding and position control of the new arm was also prototyped. · Investigation equipment C was able to be guided to a target location by combining the telescopic guide pipe extended to the top of the upper grid plate and the horizontal extension arm in the site-simulated environment with structure mockups.	Including preliminary tests and element tests
Image capturing performance evaluation	· Evaluate image capturing performance in foggy conditions. · Obtain a clear, blur-less image even if the investigation equipment shakes due to its suspended condition. (Degree of the shake of the investigation equipment should be larger than those for PCV inside investigation with proven records due to a longer suspension distance) · Development of technology to process captured images (such as a celestial-sphere image)	· The investigation equipment for prior check (AHS/AHB) and full investigation (B1/B2/B3/B4) were mounted in the access device and tested to evaluate their image capturing performance. (FY2018) · An image sharpening algorithm applicable to blurs caused by vibration was developed. · Suspend the investigation equipment at a simulated height and test to capture a celestial-sphere image (B2) and an around-view image B3). They were confirmed to be able to output a seamless composite image without any problematic blurring.	Including preliminary tests and element tests


Investigation equipment B2


Investigation equipment B3

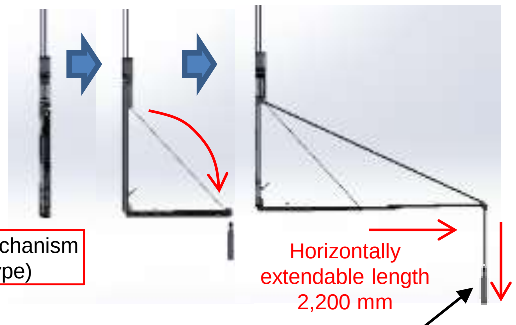
Prototype of full investigation equipment


Double-wheel cable drum



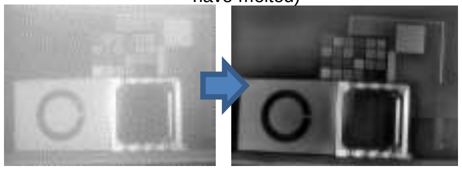
Telescopic guide pipe and positioning mechanism (for investigation equipment C)

Suspension device



Horizontal extension arm with an increased extension range

Captured celestial-sphere image
(The center of the upper grid plate was assumed to have melted)


Original image Image after sharpening
Image sharpening to compensate for blurring caused by vibration

* See Equipment and Device List (No. 57) for investigation equipment AHS, B1, etc.

6.4.1.4 Top-opening investigation method: Investigation system - Improved prototypes of investigation equipment (Investigation equipment B2)

Prototyping and evaluation in FY2018

Component function tests

- Operation and performance tests of drive
  - ➢Cables were made thinner to fit in tiny spaces of the motion mechanism, and no noises were mixed in video image data or sensor signals.
  - ➢The cables in the devices moved smoothly in response to the tilt and pan motion.
- Ability to retract the mechanism in case of failure (Effect of slip clutch)
  - ➢The mechanism could be retracted by allowing the link mechanism to slip by an external force when the tilt motion couldn't be activated.

Visibility evaluation

- Image-capturing performance was tested in foggy conditions.

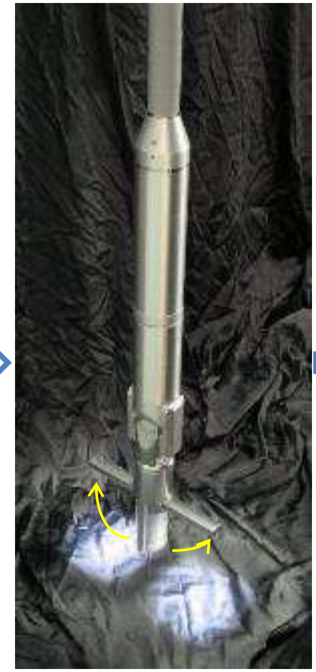
⇩

Design and prototyping in FY2019

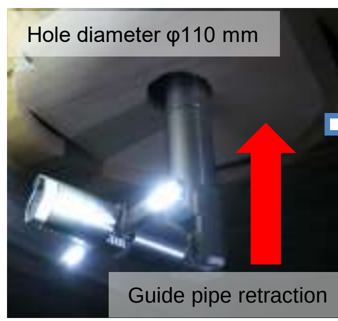
Prototype of the whole mechanism

- Addition of stretchable light mounting arms
  - ➢A slip clutch was installed in the link mechanism of the light mounting arms in addition to the tilt link mechanism so that the arms could be folded during the investigation equipment retraction operation even if the motor failed.
- Prototype of control system
  - ➢The tilt and pan angles could be kept within ±0.5° (target is ±1.0°) of intended angles by using acceleration and deceleration control to suppress the vibration of the devices.
  - ➢An automatic remote control that links to the operation of the celestial-sphere image capture system was developed.

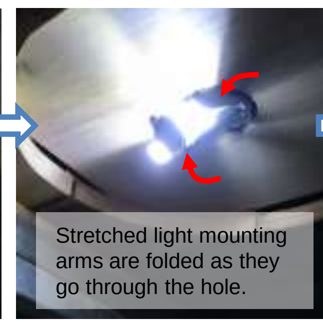
Position during up and down movement

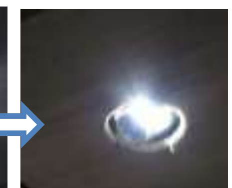

Stretching arm lights

Tilted at 90°



Tilted at 90°, light mounting arms stretched




Getting through the hole

The installation of slip clutches made it possible for the investigation equipment to be folded and straightened due to slippage caused by structural forces when pulled up. Thus, they could be safely retracted in case of failure or malfunction.

6.4.1.4 Top-opening investigation method: Investigation system
: Improved prototypes of investigation equipment (Investigation equipment B3)

Prototyping and evaluation in FY2018

Function verification of mechanism configuration

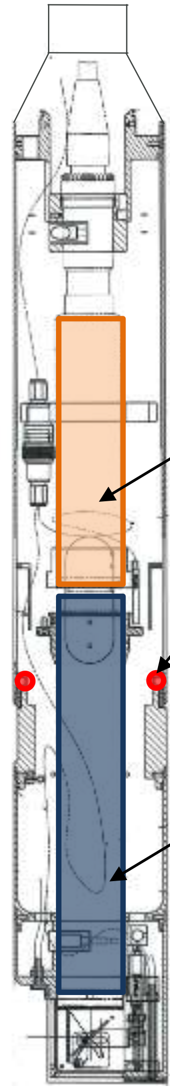
- Operation and performance tests of drive
  - The cables in the devices moved smoothly in response to the pan motion of the mechanism.
  - The friction resistance of the sealing used in the pan rotation mechanism increased about threefold (to 1.2 Nm) when the mechanism was not operated for a long time. The original design was to utilize the swivel unit of the image pick-up tube mounted in the device. Increased friction resistance could cause insufficiency in driving torque.

Visibility evaluation

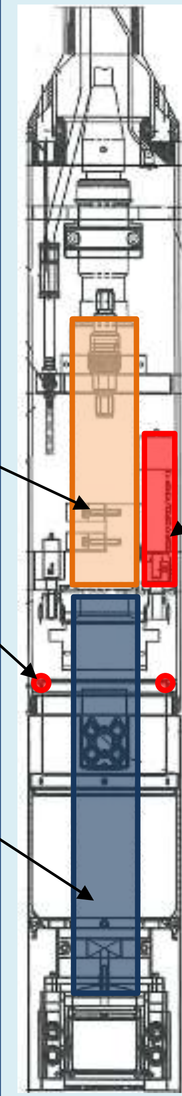
- Image-capturing performance was tested in foggy conditions.

Design and prototyping in FY2019

- Increase of pan motor torque
  - Stable pan rotation was achieved by installing an additional pan motor and doubling the drive torque to 2.6 Nm.
- Prototype of control system
  - The same control unit as the one for investigation equipment B2 was adopted. An automatic remote control linked to the operation of the around-view image capture system was developed.



Prototyping in FY2018

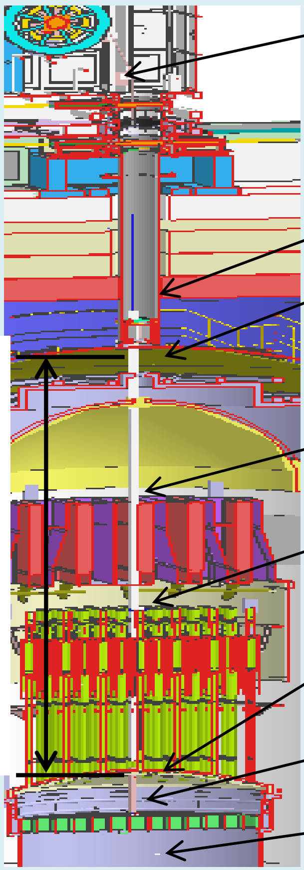


Prototyping in FY2019

Front-viewing direction

6.4.1.4 Top-opening investigation method: Investigation system - Improved prototypes of investigation equipment (Investigation equipment C) Configuration of the access equipment with the horizontal extension arm

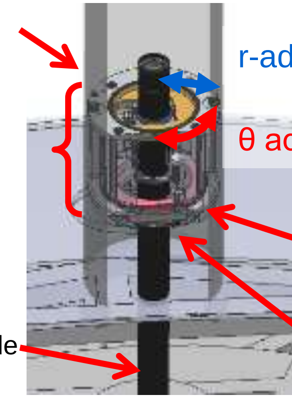
Guide the horizontal extension arm and investigation equipment C to under the shroud head by extending the telescopic guide pipe in the boundary guide pipe from the PCV head section and unfold the horizontal extension arm to send the investigation equipment to the wide area of the reactor core.



· Moving up/down and unfolding the horizontal extension arm and moving up/down investigation equipment C

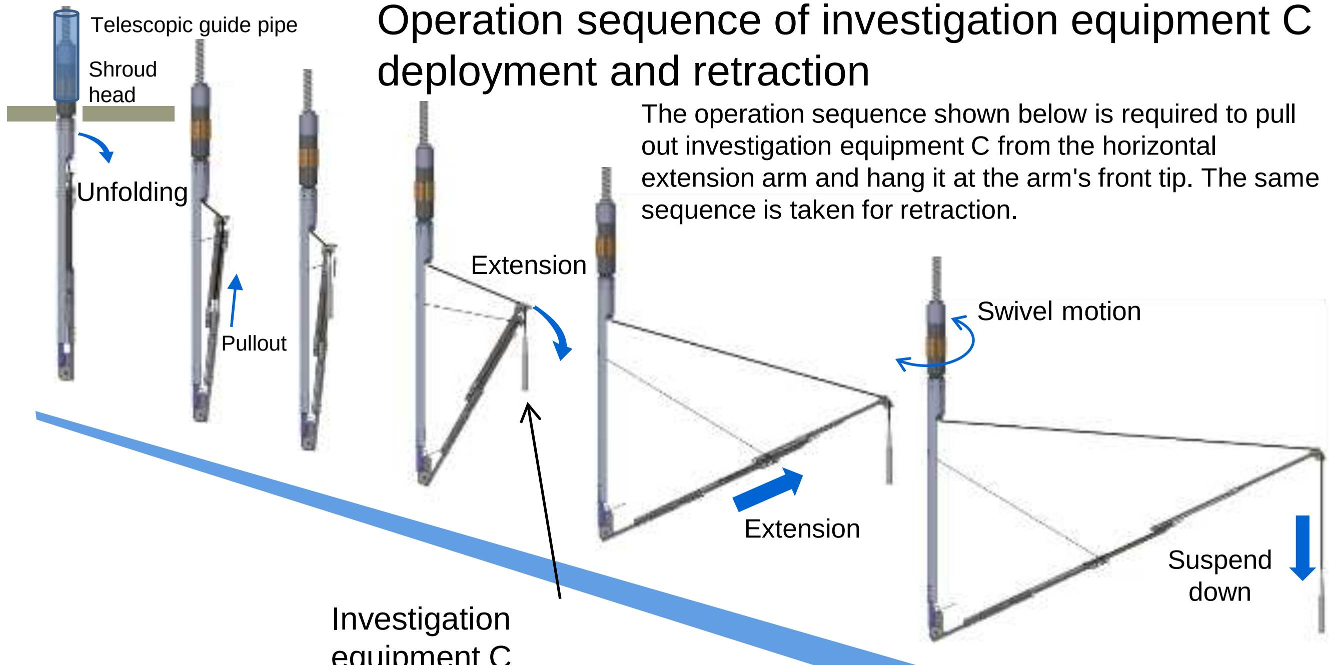
· Controlling the position of the telescopic guide pipe in the boundary guide pipe in a radial direction and axial angle

· Guiding the horizontal extension arm through the hole in the shroud head by the CFRP-made 4-draw telescopic guide pipe



Operation sequence of investigation equipment C deployment and retraction

The operation sequence shown below is required to pull out investigation equipment C from the horizontal extension arm and hang it at the arm's front tip. The same sequence is taken for retraction.



Housed in the telescopic guide pipe, unfolded after passing through the opening of the shroud head, and sending investigation equipment C to a wide area in the reactor

6.4.1.4 Top-opening investigation method: Investigation system – Improved prototypes of investigation equipment (Investigation equipment C) Horizontal extension arm

Design in FY2018

Conceptual design of the structure

- The objective is to increase the extendable length of the horizontal extension arm to expand the outreach range of investigation equipment C (1,180 mm in the FY2017 design).

➢A three-part folding mechanism was adopted for the horizontal extension arm.

⇩

Design and test manufacturing in FY2019

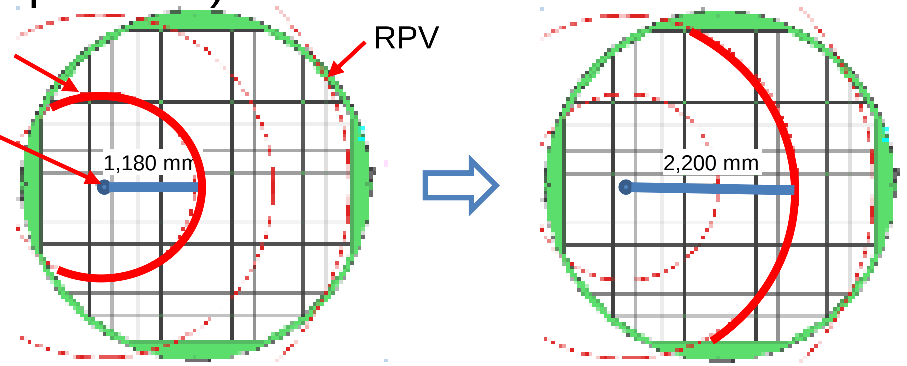
Detailed structure design and test manufacturing, including the control systems

➢The detailed design and test manufacturing of the extension arm was completed, and its extendable length was increased to 2,200 mm.

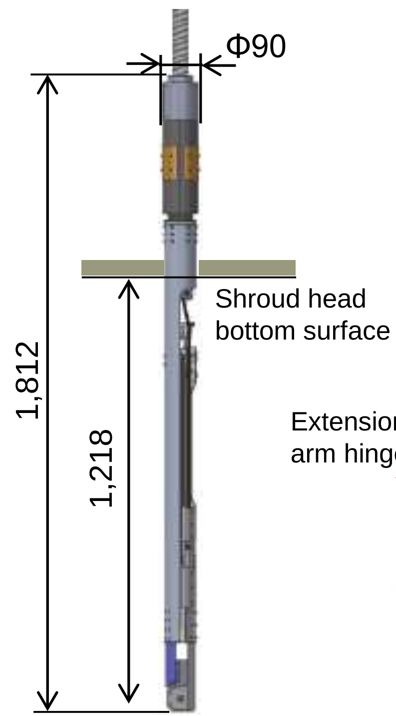
➢Stand-alone unit tests and accessibility evaluation tests were conducted.

Maximum outreach range

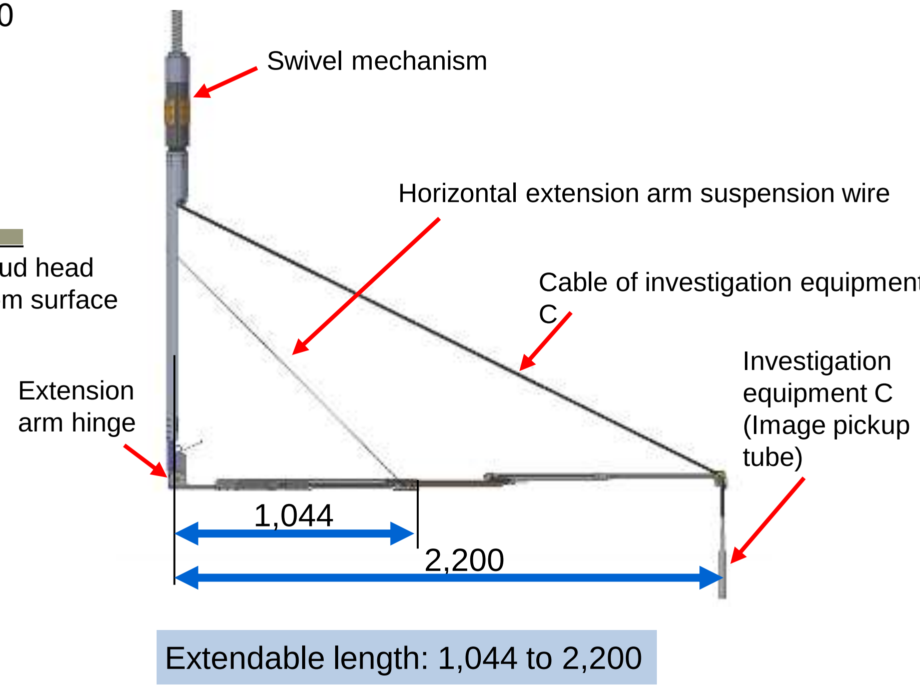
Horizontal extension arm downward position



Design in FY2017 | Design in FY2018 to 2019



Shape during descent



Extended state of the extension arm

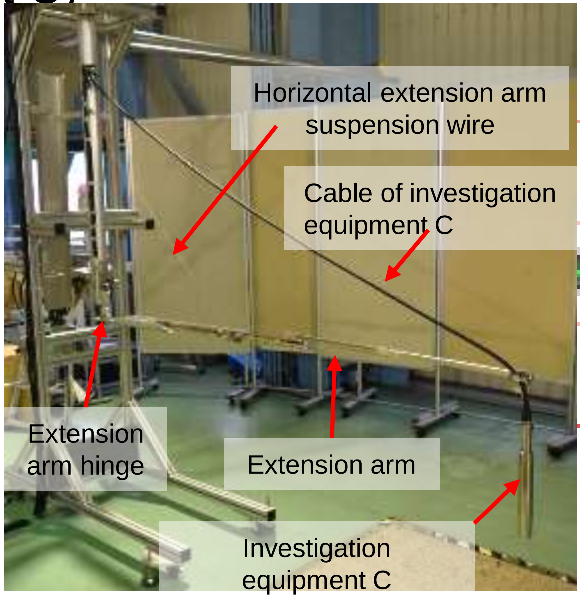
6.4.1.4 Top-opening investigation method: Investigation system – Improved prototypes of investigation equipment (Investigation equipment C) Horizontal extension arm

Unit testing for functional verification

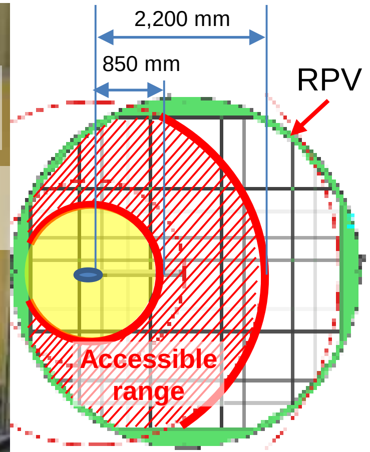
<Purposes>

To verify the following performances of the horizontal extension arm: folding/unfolding and extending/contracting operation; the ability to pull out investigation equipment C and suspend and move it up–down with a weight load equivalent to the weight of sling necessary to reach the reactor bottom; and its rigidity required to perform a stable swivel motion with the arm unfolded and extended

Test item	What to test	Test results
Folding/unfolding operation (Cables are routed manually)	· 0° to 90° folding/unfolding operation · Investigation equipment C up–down operation	The arm was confirmed to work as designed, and the operation sequence was determined.
Extension and contraction of the extendable arm (Cables are routed manually)	· Extension and contraction in the full extension range of 2,200 mm · Examination of the hinge angle range where the full extension of the arm is possible	· It was confirmed that the arm could be fully extended (2,200 mm) when the hinge angle was within 60° to 90°. · Contraction was possible regardless of the hinge angle.
±180° swivel motion by the swivel mechanism	· ±180° swivel motion	The mechanism was confirmed to work as intended. It was determined to operate at a rate of 0.3° /s to suppress shaking.
10-m-long up–down test to simulate access to the reactor bottom (with manual cable operation)	· Up–down test with a 2 kg weight to simulate the weight of a 10-m cable · Examination of the hinge angle range where the full extension of the arm is possible	· It was confirmed that up-down could be performed without problem when the hinge angle was within 55° to 90°. (850- to 2,200-mm range in the top right figure)

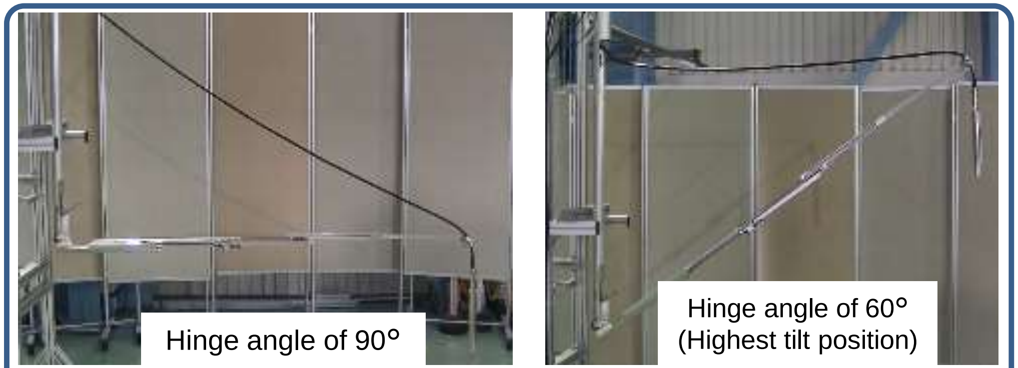


Horizontal extension arm test system

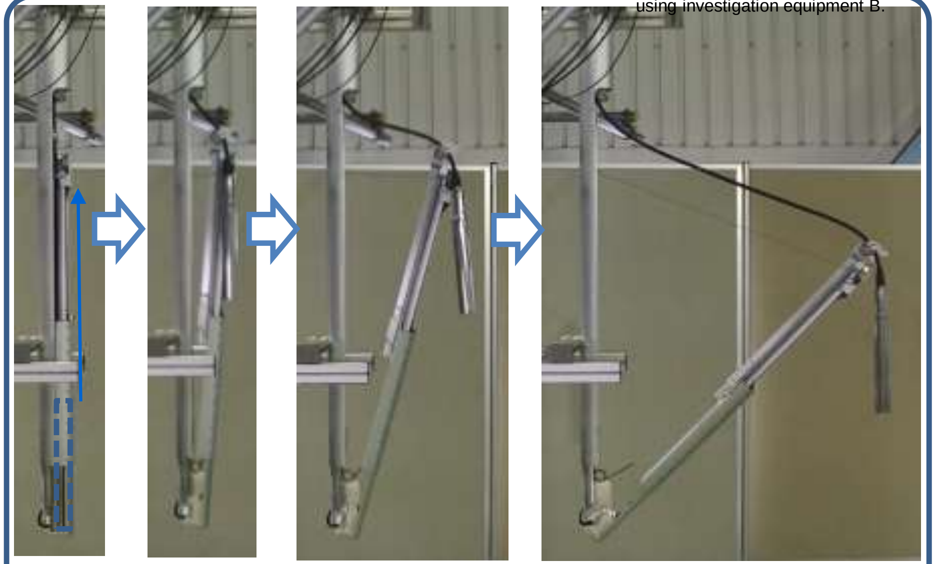


Achieved investigation equipment accessible range with the new horizontal extension arm (10-m-long suspension)

The range with a yellow fill is investigated using investigation equipment B.



Fully extended arm (to 2,200 mm) with different tilt angles



Operation sequence of the deployment of investigation equipment C

6.4.1.5 Top-opening investigation method: Element test plan (Reported)

	Test item	Purposes and reasons		Test outline
Processing apparatus	① Test to evaluate the on-site workability of PCV/RPV head small-diameter penetrating machine (Reported)	A small-diameter (φ10 mm) penetrating machine for degassing hydrogen from the upper part of S/C was tested in the element tests conducted in another project* in FY2017. The feasibility of carrying out penetrating for hydrogen degassing and penetrating for preliminary surveys (φ40 mm) together in a single work process is evaluated to streamline the construction method.		Conduct penetrating tests of simulated PCV head and RPV head with the preliminary prototype of the penetrating machine to obtain the following information: · Feasibility of penetrating a hole of φ40 mm or larger in the PCV/RPV head · Information that helps develop methods to support the reaction force and suppress vibration during penetrating and to determine their specifications
Processing apparatus	② Test to evaluate the on-site workability of the RPV insulator hole-opening and removal machine (See slide No. 45)	The feasibility of measures to address the issues found in the test in the past FY (separation and fall of insulator during processed materials collection, abrasive accumulation in the tool swivel mechanism, and tool inclination during offset operation) is evaluated. In addition, the feasibility of the insulator removal method (φ570-mm hole opening) is evaluated in response to the enlarged hole-opening diameter after access route review in FY2015.		Open a through hole in the simulated insulator and remove it with the preliminary prototype of the processing apparatus to obtain the following information: · Information that helps develop a measure for preventing cutting scraps from falling during hole opening and determine its specifications · Feasibility of the insulator removal method · Information that helps develop a measure for preventing abrasive from accumulating in the tool swivel mechanism and determine its specifications · Information that helps develop a measure against tool inclination during offset operation and determine its specifications
Processing apparatus	③ Test to evaluate the on-site workability of the reactor core internal structure processing apparatus (See slides No. 46 to 48)	(1) Hole opening in the steam separator	The validity of measures to address the issues found in the test in the past FY (vibration of the pipe sling and decrease in abrasive feed rate) and the feasibility of cutting work parameters revised to reduce the process time are evaluated.	Open a through hole in the simulated steam separator with the prototype of the processing apparatus to obtain the following information: · Vibration amplitude of the pipe sling · Abrasive feed rate · Feasibility of φ160-mm hole opening · Occurrence of cutting scraps falling into the inside of the steam separator · Process time
		(2) Hole opening in the shroud head	The feasibility and validity of measures to address the issues found in the test in the past FY (hole diameter not large enough) are evaluated.	Open a through hole in the simulated shroud head with the prototype of the processing apparatus to obtain the following information: · Interference of the surrounding structures with the tool head · Feasibility of φ110 mm or larger hole opening · Feasibility of the collection of the shroud head cutting scraps
Investigation system	④ Performance tests of the investigation equipment guiding system (See slides No. 49 to 54)	The performance of the improved investigation equipment A and B guiding system is evaluated with a focus on how the strength of the cables against bending stress is improved and how the reliability of hinges is improved. The performance of the investigation equipment C guiding system is evaluated with a focus on the extension and retraction operation of the telescopic mechanism and smooth guiding of the device through holes.		Conduct tests to guide the investigation equipment by remote control using videos through holes created in a test mockup at simulated locations and with simulated sizes along simulated interrupting factors, such as the surface condition of the inner wall, to obtain the following information: · How smoothly the investigation equipment can be guided through the holes (investigation equipment A, B, and C). · Extension and retraction operations of the telescopic mechanism (investigation equipment C)
Investigation system	⑤ Test to evaluate the video capturing performance of the investigation system (investigation system B) (See slides No. 51 to 52)	The image capturing performances of investigation equipment B2 (with a pan and tilt mechanism) and investigation equipment B3 (with a pan mechanism and tilt mirror) are evaluated with a focus on the ability to output a seamless celestial-sphere image (investigation equipment B2) and horizontal 360° -view image (investigation equipment B3) and the influence of the shaking of the device caused by the up–down motion on the image quality.		Conduct tests to move investigation equipment B2 and B3 up and down near image-capturing locations and capture images according to the planned procedures to obtain the following information: · Accuracy of celestial-sphere images (B2) and horizontal 360° -view images (B3) · Time needed to capture an image including waiting time for device shaking to diminish

*: Development of the PCV leak repair technology

6.4.1.5 Element tests for the top-opening investigation method

② Test to evaluate the on-site workability of the RPV insulator hole-opening and removal machine

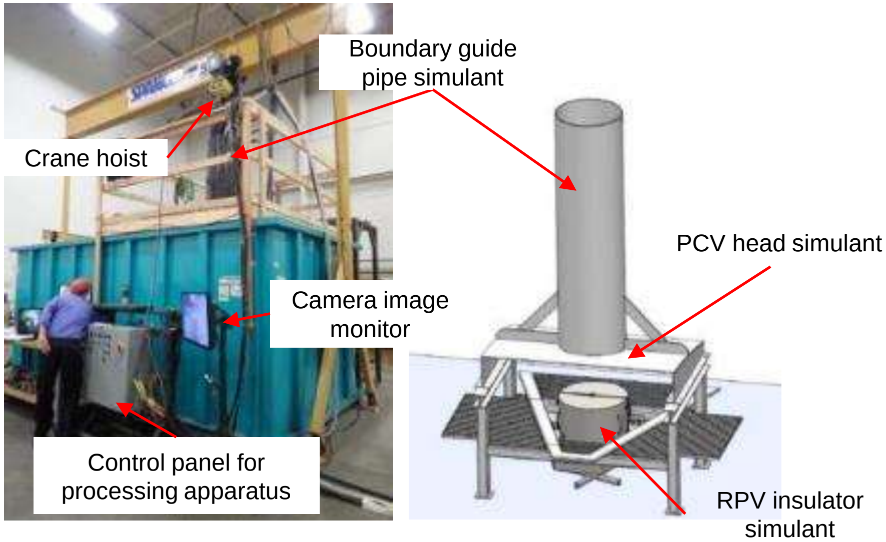
<Purposes>
Open a through hole in the simulated insulator and remove it with the preliminary prototype of the processing apparatus to obtain the following information:

- Information that helps develop a measure for preventing cutting scraps from falling during hole opening and determine its specifications
- Feasibility of the insulator fixing, fitting, cutting, and removing method
- Information that helps develop a measure for preventing abrasive from accumulating in the tool swivel mechanism and determine its specifications
- Information that helps develop a measure against tool inclination during offset operation and determine its specifications

<Test item>
Tests are conducted under the following two conditions:

- Without offset (no offset between the axis of the guide pipe and the center of the RPV spare nozzle flange)
- With an offset of 100 mm (100-mm offset between the same axis and the center)

<Test system>



<Cutting the fixing bracket>

<RPV insulator removal>

<Test results and things to be considered in detail in the design>

- The fixing bracket was able to be cut and grabbed for removal regardless of whether the 100-mm offset is used.
- The remote operability of the thermal insulation penetrating and processing apparatus needs to be further improved by downsizing, adding more cameras, etc., as this work needs to be performed in a very narrow space by remote control.
- There were two ideas to leave the pieces of the cut and removed thermal insulation near its original location: keep them in a side-lying position or in a standing position. The two positions were tested and were found to be feasible. Which position to take will be determined based on the burden of workers that will be known through the skill training of the workers for the remote operation.

6.4.1.5 Element tests for the top-opening investigation method

③ Results of the element tests to evaluate the on-site workability of the reactor core internal structure processing apparatus: (1) steam separator hole opening ①

<Purposes>

Testing the validity of the measures to address the issues found in the test in the past FY (vibration of the pipe sling and abrasive feed rate decrease) and the feasibility of cutting work parameters revised to reduce the process time

<Evaluation items>

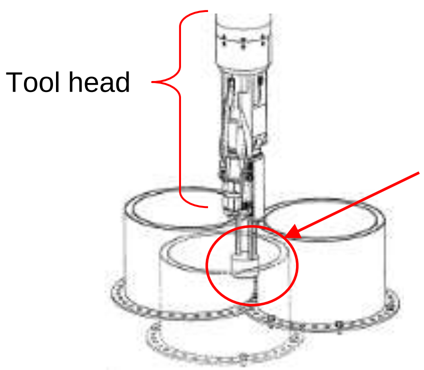
Open through holes in three types of simulants (flat-plate, steam separator upper part, and steam separator lower part) with the prototype of the the reactor core internal structure processing apparatus to obtain the following information:

- Vibration amplitude of the pipe sling due to AWJ injection
- Abrasive feed rate
- Feasibility of φ160-mm hole opening
- Occurrence of cutting scraps falling into the inside of the steam separator
- Process time

<Test results>: Flat-plate test piece cutting test

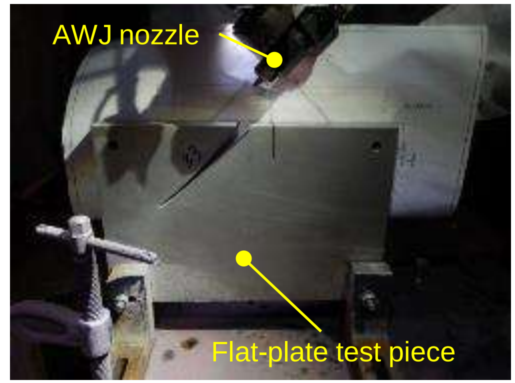
The maximum vibration amplitude of the tool head due to the reaction force of the injection was determined to be about 60 mm and was found to exceed the criteria in the test of cutting the flat-plate test piece placed at about the same height as the steam separator by AWJ.

⇒ As a measure for it, an injection reaction force receiving jig was added at the tip of the tool head.

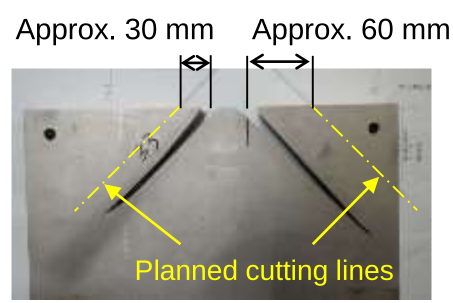


The injection reaction force receiving jig is inserted in the gap formed in the center of the three cylinders of the steam separator, so that the axis of the tool head is aligned with the center of the three cylinders, and the outer surface of the steam separator cylinder supports the reaction force *via* the receiver.

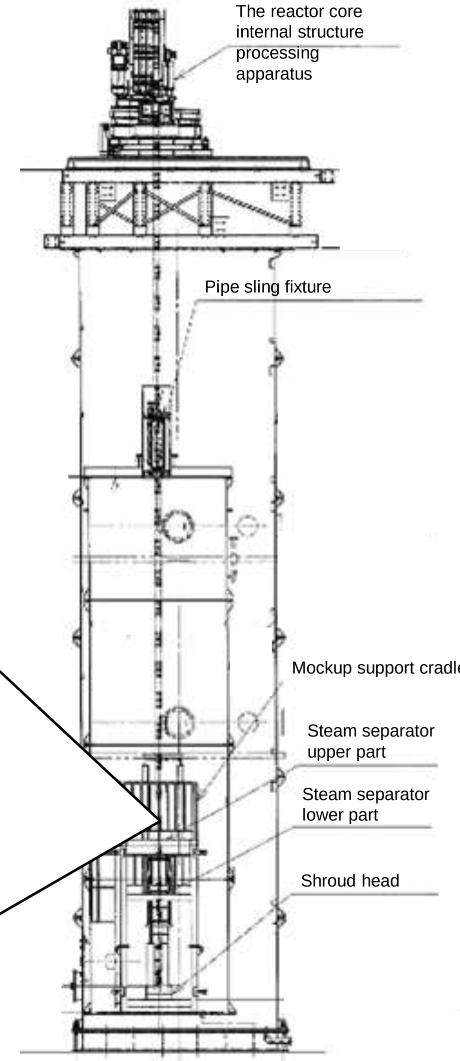
Injection reaction force receiving jig



Cutting the flat-plate test piece



Result of the flat-plate test piece cutting test



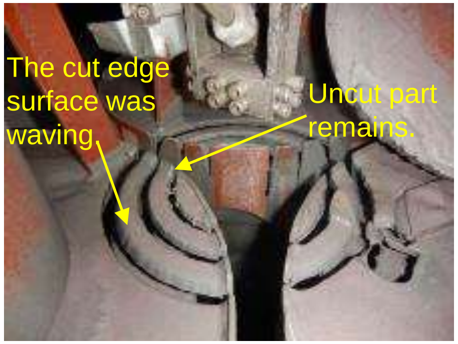
Test system

6.4.1.5 Element tests for the top-opening investigation method

③ Results of the element tests to evaluate the on-site workability of the reactor core internal structure processing apparatus: (1) steam separator hole opening ②

<Test results>: Results of steam separator upper and lower part simulants cutting tests

Evaluation items	Results
Vibration amplitude of the pipe sling due to AWJ injection	Cutting work was done as planned without leaving any uncut part, and the cut edge surface exhibited a roughly uniform condition. Based on this result, it was confirmed that the vibration of the tool head was suppressed enough to create a hole in the steam separator with sufficient quality.
Abrasive feed rate	Cutting work was done as planned without leaving any uncut part, and the cut edge exhibited a smooth and uniform surface. Based on this result, it was confirmed that the abrasive feed rate was kept constant enough to create a hole in the steam separator with sufficient quality. (Abrasive feed rate in the test: 589 to 703 g/min)
Feasibility of φ160-mm hole opening	It was confirmed that a hole with a diameter of ≥φ160 mm was created by inserting a cylinder with an outer diameter of 160 mm through the opened hole.
Occurrence of cutting scraps falling into the inside of the steam separator	Although cutting scraps were found to fall into the inside of the steam separator, the size of all the pieces was less than 16 kg, which is considered to pose a moderate risk of a criticality event due to fuel debris even if they reach the reactor core.
Process time	Based on this test result, the total hours necessary to open a hole in the steam separator (AWJ injection time) was estimated to be about 228 h, which is 70% less than that estimated from the FY2017 test result (702 h). The total required abrasive was estimated to be about 9 t, which is about 60% less than that obtained from the FY2017 test result (about 21 t). The amount can be further reduced by optimizing the parameters.



The cut edge surface tested in FY2017 (example)

The Cut edge surface tested in FY2019 (example)

Measurement of the hole diameter

Falling cutting scraps found inside the steam separator (example)

6.4.1.5 Element tests for the top-opening investigation method

③ Results of the element tests to evaluate the on-site workability of the reactor core internal structure processing apparatus: (2) Shroud head hole opening

<Purposes>

The feasibility and validity of the measures to address the issues found in the test in the past FY (hole diameter not large enough) is evaluated.

<Evaluation items>

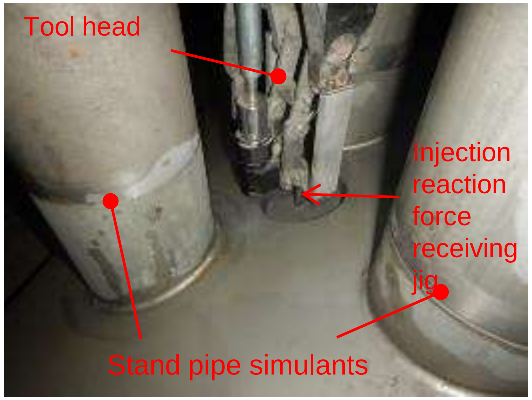
Open a through hole in the shroud head simulant with the prototype of the the reactor core internal structure processing apparatus to obtain the following information:

- Interference of the surrounding structures with the tool head
- Feasibility of φ110-mm or larger hole opening in the shroud head
- Feasibility of the collection of the shroud head cutting scraps

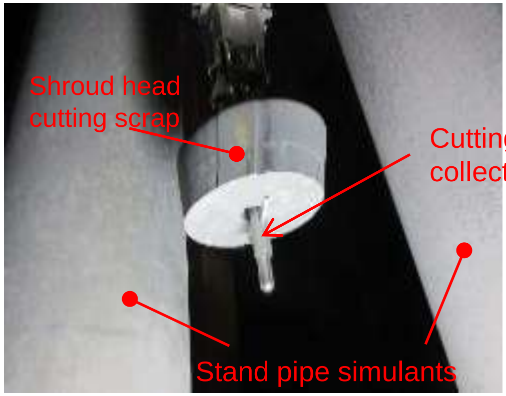
<Test results>

- An injection reaction force receiving jig with a different shape from the one used for the steam separator was attached to the tip of the tool head and then tested. No interference of the surrounding structures (stand pipe) with the tool head was observed.
- Since the hole opened in the shroud head mockup was not as large as φ110 mm, the cutting parameters were changed, and cutting was retried. As a result, opening a φ110-mm or larger hole was confirmed to be possible.
- The feasibility of collecting the shroud head cutting scraps was also confirmed.
- It was decided to add the injection reaction force receiving jig to the tool head and reflect the changed cutting parameters to the tool head design.

Injection reaction force receiving jig for the shroud head cutting



Appearance of the shroud head after cutting



Shroud head cutting scrap

Shroud head hole diameter measurement

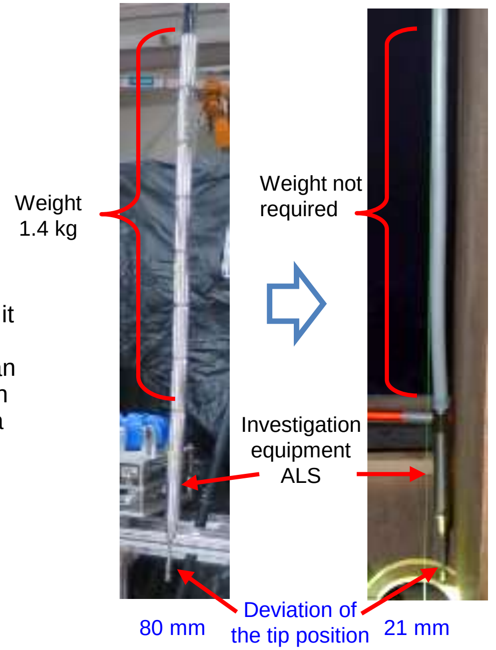
6.4.1.5 Element tests for the top-opening investigation method

④ Maneuverability evaluation test of the investigation equipment (investigation equipment ALS)

<Purposes>
The maneuverability of the investigation equipment is evaluated after adopting a new cable with an improved flexibility (through the use of a flexible sheath tube and its jacket as well as a flexible industrial endoscope cable) for the purpose of improving maneuverability. Evaluation tests are conducted in combination with the use of the prototype of the cable drum.

<Test results>

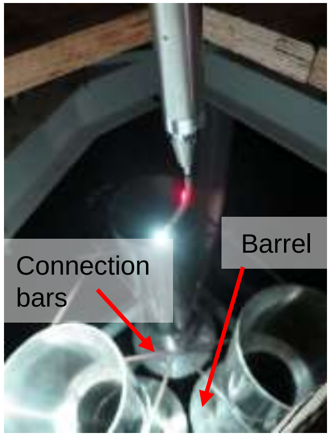
- It was confirmed that the investigation equipment was accurately located right above the target small hole (φ40 mm) and guided through it without getting stuck by remote control. Especially, the ability to pass through a long hole (in the well cover) was improved.
- The shaking motion of the investigation equipment during position adjustment (at a horizontal travel speed of 1mm/s) increased more than before the improvement due to the adoption of a flexible cable. Despite this adverse effect, the horizontal travel speed of the investigation equipment guiding system was concluded to be adequate since all the device guiding tests through different holes were successful and a further decrease in the speed would make it difficult to determine a traveling direction from the change of the captured videos.
- The investigation equipment was also able to pass through the hole without problems during the retraction operation even if the guiding system was operated to intentionally cause the investigation equipment to get stuck at the hole.



Before improvement (Weight did not help improve the maneuverability due to a larger deviation)

After improvement

Investigation step	What to test	Test results
Preliminary survey of the area under the well cover (PCV head)	Ability to guide the investigation equipment to the center of the through hole with the smallest diameter (φ40 m) and the longest length (618 mm) and through the hole	Although the investigation equipment got caught at the edge of the hole when inserted into the hole, the position was adjusted with the assistance of the videos it captured. The investigation equipment had often hit the inner wall of the hole and got stuck in it due to the insufficient flexibility of the sheath tube. After improvement, it was confirmed that it could smoothly pass through the hole. The round-trip travel time is about 15 min.
Preliminary survey of the area under the steam dryer bottom plate (above the steam separator)	Ability to guide the investigation equipment to the center of the φ40-m through hole located at the lowest position and through the hole	It was confirmed that the investigation equipment was moved down about 18 m, located at the right above the hole, guided through the hole. It did not get stuck in the hole at all. The round-trip travel time is about 25 min.
Investigation of the area between the outside of the steam separator and the shroud head	Ability to guide the investigation equipment to a narrow area surrounded by the barrels of the steam separator and connection bars and through the area	It was confirmed that the investigation equipment was guided to the shroud head through the outside of the steam separator after its position was adjusted to be above the steam dryer, right above the bottom plate, and right above the connection bars of the steam separator. The round-trip travel time is about 45 min.



Investigation of the area under the steam dryer bottom plate (above the steam separator)

Investigation equipment passing through the area under the steam separator barrel

6.4.1.5 Element tests for the top-opening investigation method

④ Maneuverability evaluation test of the investigation equipment (investigation equipment ALB/AHB: intermediate flexible link mechanism)

<Purposes>

The maneuverability of the improved investigation equipment ALB/AHB is evaluated.

Investigation equipment ALB: The flexibility of the industrial endoscope cable was increased. The weight at the tip was downsized by the material change

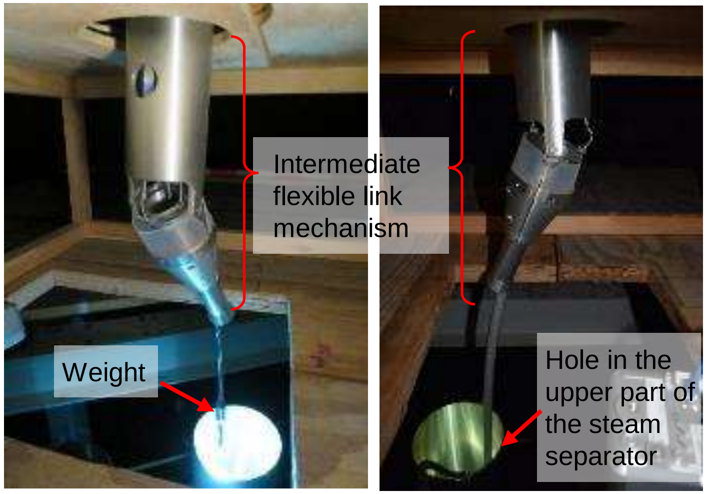
Investigation equipment AHB: The weight is increased by changing the material of the housing to gain more thrust by gravity force.

<Test results>

- It was confirmed that both investigation equipment ALB and AHB were guided toward the shroud head through any one of the three steam separator cylinders located near the hole opened in the steam dryer bottom plate. It was also confirmed that they could be guided through the narrow swirler section without getting stuck.

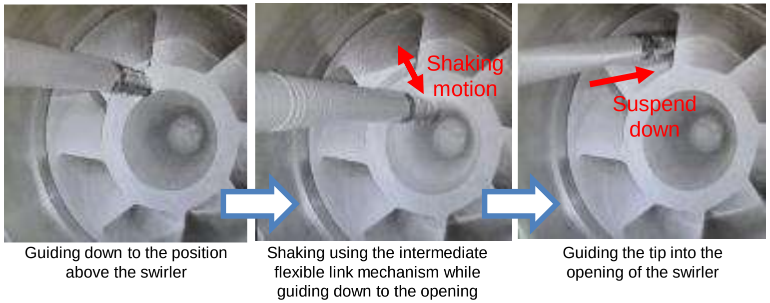
Investigation step	What to test	Test results
Approach to the hole in the upper part of the steam separator	Guiding the investigation equipment through the hole in the upper part of the steam separator using the operation of the intermediate flexible link mechanism	**Investigation equipment ALB:** It was confirmed that the investigation equipment was guided through the target hole by pointing it toward the target hole using the flexible link mechanism and moving it close to the hole using the XY positioning mechanism. **Investigation equipment AHB:** It was confirmed that the investigation equipment was guided through the target hole by pointing it toward the target hole using the flexible link mechanism without the help of the XY positioning mechanism. The round-trip travel time from the tool box is about 15 min for both ALB and AHB.
Maneuvering through the inside of the steam separator (internal gap and swirler)	Maneuvering through the gap and swirler in the steam separator using the intermediate flexible link mechanism and cable drum	**Investigation equipment ALB:** The tip of the investigation equipment was inserted into the opening of the swirler without getting stuck after maneuvering around a gap, taking advantage of the front-end bending motion of the industrial endoscope. **Investigation equipment AHB:** Although this device does not have a front-end bending mechanism, the tip of the investigation equipment was inserted into the opening of the swirler without getting stuck by shaking it using the intermediate flexible link mechanism while guiding it.
From the investigation of the area under the shroud head (reactor core) to withdrawal	Guiding to the reactor core and withdrawal from there by the cable drum	**Investigation equipment ALB:** It was confirmed that the investigation equipment was deployed and withdrawn without getting stuck. The round-trip travel time from the top of the steam separator to the reactor bottom is about 50 to 55 min. **Investigation equipment AHB:** The same as above The round-trip travel time along the abovementioned route is about 50 min. * When the investigation equipment was suspended outside the simulation scope of the upper grid plate and core support plate, tests were conducted within a reachable range.

* Camera video: Separately provided cameras were used to capture the overall view of the device position control as investigation equipment ALB only outputs the videos of industrial endoscope, and the fiber scope of investigation equipment AHB is a structural dummy.



Investigation equipment ALB   Investigation equipment AHB

Investigation equipment being guided to the hole in the upper part of the steam separator



Investigation equipment (AHB) being guided into the hole of the swirler of the steam separator

* Investigation equipment ALB can be guided into the hole of the swirler without the shaking motion by the front-end bending mechanism.

6.4.1.5 Element tests for the top-opening investigation method

④ Performance tests of the investigation equipment guiding system (investigation equipment B2/B3)

⑤ Test to evaluate the video capturing performance of the investigation system (investigation equipment B2/B3)

<Purposes>

The maneuverability of the investigation equipment guiding system is evaluated using the prototypes of the investigation equipment and the cable drum in combination. In addition, the tests to create celestial-sphere images (B2) and horizontal 360°-view image (B3) are conducted to evaluate the influence of the shaking of the device on the image quality and time needed to capture images, including the waiting time for the device shaking to stop.

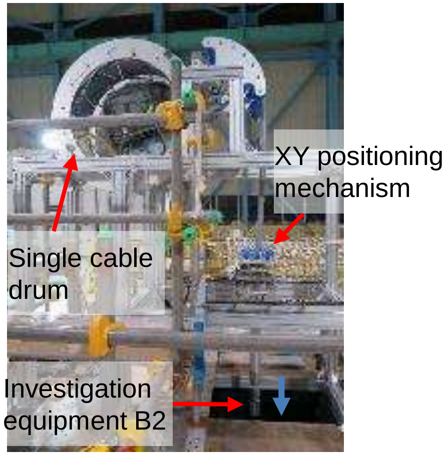
<Test results>

- It was confirmed that the investigation equipment were guided through each hole by the control of the guiding system assisted by videos captured by themselves. It was confirmed that the investigation equipment was released from the get-stuck condition in the hole by operating the guiding system using the videos captured by itself, which provide information on the occurrence of the get-stuck event and what part of the device had been caught from the inclination of videos.
- It was confirmed that none of the up–down movements, XY positioning, and pan/tilt operations of the guiding system caused shaking of the investigation equipment, which adversely affected the guidance of the devices to the holes or the creation of composite panoramic images.

Investigation step	What to test	Test results
Detailed investigation of the area under the RPV head	Celestial-sphere image and horizontal 360° -view image capturing performance, including the influence of the device shaking	B2: The round-trip travel time from the tool box is about 25 min. Celestial-sphere image capturing: about 140 min B3: The round-trip travel time from the tool box is about 20 min. Horizontal 360° -view image capturing: about 60 min
Reactor core section (under the upper grid plate) Detailed investigation	Celestial-sphere image and horizontal 360° -view image capturing performance, including the influence of the device shaking under the upper grid plate	B2: Celestial-sphere image capturing: about 150 min B3: Horizontal 360° -view image capturing: about 60 min
Detailed investigation of the area under the core support plate	Celestial-sphere image and horizontal 360° -view image capturing performance, including the influence of the device shaking above the core support plate	B2: The round-trip travel time from the tool box is about 65 min. Celestial-sphere image capturing: about 130 min B3: The round-trip travel time from the tool box is about 50 min. Horizontal 360° -view image capturing: about 60 min

· The slight shaking motion of investigation equipment B2 caused by its pan/tilt operation lasted less than 1 min and was considered to be negligible for the creation of composite panoramic images.
· No shaking motion was caused on investigation equipment B3 by its pan and mirror tilt operation.

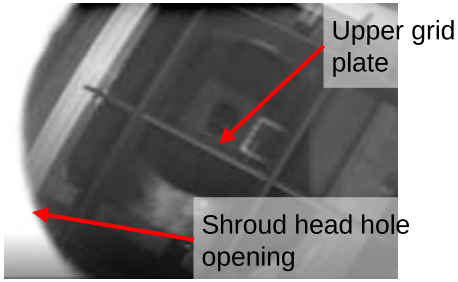
<Number of captured images>
Celestial-sphere image: 276 images, horizontal 360°-view image: 126 images (for the height range of 1.25 m)



Access device

Investigation equipment passing through the hole in the steam dryer bottom plate (Investigation equipment B3)

Investigation equipment B2 with its pan/tilt mechanism activated and stretchable light arms fully extended after passing through the hole in the shroud head

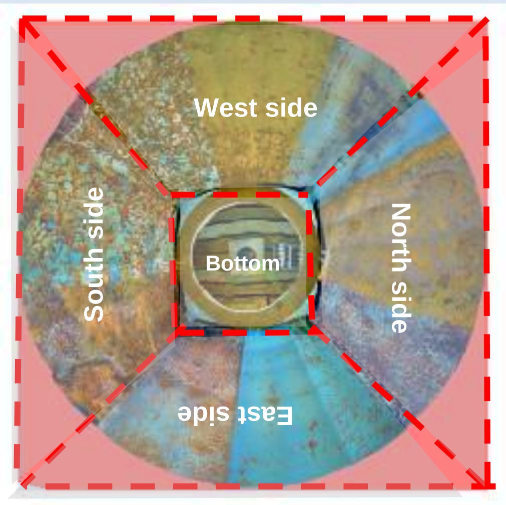


Video captured by investigation equipment B3 while it was passing through the hole in the shroud head

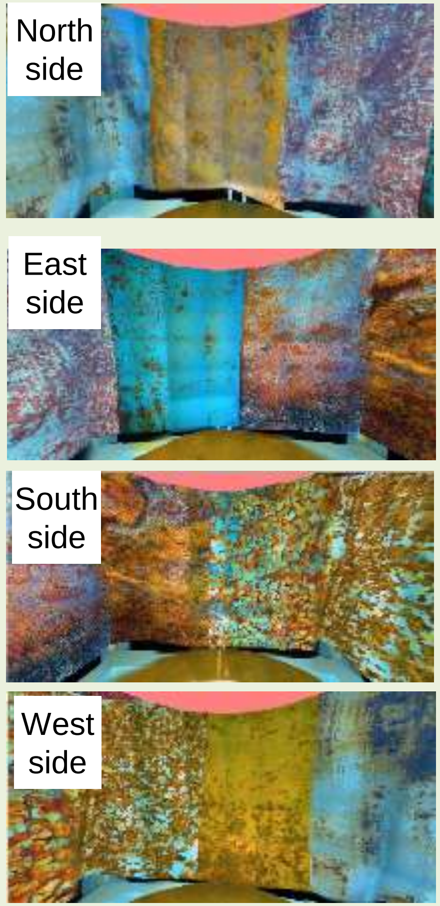
6.4.1.5 Element tests for the top-opening investigation method

④ Performance tests of the investigation equipment guiding system (investigation equipment B2/B3)

⑤ Test to evaluate the video capturing performance of the investigation system (investigation equipment B2/B3)

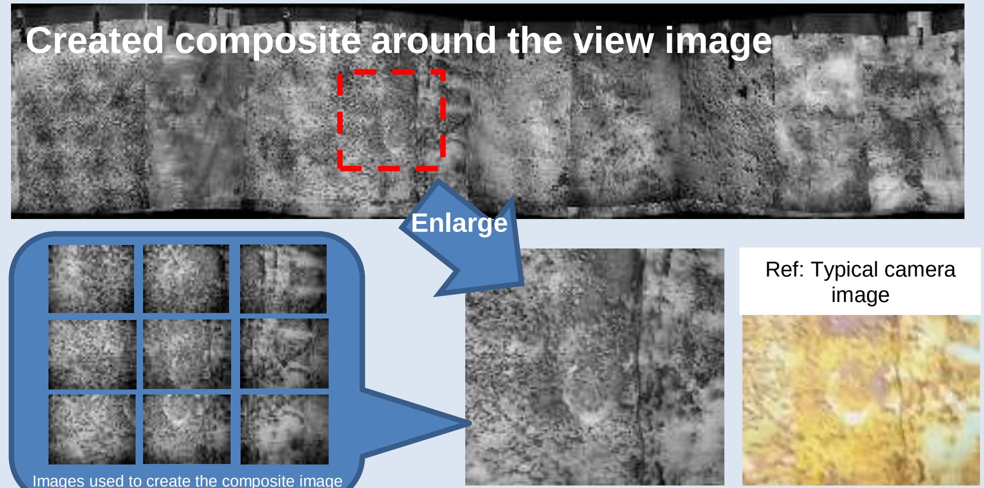


Created composite celestial-sphere image



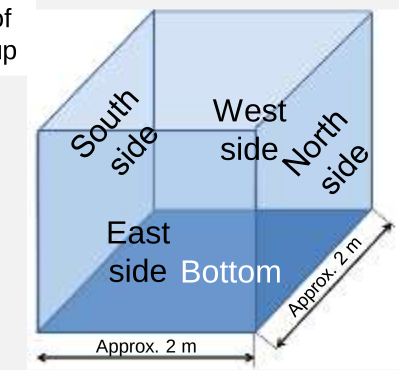
Enlarged composite celestial-sphere images

Created composite celestial-sphere images (investigation equipment B2): Under the upper grid plate



Created composite around the view image (investigation equipment B3): Under the upper grid plate

Investigation equipment B2 test



Viewed from the center of the mockup The mockup was covered by blackout curtains, and cloth with rust-simulating pattern printing was put on the inner walls.

Test environment

It was confirmed that no shaking motion occurred in the investigation equipment, and seamless composite panoramic images were obtained even if the pan/tilt mechanism of the investigation equipment was in operation.

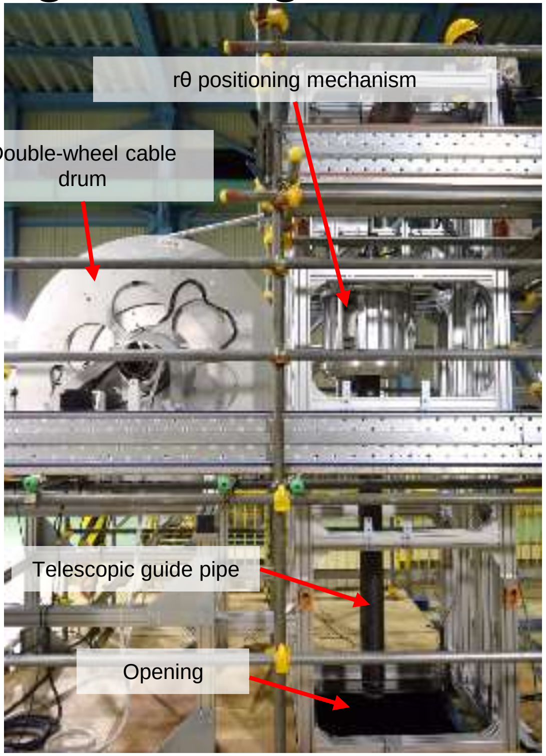
6.4.1.5 Element tests for the top-opening investigation method

④ Performance tests of the investigation equipment guiding system (investigation equipment C)

1. Telescopic guide pipe extension and retraction tests

<Purposes>
The ability of the guiding system to guide investigation equipment C through the holes in the reactor core internal structures to the top of the upper grid plate by relying on videos captured by investigation equipment C and information shown in the operation panel about the axial positions of all involved devices is tested. Tests were conducted, starting from the condition where the rθ positioning mechanism was seated.
<Test results>

Test item	What to test	Test results
Ability to guide investigation equipment to the reactor core internal structures	① Going through φ200 opening in the steam dryer bottom plate ② Going through φ140 opening in the barrel of the steam separator ③ Going through φ110 opening in the shroud heads (iv) Reaching the top of the upper grid plate ⑤ Telescopic guide pipe positioning	· It was confirmed that the guiding system was capable of guiding the investigation equipment through all the holes and locating it at target positions. · It was confirmed that the telescopic guide pipe position adjusting mechanism could be operated accurately using the information on the positional relationship between the guide pipe and the hole shown in the videos. · The process time from the start of the telescopic guide pipe positioning to the arrival of its front end at the top of the upper grid plate was about 30 min.
Test to detect and recover from a get-stuck condition	Is it possible to detect the occurrence of the getting-stuck event of the telescopic guide pipe and recover the telescopic guide pipe by relying on videos captured by investigation equipment C?	· It was confirmed that detection of the event was possible using the videos, regardless of when it occurred (i.e., during the extension or retraction), as investigation equipment C travels inside the telescopic guide pipe. (The inner wall of the telescopic guide pipe needs to be in the viewing field.) · It was confirmed that a get-stuck event was not likely to occur during the extension because the play of the telescopic mechanism provided flexibility to its movement. · It was found that the shape of the fitting at the tip of the telescopic guide pipe needed to be changed as it could get stuck during the extraction. It took time to recover from the condition due to the lack of information on the location of the contact point between the fitting and the structure.



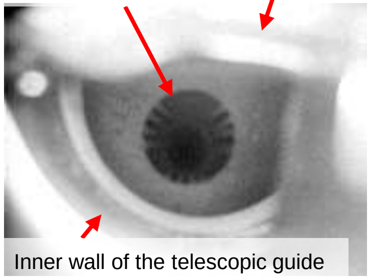
Test system for the investigation equipment C guiding system

Seating position

Half-unfolded horizontal extension arm

Opening in the upper part of the steam separator barrel

Horizontal extension arm bottom end



Video captured by investigation equipment C


Passing through the hole in the steam separator barrel

Fitting at the tip of the telescopic guide pipe (for hooking and pulling up upper pipes)


Hitching position

6.4.1.5 Element tests for the top-opening investigation method

④ Performance tests of the investigation equipment guiding system (investigation equipment C)

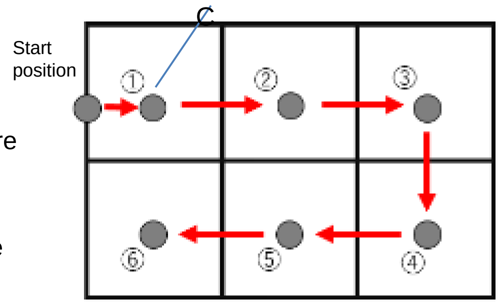
2. Horizontal extension arm unfolding/extending and investigation equipment C suspention test

<Purposes>
The ability of the guiding system to control swivel, unfolding, and extending motions and guide investigation equipment C to the target cell of the upper grid plate is tested. In addition, the ability of the guiding system to release investigation equipment C from a get-stuck condition at the upper grid plate by solely relying on videos captured by the device itself is tested. Note that these tests are conducted using only the horizontal extension arm from the dimensional constraints of the simulated structural environment.

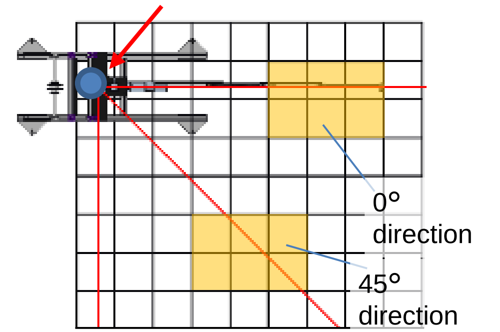
<Test outline>

➢Test to evaluate accessibility to the upper grid plate
Place investigation equipment C on the upper grid plate simulant at the start position in the figure; then, lift it, move to position ①, and down it there. Repeat these steps along the arrows presented in the figure until the position is reached ⑥. Two upper grid plate simulants were placed along the 0° line (for horizontal extension/retraction operation) and 45° line (for combination operation of extension/retraction and swivel) as presented in Figure (b). The test was conducted in darkness to simulate the site environment, and the guiding system was operated using only videos from investigation equipment C.

➢Recovery test from the get-stuck condition at the upper grid plate
Cause investigation equipment C to get stuck at the upper grid plate intentionally during the retraction operation and test the ability of the guiding system to locate the contact point and release the device from that condition by relying on videos captured by the device.



(a) Investigation equipment C descent procedures

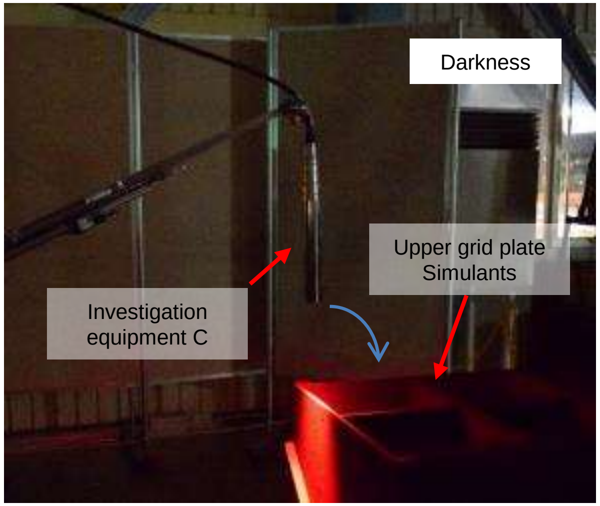


(b) Layout of upper grid plate simulants

<Test results>

Test item	What to test	Test results
Test to evaluate accessibility to the upper grid plate (Cables are routed manually)	Is it possible to guide investigation equipment C to each target cell by relying only on videos captured by itself?	It was confirmed to be possible to guide it to each target cell. The upper and side surfaces of the grid plate could be used as navigation information. The process time to move from a cell to the one next to it is about 5 to 6 min.
Upper grid plate Get-stuck condition recovery test (Cables are routed manually)	Is it possible to detect and recover from a get-stuck condition by relying only on videos captured by investigation equipment C?	It was found that the occurrence of the get-stuck event with investigation equipment C could be detected by the captured videos, but it could not be released from that condition, as the get-stuck event did not change the position of the device, so that information on the location of the contact point between the device and the grid was not available. It was decided to prepare a support tool that displays the location of the investigation equipment based on the axial positions of all the involved devices for the guiding system used for the investigational works at the site. It was found that the connector of the investigation equipment caused a get-stuck event. It was confirmed that changing the connector design to a tapered shape could prevent it.

Shape improvement of investigation equipment C



Guiding system performance test

6.4.1.6 Top-opening investigation method: Specifications of equipment - Parameters for water volume to be used in abrasive and cutting works (rough estimate)

Structures to be cut		Required hole specifications	Construction method	Process time (min)	Water consumption (L)	Amount of abrasive (Kg)
Well cover	1st and 2nd layer penetrating	φ950 mm	Core boring	900	30,000	—
	3rd layer penetrating	φ750mm	WJ/AWJ	420	10,000	500
PCV head	Surface treatment	—	WJ	120	600	—
	Small-hole penetrating	φ40 mm	Drill	15	—	—
	Large-hole penetrating	φ550 mm	AWJ	160	700	130
RPV insulator	Cutting the fixing bracket	—	AWJ	60	300	50
	Remove	φ570 mm	Grabbing and transferring	60	—	—
RPV head	Spare nozzle cleaning	—	WJ	180	700	—
	Small-hole penetrating	φ40 mm	Drill	30	—	—
	Hole opening in flange	φ385 mm	AWJ	90	400	80
	Nozzle removal		AWJ	40	200	40
	Base structure removal		AWJ	240	1,000	190
Steam dryer	Bottom plate, small hole	φ40 mm	AWJ	5	19	3
	Bottom plate, large hole	φ184 mm	AWJ	30	111	15
Steam separator	Connection bars	φ190 mm	AWJ	120	444	60
	Main body	φ162 mm (78 tubes)	AWJ	42,120	156,000	21,060
Shroud head	Cutting scrap collection hole	φ12 mm	AWJ	10	37	5
	Investigation equipment guiding hole	φ120 mm	AWJ	40	148	20
Total				**44,640**	**200,659**	**22,153**
				Approx. 745 h **Approx. 31 days**	**Approx. 201 t**	**Approx. 22 t**

6.4.1.6 Top-opening investigation method: Specifications of equipment – Equipment and device list (1/2)

No.	Equipment/device name	Outlines
1*	Entire work cell	A temporary facility to prevent contaminated materials from spreading to the surrounding environment, to protect workers from radiation exposure, and to provide devices with a safe environment by maintaining negative pressure if by any chance the PCV boundary fails to function
2	Tool box transfer carrier	Equipment to transfer the tool box to the position of holes *via* remote control
3	Connection mechanism	Mechanism to connect the tool box with the boundary guide pipe *via* remote control
4	Gate valve on the boundary guide pipe side	A valve to isolate the boundary guide pipe that is connected to the PCV
5*	Boundary guide pipe	Equipment for maintaining the boundaries after a hole is opened in PCV head
6	Boundary guide pipe installation equipment	Equipment to install the boundary guide pipe
7	Movable shielding	Movable shielding used to shield a hole for which the tool box is not installed
8	Crane-equipped carrier	Crane-equipped carrier used for the maintenance of the gate valve on the boundary guide pipe side
9	Water injection equipment for the inner wall of the boundary guide pipe	Equipment to inject water to the inner wall of the boundary guide pipe
10	Tool box 1	Container to house the investigation equipment, access devices, and the reactor core internal structure processing apparatus
11	Tool box 2	Container to house the processing apparatus used until reaching the RPV head, etc.
12	Tool box 3	Container to house the processing apparatus used until reaching the RPV head
13	Well cover core boring machine	A machine to bore holes in the 1st and 2nd layers of the well cover
14	Well cover AWJ chipping machine	A machine to bore small holes in the well cover, remove its 3rd layer, and serve as a backup in case of the deformation of the 1st and 2nd layers
15	PCV head surface treatment system (WJ)	Equipment to process a specific part of the surface of the PCV head where the guide pipe is installed and its periphery, specifically removing the coating and foreign materials there, to prevent adverse effects of the surface condition on the sealing of the gap between the PCV head and the guide pipe
16	PCV head surface treatment system (brush)	Equipment to remove coating and foreign materials that remain on the surface of the PCV head after treatment by the PCV head surface treatment system (WJ)
17	PCV head surface measuring equipment	3D laser scanner to measure the shape of a specific part of the PCV head surface where the guide pipe is installed and its periphery
18	PCV head small-hole penetrating machine	A penetrating machine to open small holes in the PCV head to eliminate the risk of adverse effect of the accumulated hydrogen in the PCV head prior to large-hole opening work
19*	PCV head hole opening machine	Machine to open holes in the PCV head
20	Processing apparatus for fixing bracket on RPV insulator	Machine to cut RPV insulator fixing fittings
21	RPV insulator removal equipment	Equipment to remove a part of the insulator which does not affect the removal of RPV spare nozzle
22	RPV spare nozzle cleaning equipment	Equipment to remove the pieces of the insulator and other metal pieces left in the area where the RPV spare nozzle removing work is carried out
23	RPV spare nozzle surface measuring equipment	3D laser scanner to measure the shape of the area around the RPV spare nozzle
24	Small-hole penetrating machine for RPV spare nozzle flange	A penetrating machine to open small holes in the RPV spare nozzle flange to eliminate the risk of adverse effect of the accumulated hydrogen in the RPV spare nozzle prior to large-hole opening work
25	Hole opening machine for the RPV spare nozzle flange	A machine to open a hole in the RPV spare nozzle blind flange
26	AWJ machine to cut the RPV spare nozzle from the inside	An AWJ machine to cut the RPV spare nozzle from the inside and remove its upper part by inserting its head into the nozzle
27	AWJ machine to cut the RPV spare nozzle from the outside	An AWJ machine to cut the joint between the RPV spare nozzle and the RPV head from the outside and remove its lower upper part
28*	The reactor core internal structure processing apparatus	Machine to open a hole in the steam dryer, steam separator, and shroud head
29	Fixture for the the reactor core internal structure processing apparatus	Equipment to fix the pipe sling for the the reactor core internal structure processing apparatus

No.	Equipment/device name	Outlines
30	Investigation equipment ALS	An investigation machine sent to the reactor through small holes (φ40mm) opened in the the reactor core internal structures to perform preliminary surveys, such as investigation of the condition of the structures and environment (air dose rate and temperature) and examination of the feasibility of planned works to proceed with investigation activities
31	Investigation equipment AHS	An investigation machine sent to the reactor through small holes (φ40mm) opened in the the reactor core internal structures to perform preliminary surveys, such as investigation of the condition of the structures and environment (air dose rate and temperature) and examination of the feasibility of planned works to proceed with investigation activities
32	Investigation equipment ALS and AHS guiding system	A mechanical system to guide investigation equipment ALS and AHS from the tool box down to the shroud head
33	Investigation equipment ALB	An investigation equipment for the reactor core section deployed only in case an access route through the inside of the steam separator is established
34	Investigation equipment AHB	An investigation equipment for the reactor core section deployed only in case an access route through the inside of the steam separator is established
35	Investigation equipment ALB and AHB guiding system	A mechanical system to guide investigation equipment ALB and AHB into the steam separator
36	Investigation equipment B1	A device that is sent to the reactor through large-diameter holes (≥ φ110 mm) opened in the the reactor core internal structures and used to investigate the condition of the structures and fuel debris as well as the environmental conditions (air dose rate and temperature) in the reactor in detail
37*	Investigation equipment B2	A device that is sent to the reactor through large-diameter holes (≥ φ110 mm) opened in the the reactor core internal structures and used to investigate the condition of the structures and fuel debris as well as the environmental conditions (air dose rate and temperature) in the reactor in detail
38	Investigation equipment B3	A device that is sent to the reactor through large-diameter holes (≥ φ110 mm) opened in the the reactor core internal structures and used to investigate the condition of the structures and fuel debris as well as the environmental conditions (air dose rate and temperature) in the reactor in detail
39	Investigation equipment B4	A device that is sent to the reactor through large-diameter holes (≥ φ110 mm) opened in the the reactor core internal structures and used to investigate the condition of the structures and fuel debris as well as the environmental conditions (air dose rate and temperature) in the reactor in detail

L: Low radiation, H: High radiation, S: Straight, B: Bend

No.	Equipment/device name	Outlines
40	Investigation equipment B guiding system	A mechanical system to guide investigation equipment B1, B2, B3, and B4 from the tool box down to the shroud head
41	Investigation equipment C	An investigation equipment for the reactor core section where a high environmental dose rate is estimated. It can be moved around in a wide area of the reactor core section by the XY position control above the upper grid plate using the guiding system (horizontal extension arm) in combination with its position control functions.
42	Investigation equipment C accessing system	A guiding system to guide investigation equipment C to the reactor core section. It suspends the investigation equipment, brings it down to the area above the upper grid plate, and moves laterally by unfolding the horizontal extension arm in a space between the shroud head and the upper grid plate. The final XY position of the device is controlled by the extension of the horizontal extension arm, and the device is moved down to the reactor bottom.

*) Some of the main equipment and devices in this table are further explained in detail in the next and subsequent pages.

6.4.1.6 Top-opening investigation method: Specifications of the equipment and devices No. 1: Entire work cell

<Outlines>

A facility to prevent radioactive materials that leaked from the joints with the tool box and boundary guide pipe on the operation floor, if any, from spreading to the surrounding environment

The floor of the work cell at and around the connection with the hole is elevated to the height of the newly installed shielding floor with a work pit in the space created by the elevation, considering repair work by workers which may be required in case of the failure or malfunction of the equipment associated with the connection with the boundary guide pipe or the gate valve on the guide pipe side.

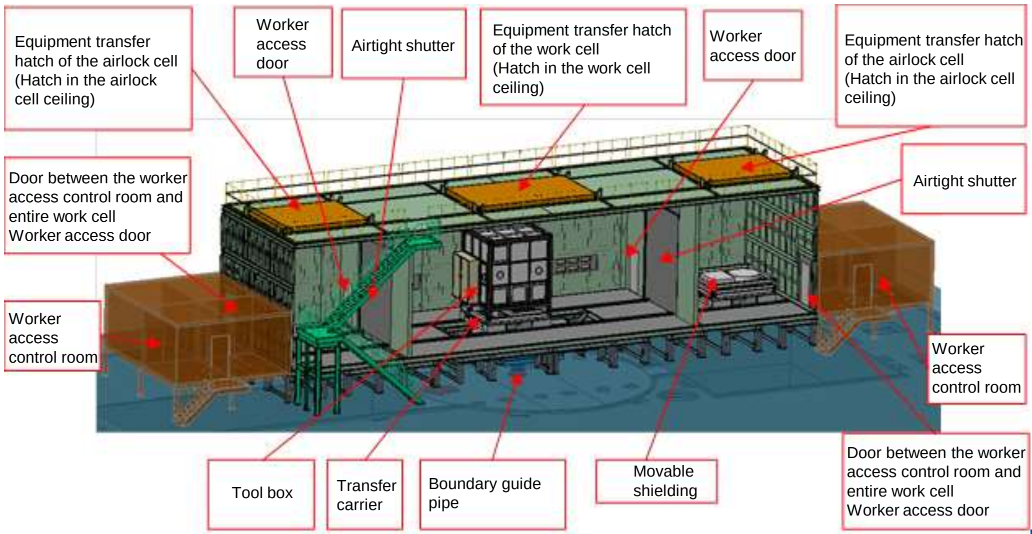
Guide rails are laid on the floor of the entire work cell between the airlock cells and work cell so that a transfer carrier can travel on them to carry the tool box to the area above the boundary guide pipe.

Airtight shutters are installed between the work cell and airlock cells to prevent direct airflow between the outside of the work cell and the work cell when equipment and devices are carried in or out and also to maintain a negative pressure. Two airlock cells are attached to both sides of the work cell to enable the inbound transfer of one device and the outbound transfer of another at the same time to support device change.

Utility interface wall boards are installed on the side wall of the work cell to help supply utilities to the devices in the tool box.

A hatch is installed on the ceiling board of the entire work cell to enable the transfer of devices around the boundary guide pipe. Similarly, a hatch is installed on the ceiling board of each airlock cell to enable the transfer of the tool box, etc.

<External appearance>



<Main functions and features>

[Negative-pressure control function]

· The negative pressure in the entire work cell is maintained below the atmospheric pressure using an exhaust fan (blower) and gravity dampers to confine contaminated materials that leaked through the joints with the tool box and boundary guide pipe in it, if any. In addition, the entire work cell is divided into the following three compartments to maintain its negative pressure even when workers go in or out from the cell or when the equipment is carried in or out from it: a compartment positioned right above a hole (hereinafter referred to as “work cell”) and two compartments attached to both sides of the work cell for carrying in and out the tool box (hereinafter referred to as “airlock cell”).

[Utility supply function]

· Detachable utility interface wall boards with sealing ability, each of which is designed unique to different equipment and devices, are provided to the interface utility supply lines between the sources outside and equipment and devices in the entire work cell through its wall.

<Basic specifications>

[Structure]

· Constructed by wall boards to exhibit an airtight capability.

[External dimensions]

· Entire work cell: approximately 7.85 m(W) × 28 m(D) × 7.8 m(H)

[Total volume]

· 1,365 m^3

<Cells>

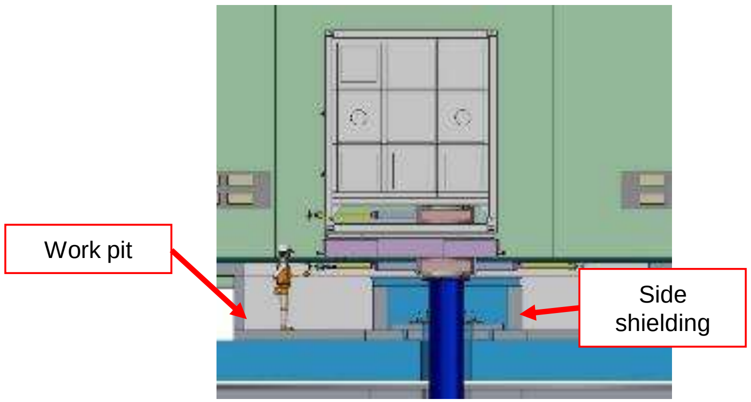
Airlock cell A: 290 m^3
Airlock cell B: 290 m^3
Work cell: 785 m^3

[Approximate weight]

· About 196 t

[Exhaust fan capacity]

· 4,095 m^3/h

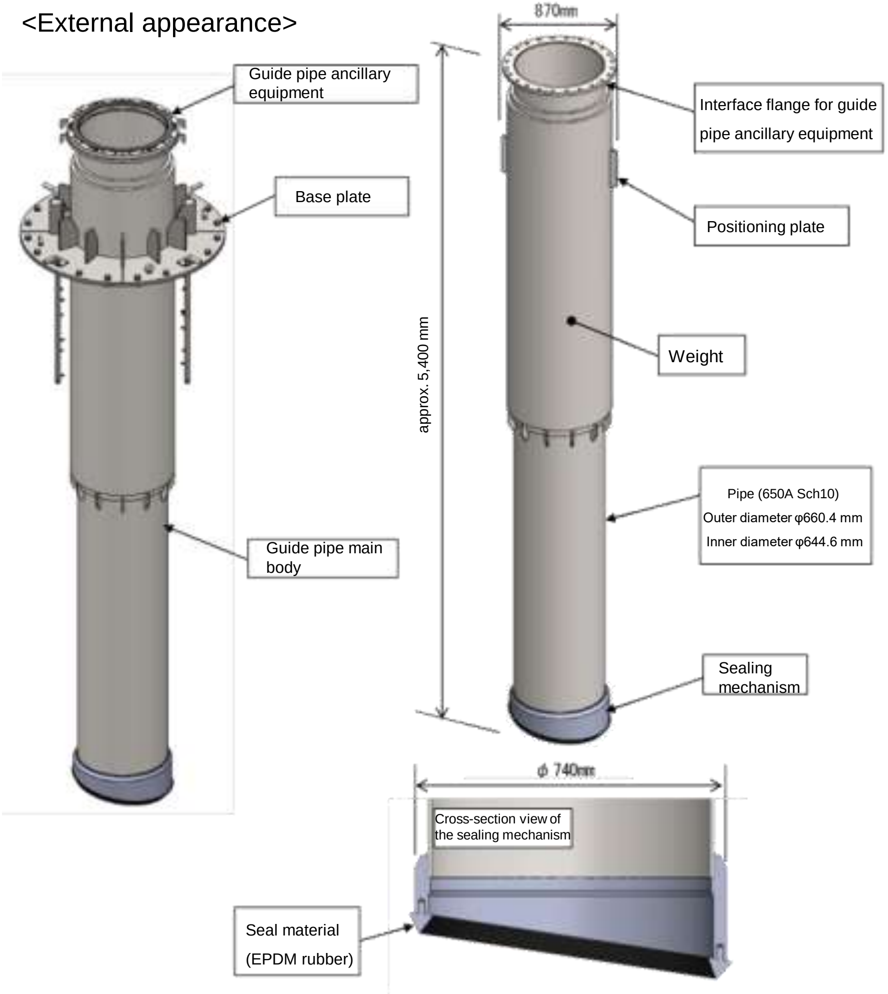


6.4.1.6 Top-opening investigation method: Specifications of the equipment and devices No. 5: Boundary guide pipe

<Outlines>

Equipment for maintaining the boundaries between the work cell and the PCV head after a hole is opened in the PCV head

<External appearance>



<Main functions and features>

[Configuration]

- This equipment consists of the guide pipe (main component), sealing mechanism attached to the guide pipe, base plate used to fix the guide pipe to the work cell, and ancillary unit equipped with utility ports and pressure indicator, etc.
- A weight is attached to the outer surface of the upper part of the guide pipe to exert sufficient gravity force to achieve a stable rubber sealing function.

[Double-sealing function]

- A rubber sealing (such as EPDM rubber) is provided at the bottom end of this equipment, which comes in direct contact with the PCV head, to secure the airtightness of the connection. The sealing is pushed against the PCV head by the gravity force of the weight.
- The sealing mechanism has the following sealing performance:
  Positive pressure: 10 kPa
  Negative pressure: inside PCV (guide pipe) < Entire work : −100 Pa,
  Inside PCV (guide pipe< inside Reactor well (section with atmospheric pressure): negative pressure 160 Pa

[Position adjustment function]

- Tapped holes are supposed to be prepared on the floor of the work cell in advance so that the base plate is fixed using them.
- Position guiding blocks attached to the base plate help the guide pipe to be placed at the right position.

[Measuring function]

- Pressure indicators, nitrogen flow meters, hydrogen and oxygen gas detectors, and exhaust gas line connection ports are installed on ancillary equipment of the guide pipe to measure various parameters.

[Cleaning function]

- A spray tube is attached to the base plate to wash the surface of the guide pipe.

<Basic specifications>

[Main body]

- Approximate dimensions: 870 mm × L 5,400 mm
- Pipe size: 650A Sch10 (outer diameter: φ660.4 mm, inner diameter: φ644.6 mm)
- Approximate weight: 2,000 kg

[Base plate]

- Approximate dimensions: φ1,500 mm × H280 mm
- Approximate weight: 400 kg

[Ancillary equipment]

- Approximate dimensions: φ825 mm × t 50 mm
- Approximate weight: 65 kg

[Installation position accuracy] (rough guideline)

- Inclination: 1° , XY position: ±10 mm

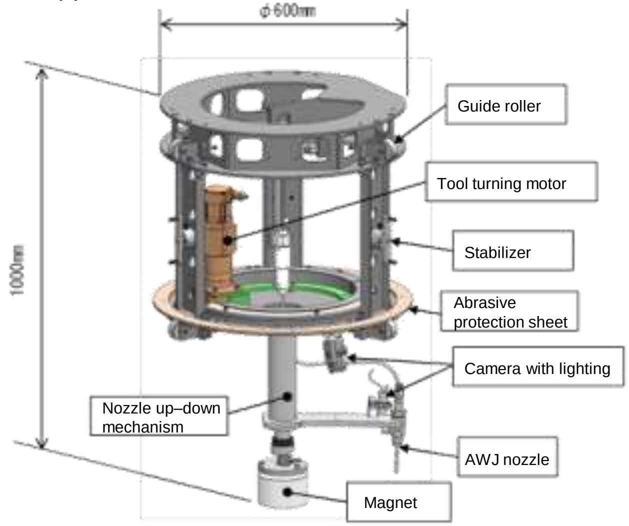
6.4.1.6 Top-opening investigation method: Specifications of the equipment and devices

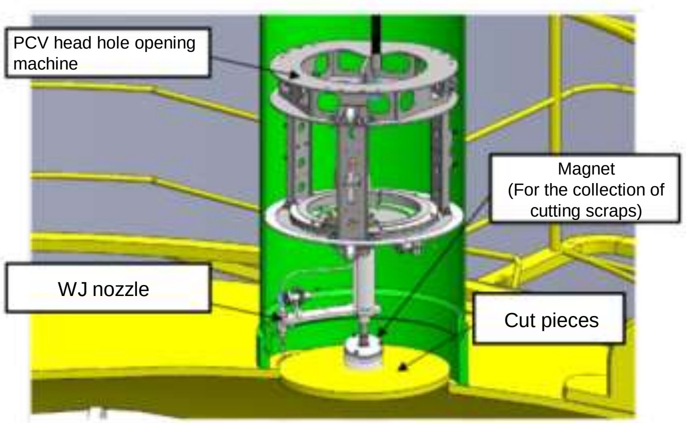
No. 19 PCV head hole opening machine

<Outlines>

A machine to open a hole in the PCV head at the predetermined position (right above the spare nozzle) after a small hole is bored in the PCV head

<External appearance>





<Main functions and features>

[Configuration]

· This machine consists of the tool frame and AWJ penetrating tool attached to it. The tool frame is equipped with guide rollers to guide it smoothly and stabilizers to stabilize it in the guide pipe by making contact with the inner wall of the pipe.

[Lifting function]

· The tool frame can be moved up and down in the guide pipe (between the tool box and the top of the PCV head) using a hoist in the tool box installed above the guide pipe.

· Once it reaches the top surface of the PCV head, it is fixed to the inner wall of the guide pipe by the air-driven stabilizers (pneumatic cylinder).

[Penetrating function]

· The machine has a function to open a round hole with a diameter of about φ550 mm and its center exactly matching the center of the tool (center of the guide pipe) in the PCV head by swiveling the AWJ tool using an electric tool swivel mechanism.

[Abrasive protection function]

· The tool frame is equipped with the abrasive protection sheet so that the flying abrasive can be blocked during AWJ injection.

[Function to hold and collect cutting scraps]

· A cutting scrap collection magnet (permanent magnet) is installed at the center of the AWJ penetrating tool so that it can hold and collect the cutting scraps generated during the PCV head penetrating by AWJ. This permanent magnet can be switched on and off using compressed air.

[Monitoring function]

· A small camera is installed on this machine along with lighting so that it can monitor the condition of the transfer, installation, and operation of this machine.

<Basic specifications>

[Entire machine]

· Main dimensions (approximate values): φ600 mm × H1,000 mm

· Weight: approx. 100 kg

· Material (main structure): SUS304

[Hoisting mechanism]

· An electric hoist is installed on the tool box to move this machine up and down. Two sets of the hoists are installed to suspend the machine with two slings to prevent the machine from falling.

[Tool turning mechanism]

· Swivel motion of the bottom part of the tool by an electric motor

· Swivel range: more than 0° to 360°

[Tool fixing stabilizer]

· Fixing the tool by three pneumatic cylinders

· Pressing force: approx. 150 kgf

[AWJ penetrating tool]

· AWJ mechanism: injection pressure, approx. 345–380 Mpa; abrasive feed rate, approx. 0.78 kg/min

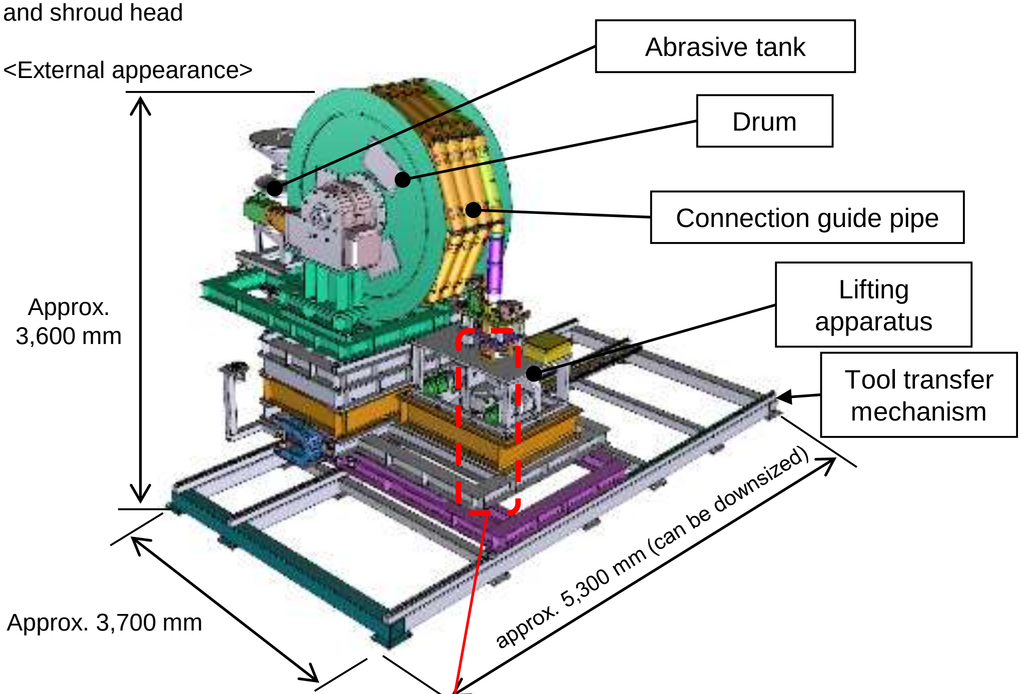
· AWJ nozzle up–down mechanism: a mechanism to keep the distance between the surface of the PCV head and the nozzle constant in response to the undulation of the PCV head surface and perform AWJ penetrating using the nozzle position controller with a vertical extension and contraction mechanism. This mechanism moves the nozzle up and down using the link mechanism and spring reaction force without using any actuator.

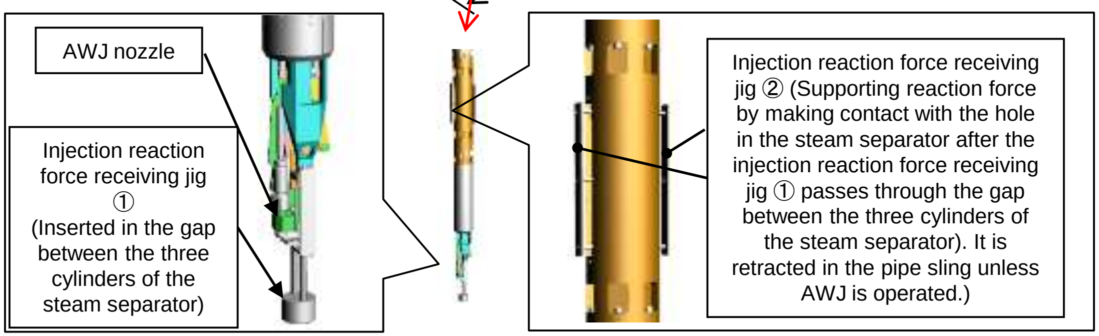
· Cutting scrap holding and collection mechanism: a permanent magnet with a pneumatic cylinder position controller and a holding power of ≥approx. 120 kg (weight of a single cutting scrap: approx. 60 kg)

6.4.1.6 Top-opening investigation method: Specifications of equipment and devices
No. 28: The reactor core internal structure processing apparatus

<Outlines>
A machine that is installed on the work cell at a planned position along the vertical line that goes through the RPV spare nozzle and opens holes in the steam dryer, steam separator, and shroud head

<External appearance>





Tool head (for the steam separator cutting)

<Main functions and features>

[Configuration]
- This machine consists of the tool head with the AWJ nozzle, pipe sling, hoisting mechanism, drum, abrasive tank, and tool transfer mechanism.
- High-pressure water for AWJ is supplied from a super-high-pressure pump installed on the outside of the entire work cell.

[Tool head]
- The tool head consists of the AWJ nozzle, injection reaction force receiving jig, link mechanism to control the position and angle of the AWJ nozzle, and θ-axis motor to swivel the tool head.

[Pipe sling]
- Each pipe forming the pipe sling is 700-m long, and the tool head is attached to the distal end of the pipe sling. The other end is connected to the drum.
- The drum turns to wind and unwind the pipe sling, which in turn causes the tool head to move up and down.
- Each link of the pipe sling is fixed as it passes through the hoist assist mechanism, so that the axis of each pipe is aligned straight, and the tool head is stably held by it.

[Hoisting mechanism]
- This mechanism is composed of the hoist rollers and toggle lock and assists the vertical movement of the pipe sling.

[Drum]
- This equipment winds and unwinds the pipe sling.

[Abrasive tank]
- This equipment consists of a tank and a weight scale.

[Tool transfer mechanism]
- This mechanism controls the horizontal position of the the reactor core internal structure processing apparatus.

<Basic specifications>

[Entire machine]
- Main dimensions (approximate values): 5,300 mm* × 3,700 mm × H3,600 mm
  * This can be downsized according to the required stroke for the tool transfer mechanism
- Approximate weight: 10,000 kg

[Penetrating machine]
- AWJ nozzle

[Control methods for the mechanisms]
- Electric and hydraulic remote control

6.4.1.6 Top-opening investigation method: Specifications of the equipment and devices No. 37: Investigation equipment B2

<Outlines>

A device that is inserted into the reactor through large-diameter holes (≥φ 110 mm) opened in the reactor core internal structures and used to investigate in detail the condition of the structures and fuel debris as well as the environmental conditions (air dose rate and temperature) in the reactor It is used in high-radiation areas as its camera has a high radiation resistance. It can create a panoramic image by scanning a target using its pan and tilt mechanism. It is used mainly in the investigation in the following areas:

- · Inside the well cover
- · Inside the PCV head
- · Inside the RPV head
- · Inside the reactor core

<External appearance>

Position during the up and down movements

Light arms fully stretched

Tilted at 90°

<Main functions and features>

[Configuration]

- · Color CID camera, pan/tilt mechanism, LED lights (with stretchable mounting arms), dosimeter, and thermometer
- · Cables are bundled in a sheath tube (flexible SUS tube) for protection.

[Function]

- · Slip clutches installed on the head tilting and light arm stretching mechanisms make it possible for the head and light mounting arms to return to their retracted position as the head goes through holes, so that the head can be withdrawn by forceful pull-up in case of failure.
- · A celestial-sphere image (panoramic image) can be created.

[Advantages]

- · A color image can be captured.
- · It has a wide eyesight in the vertical direction.
- · A lookdown-view celestial-sphere image (lookdown overview image) can be captured.

[Disadvantages]

- · The head loses its horizontal position when tilted due to the change in the center of the gravity. (Position compensation is required)

<Basic specifications>

[Outer dimensions]

- · Main dimensions : Outer diameter, Φ95 mm; length, 835 mm
- · Weight : approx. 6 kg

[Image capturing performances]

- · Type of camera : CID (color); diagonal angle of view, 35° ; number of pixels, approx. 300,000
- · Lighting : LED (3W × 6 when the arm is fully stretched); distance between the optic axes of the camera and the light, 117.5 mm
- · Visibility range : 2,000 mm (defined as the maximum distance at which a φ10-mm fuel rod can be recognized in a fog with an absorption coefficient of 0.223)

[View direction control]

- · Pan and tilt method: pan motion range, ±180° ; tilt motion range, 0° (vertical) to 110°

[Mounted sensors]

- · Dosimeter : 1 to 5,000 Gy/h, sufficient accuracy for determining the digit number of the dose rate
- · Thermometer : Range 0° to 50° C; accuracy ±1.5°

[Radiation resistance]

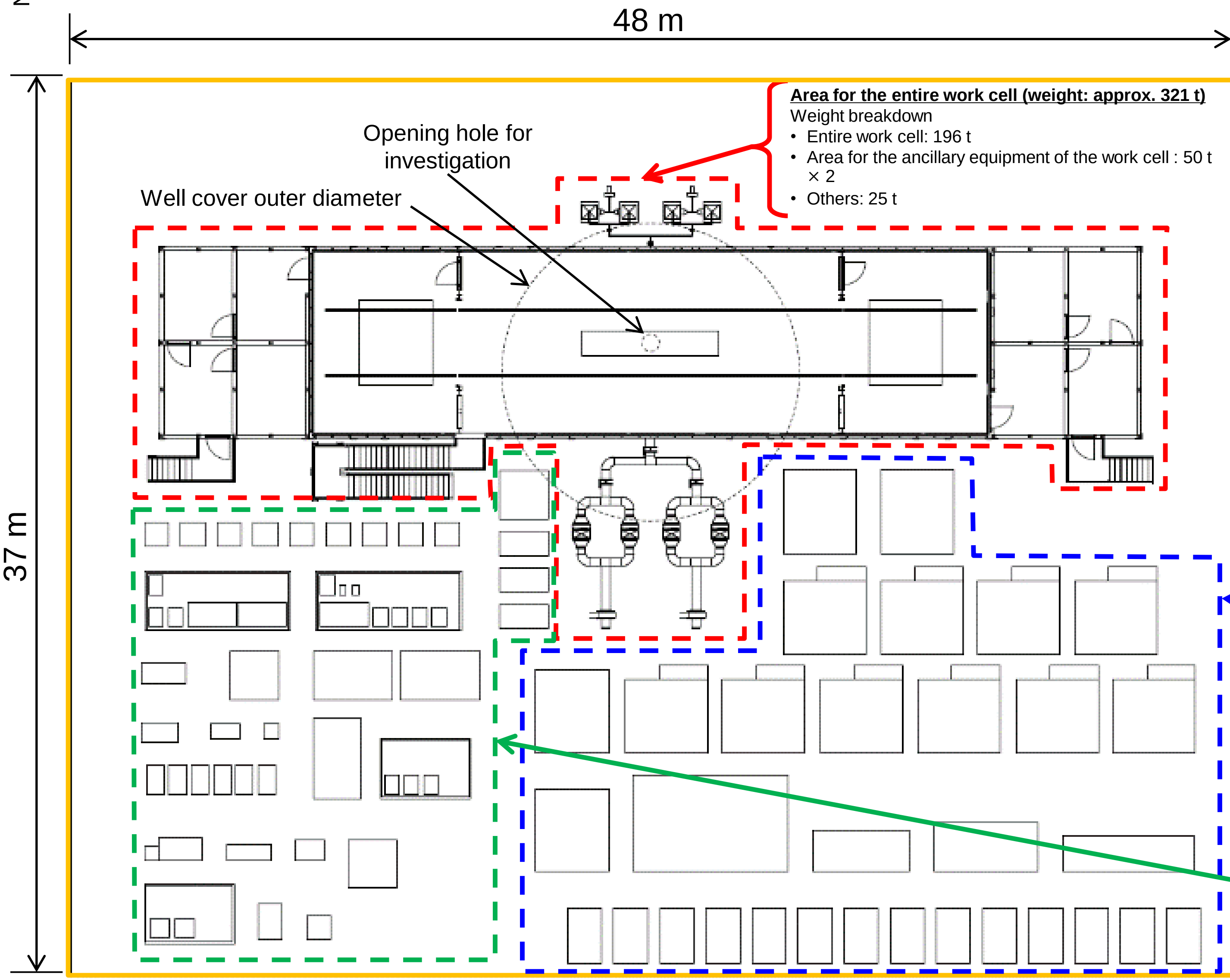
- · Cumulative dose rate : 30 kGy
- · Maximum permissible exposure time : 10 h (exposure limit for the LED light in 3,000 Sv/h environment)

[Waterproof and dust proof]

- · Equivalent to IPX4

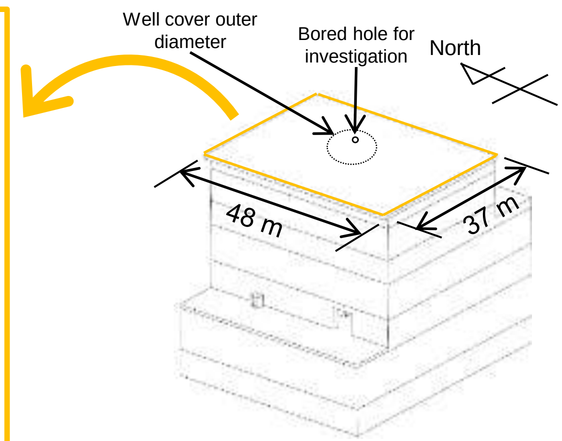
6.4.1.6 Top-opening investigation method: Equipment and device layout design (operation floor layout)

North



Upper section of the operation floor of Fukushima Daiichi Nuclear Power Station Unit 3 (top view)

Total weight: approx. 600 t
(When all the equipment and devices are installed on the operation floor)



Upper section of the operation floor of Fukushima Daiichi Power Station No. 3 Unit (Bird's-eye view)

Area for equipment and device area (weight: approx. 213 t)

Weight breakdown

- Boundary protection equipment and devices: 10 t
- Machines used to cut the structures until reaching the RPV head: 113 t
- The reactor core internal structure processing apparatus: 24 t
- Investigation systems: 66 t
  ⇒ Can be placed in places other than the operation floor.

Area for control boards (weight: approx. 52 t)

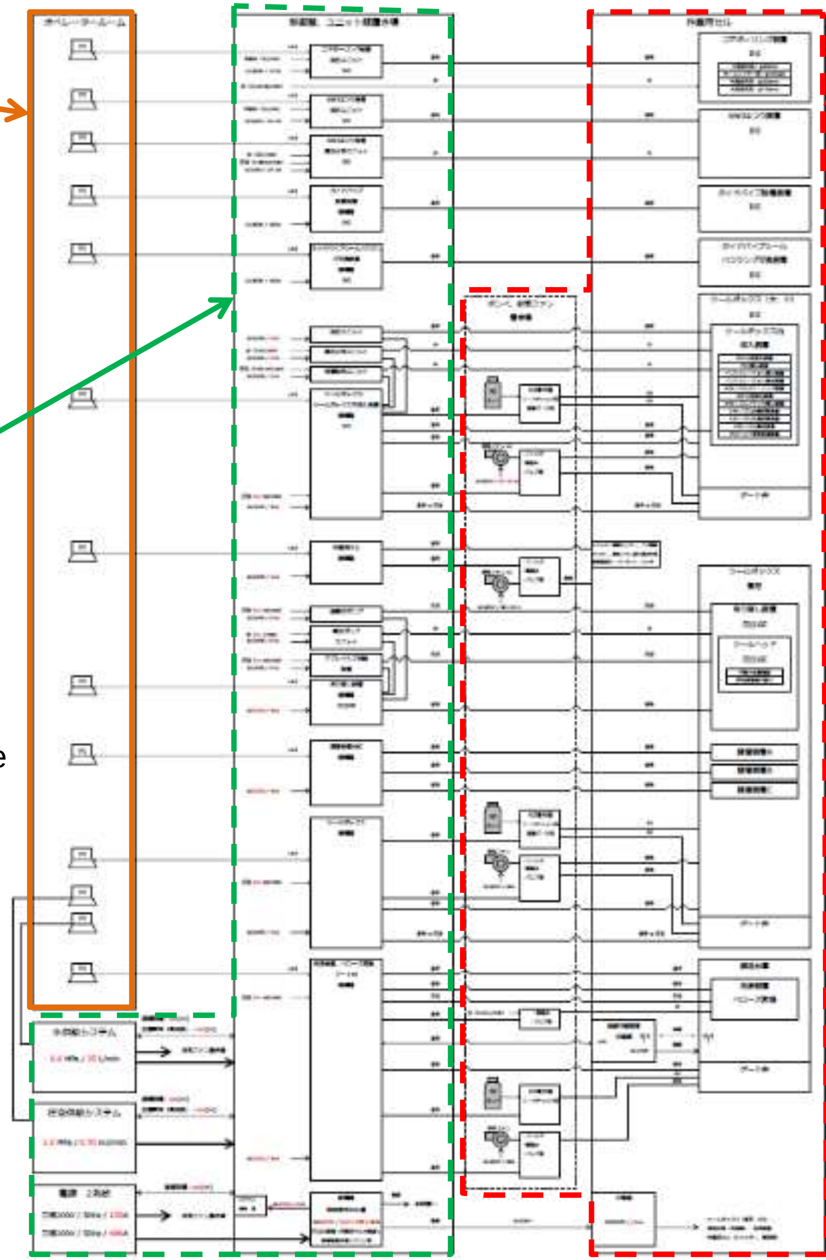
Weight breakdown

- Boundary protection equipment control systems: 21 t
- Control systems for machines used to cut structures until reaching the RPV head: 20 t
- Control systems for the reactor core internal structure processing apparatus: 8 t
- Investigation system controllers: 3 t
  ⇒ Can be placed in places other than the operation floor.

6.4.1.6 Overview of system configuration for Top-opening investigation method

<Remote control room area>
- Control PC

<Control panel area>
- Boundary protection equipment control systems
- Control systems for machines used to cut the structures until reaching the RPV head
- Control systems for the reactor core internal structure processing apparatus
- Investigation system controllers

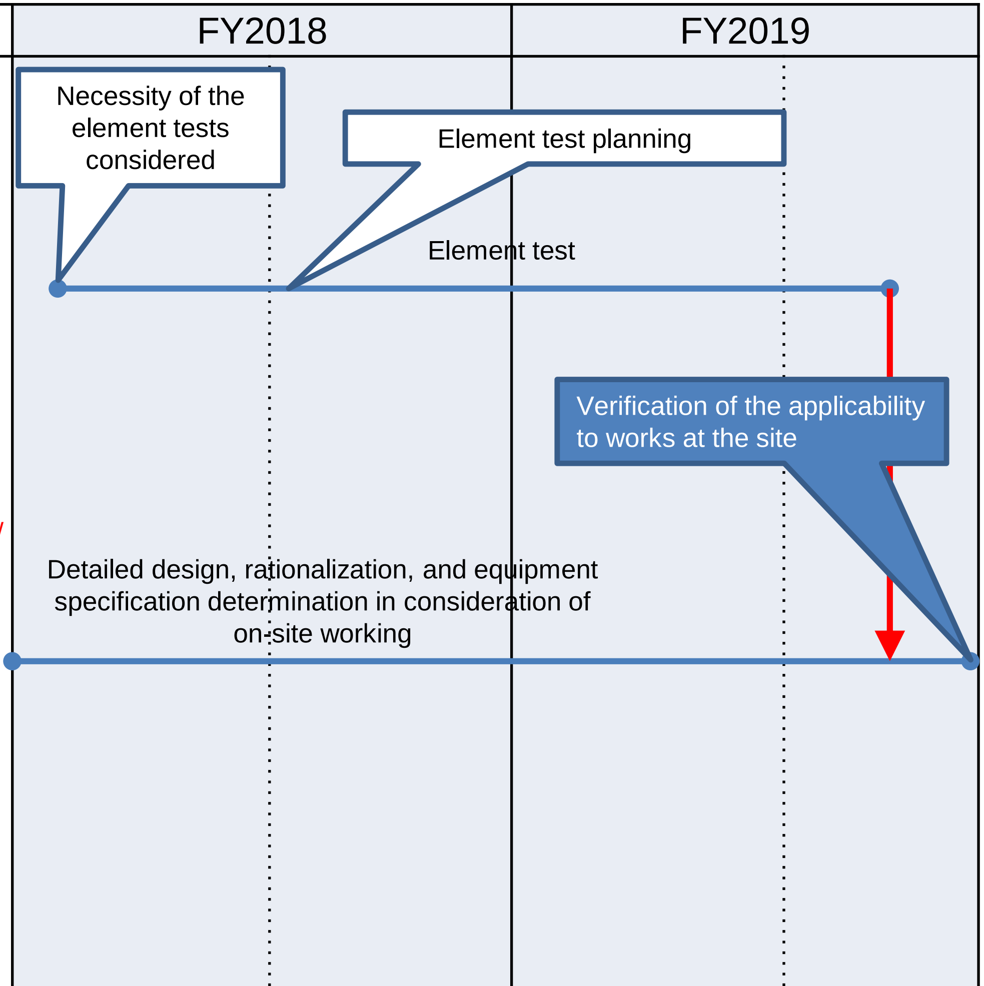


<Entire work cell area>
- Boundary protection equipment
  - ✓ Boundary guide pipe
  - ✓ Boundary guide pipe installation equipment
  - ✓ Gate valve on the boundary guide pipe side
  - ✓ Tool box (1, 2, 3)
  - ✓ Gate valve on the tool box side
  - ✓ Tool box transfer carrier (including the link mechanisms)
  - ✓ Movable shielding
  - ✓ Crane-equipped carrier
  - ✓ Water injection equipment for the inner wall of the boundary guide pipe
  - ✓ Exhaust blower for the entire work cell
  - ✓ Exhaust blower for the tool boxes
- Machines used to cut the structures until reaching the RPV head
  - ✓ Well cover core boring machine
  - ✓ Well cover AWJ chipping machine
  - ✓ PCV head surface treatment system (WJ, brush)
  - ✓ PCV head surface measuring equipment
  - ✓ PCV head small-hole penetrating machine
  - ✓ PCV head hole opening machine
  - ✓ Processing apparatus for fixing bracket
  - ✓ RPV insulator removal equipment
  - ✓ RPV spare nozzle cleaning equipment
  - ✓ RPV spare nozzle surface measuring equipment
  - ✓ Small-hole penetrating machine for the RPV head
  - ✓ Hole opening machine for the RPV spare nozzle flange
  - ✓ AWJ machine to cut the RPV spare nozzle from the inside
  - ✓ AWJ machine to cut the RPV spare nozzle from the outside
  - ✓ PCV head plugs
- The reactor core internal structure processing apparatus
  - ✓ The reactor core internal structure processing apparatus (for Units 1 and 2)
- Investigation systems
  - ✓ Investigation equipment (ALS, AHS, ALB, and AHB)
  - ✓ Investigation equipment (B1, B2, B3, and B4)
  - ✓ Investigation equipment C
  - ✓ Investigation equipment guiding systems (A, B, C)

6.4.2 Development of investigation equipment for side access method

With regard to machines used for penetrating from the outside of R/B to the shroud head, equipment to prevent dust spread, and devices that guide investigation equipment to the investigation target points, <u>technologies that can solve issues for the realization of on-site investigation are developed, and necessary devices and systems are designed in detail and rationalized.</u> In addition, <u>element tests are necessary for device development; thus, they should be conducted</u> if necessary in FY2018 <u>to verify the applicability of the devices to investigational works at the site based on the correct understanding of the actual site conditions.</u>

	Item	Outlines	Progress
1	Entire work cell development	Develop a system to maintain a negative pressure, in preparation for the possibility of radioactive dust leak from the tool box.	See the pages below
2	Development of processing apparatus used until reaching the shroud head	Develop a system and equipment that can prevent radioactive materials from spreading to the surrounding environment during cutting. More specifically, develop a method and equipment to establish a boundary by inserting the guide tube into the telescopic guide pipe whenever the penetrating and cutting of the biological shielding wall, PCV, and RPV are implemented. Especially, conduct element tests for systems to handle processed materials and wastewater generated by the use of abrasive water jet, which is a key technology for this method, at an early stage and reflect the results in the design work.	
3	Development of equipment to prevent radioactive materials from spreading		
	Development of investigation equipment guiding systems		
4	Development of a maintenance unit	The tool boxes house the hole opening machines and equipment to prevent radioactive materials from spreading. They will be preconditioned and decontaminated before and after use in a maintenance unit built in a ground-level area according to the plan. Develop a maintenance unit capable of preventing radioactive materials from spreading.	

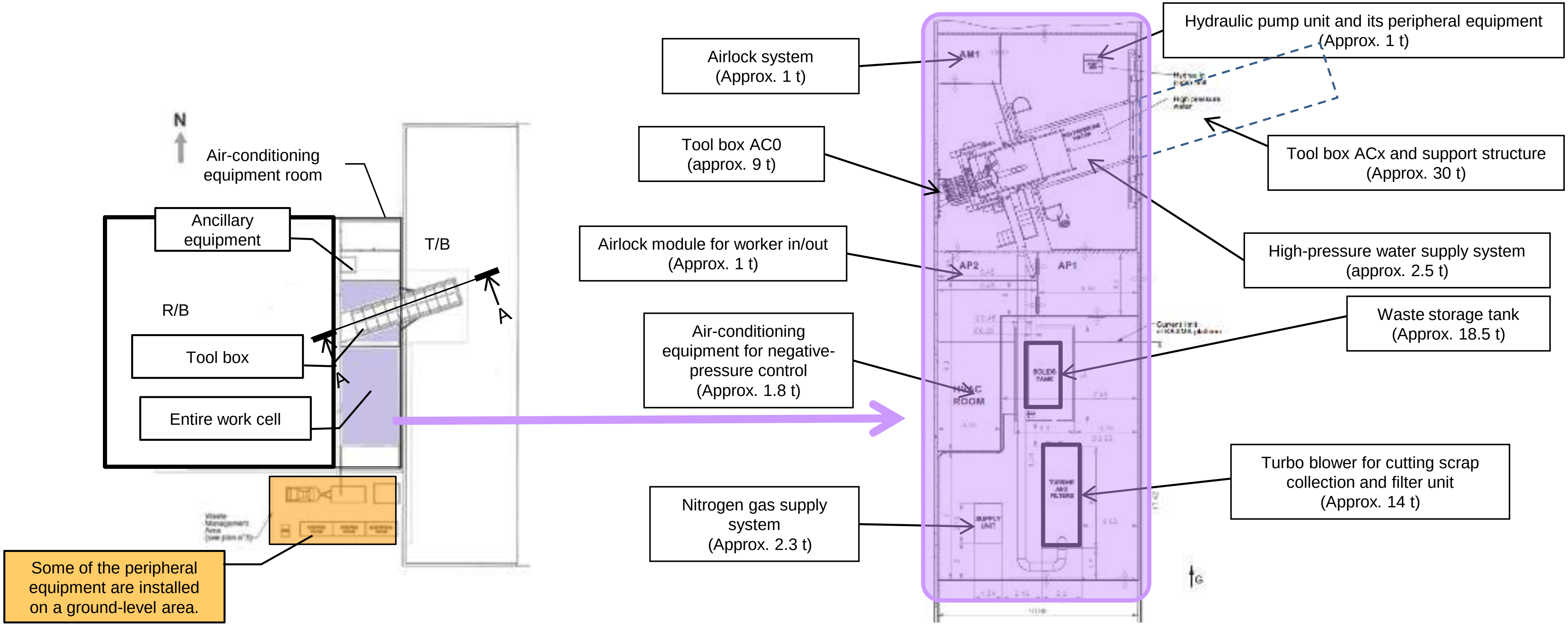


6.4.2 Development of investigation equipment for side access method No.66

Item	Implementation plan	Implementation items and results
Entire work cell	· Rationalization of the structure and construction method, taking into consideration the work steps, as well as weight reduction, including support structure · The device and equipment layout plans in and around the entire work cell were rationalized. · Clarification of the location of potential interfering objects on access route candidates and space availability · Detailed design of the negative-pressure control system	· Layout plans were established for the inside and outside of the work cell in consideration of the worker's traffic line in the entire work cell. · The methods to reduce the weight of the entire work cell and support structures and also distribute their weight evenly were devised in consideration of the maximum bearing capacity of the concrete slab roof of the air-conditioning equipment room. The feasibility of the devised methods was verified. · An airflow rate balance required to maintain the negative pressure was set, and system configuration and the capacity of components to realize the airflow rate balance were elucidated.
Processing apparatus used until reaching the shroud head	· Feasibility verification (evaluating the cutting performance and wastewater collection method) and rationalization of the penetrating tools · Rationalization of the structure and construction method of the tool boxes · Interface between the investigation equipment and the tool box	· The basic structures of the tool box and cutting tool heads were designed through the cutting performance tests and wastewater collection tests. In addition, system design was performed along with the component selection.
Boundary protection	· Rationalization of the structures and construction methods in consideration of the ease of construction · Verification of the sealing performance (confinement performance) of the guide pipe · Detailed design of a high-sensitivity pressurization control system	· The sealing performance of the guide tube was evaluated by an element test. · The basic structures of the guide tubes were determined. · Mass balance required to maintain a slight positive pressure than the PCV inner pressure was calculated, and system configuration and the capacity of components to realize the mass balance were elucidated.
Investigation equipment guiding systems	· Develop a mechanism to guide the investigation equipment in the reactor core area based on the policy that investigation equipment, including cameras, under development for the top-opening investigation method are used for the side-opening investigation method.	· Information on the interface required to operate the investigation equipment (such as shape, weight, electricity, and communication) was made clear as design conditions, and the guiding mechanism was designed based on it.
Maintenance unit	· Rationalization of the layout plans for the inside of the maintenance unit and its periphery · Development and design of the devices and systems and verification of their on-site operability	· The functions of the maintenance unit and the configuration of the equipment in it were studied, and a layout plan was created. · The strength of the maintenance unit was evaluated based on the layout plan. In addition, the design specifications were determined.

6.4.2.1 Side-opening investigation method: Entire work cell (1/2) No.67

Item	Implementation plan	Implementation items and results
Weight reduction of the entire work cell and support structures Rationalization of a layout plan for periphery	· The weight of the entire work cell was estimated to be heavier than the original plan in the study in FY2017. Weight reduction needs to be achieved for the entire work cell itself as well as for its support structures. · Estimate the total weight of the main equipment installed on the periphery of the entire work cell, such as a wastewater collection and discharge system and negative-pressure control system, and develop an equipment layout plan that fulfills the maximum bearing capacity of the concrete slab roof of the air-conditioning equipment room based on the estimated weight.	· A method for reducing the weight of the work cell and a layout plan to achieve an adequate weight-load distribution on the roof of the air-conditioning equipment room were devised in consideration of the maximum bearing capacity of the concrete slab roof of the room. The weight-load distribution to R/B pillars was calculated, and the method and layout plan were confirmed to be feasible. (The entire work cell was downsized, reinforcing support structures were strengthened, and some of the equipment were relocated to a ground-level area)

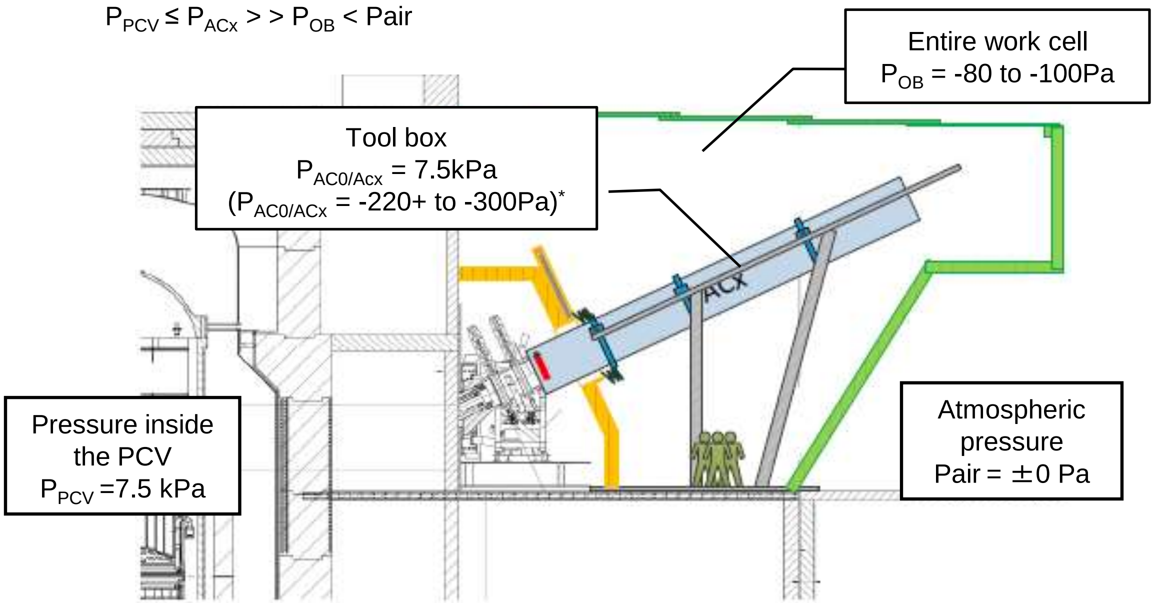


6.4.2.1 Side-opening investigation method: Entire work cell (2/2)

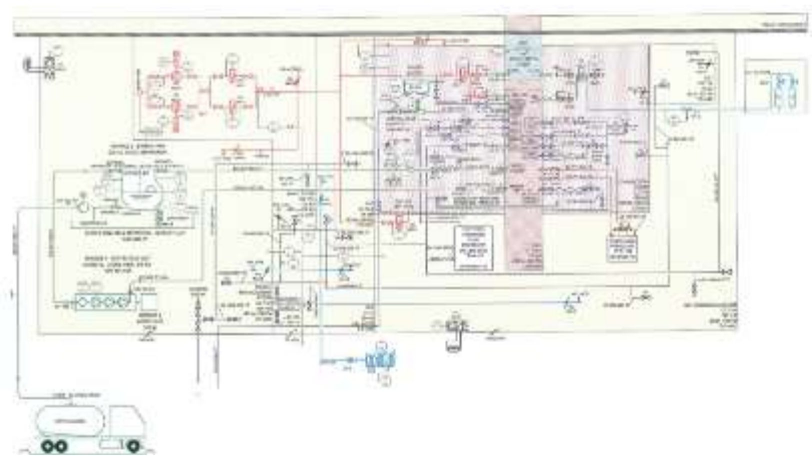
Item	Implementation plan	Implementation items and results
Clarification of the location of potential interfering objects on access route candidates and space availability	· Study the best access route for investigation that can minimize cutting and penetrating works, such as cutting piping in the reactor, and determine the tool installation position (penetrating angle for investigation hole penetrating). · Determine the available space for the installation of the entire work cell and seismic design conditions.	· An access route plan that could avoid cutting of piping and other interfering objects in the reactor was formulated. (Reported)
Detailed design of the negative-pressure control system	Study functional requirements for the negative-pressure control system of the entire work cell from the point of view of safety and reflect the result in the system specifications.	· Target pressure values (negative pressure of up to −300 Pa) were determined for each of the boundary protection equipment, a system diagram was created, and airflow rate balance between adjacent compartments was designed. (Reported) · The system specifications were fixed.

Maintain the inner pressure of ACx and AC0 at 1.25 times higher than the PCV inner pressure by feeding nitrogen gas to ACx and AC0 before opening the isolation valve of AC0. Prevent the spread of radioactive dust in the PCV to the surrounding atmosphere by maintaining the inner pressure of each boundary protection equipment as defined by the inequality below after opening the isolation valve. (A design value that was set by adding margin to the maximum operation data of the plant should be used as the PCV inner pressure)

$P_{PCV} \leq P_{ACx} >> P_{OB} < Pair$



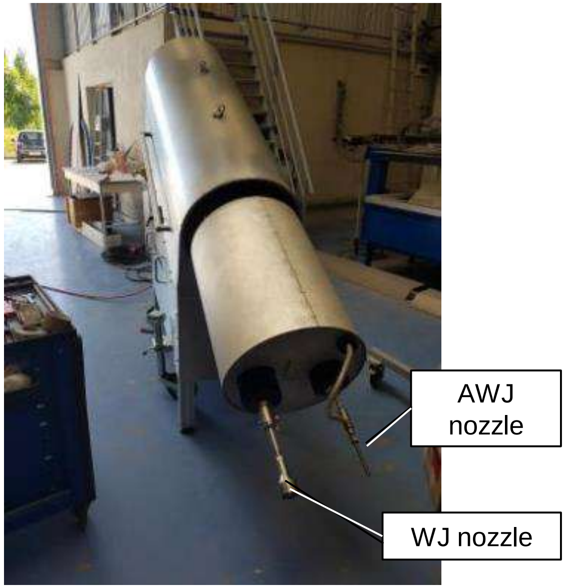
*) The equation in the parentheses expresses the state before the isolation valve is opened.



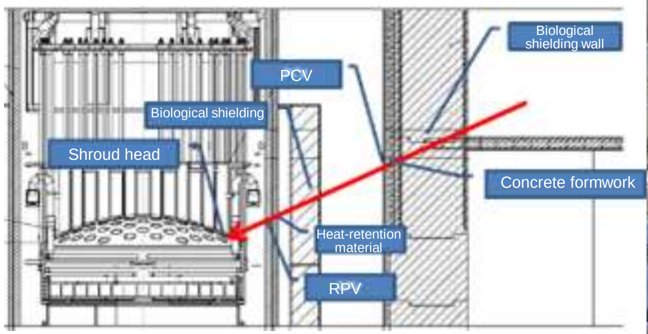
System diagram of the equipment installed on the roof of the air-conditioning equipment room (ACx is docked with AC0)

6.4.2.2 Side-opening investigation method: Processing apparatus used until reaching the shroud head (1/2)

Item	Implementation plan	Implementation items and results
Feasibility verification (evaluating the cutting performance and wastewater collection method) and rationalization of the penetrating tools	· Conduct element tests to verify the feasibility of element technologies and collect basic data for equipment design.	· Element tests to evaluate the cutting performance and wastewater collection ability were conducted using test samples made for these purposes. (Reported) · The results of the tests were reflected in the design of the machines, and the amount of abrasive and water required for the cutting works was estimated.



Tool head used in the cutting



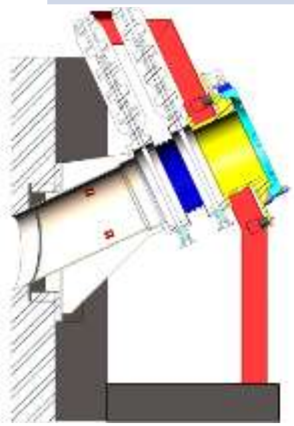
Structures to be cut on the access route

Equipment for wastewater collection test

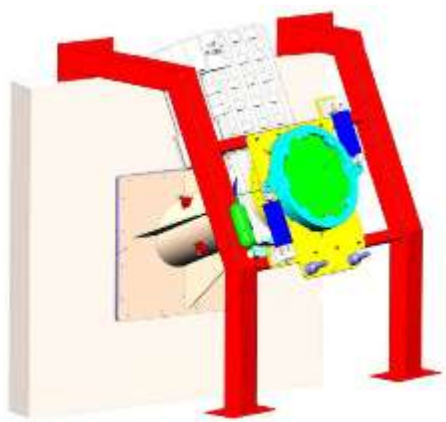
Structures to be cut	Total water consumption (L)	Total abrasive consumption (kg)	Process time (hours and minutes)	Remarks
Biological shielding wall +PCV	83,986	4,520 (4290 + 230)*1	176:04	*1) A large part of the abrasive used for the AWJ cutting process was consumed for cutting rebars in the biological shielding wall into small pieces (see the photo below on the left). The amount of abrasive needed for penetrating the PCV itself was 230 kg. Based on this data, about 4,300 kg of consumed abrasive was estimated to be collected together with the wastewater.
RPV shield wall + insulator + RPV	15,671	705	31:25	
Shroud head	1,270	163*2	4:30	*2) To ensure sub-criticality, it is important to limit the weight of a single piece of scraps 16 kg that may fall in the reactor core area during the cutting work.

6.4.2.2 Side-opening investigation method: Processing apparatus used until reaching the shroud head (2/2)

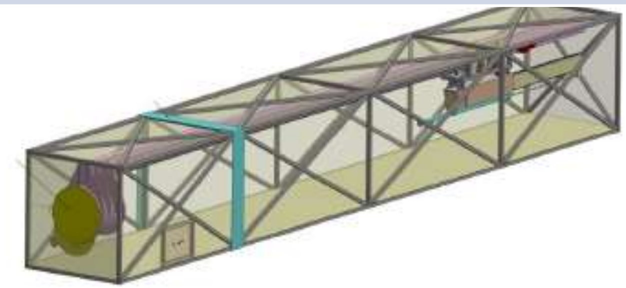
Item	Implementation plan	Implementation items and results
Rationalization of the structure and construction method of the tool boxes	· Design the basic structure with consideration of the weight of the tool boxes and the gravity center during handling. · Design the structure of the tool boxes in detail based on the specifications of the tools equipped in it.	• The basic structures of the tool boxes and tool heads were designed. AC0: The tool box that is permanently installed on R/B and functions as the base for connecting other tool boxes (ACx) AC2: The tool box used to insert the guide tube AC3: The tool box to house the processing apparatus AC5: The tool box used to insert the investigation equipment • A mechanism capable of stably moving the tool forward and backward in the guide tube without shaking was designed. (A guide tube laid inside another guide tube is guided in the latter by the crawler that has rollers and rotation preventing mechanisms on it. The rollers and rotation preventing mechanisms of the crawler comes into contact with the inner surface of the latter to maintain an exact concentric relationship between the two while they are moved forward and backward as presented in the figures below)



AC0 side view



AC0 bird's-eye view



Basic structure of the tool boxes (AC2, AC3, and AC5)

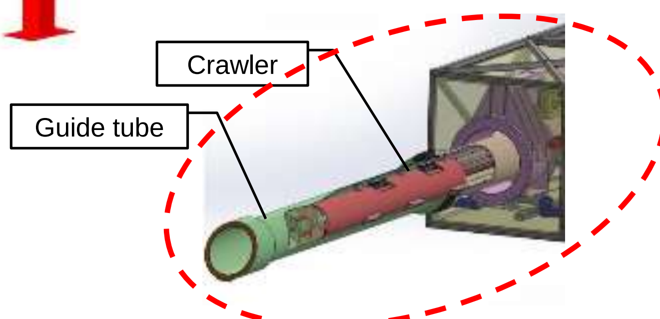
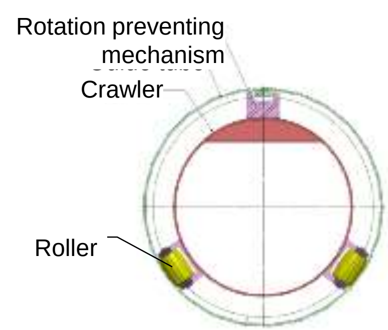


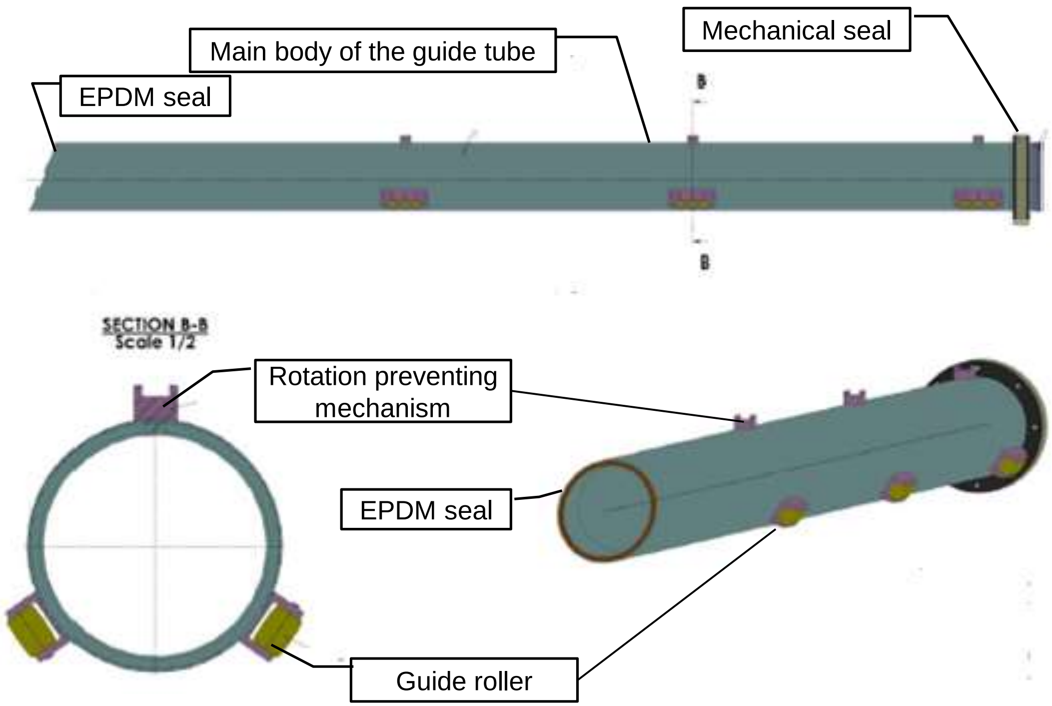
Illustration of the guide tube with the crawler inserted in it from the tool box



Guide tube inside cross-sectional view

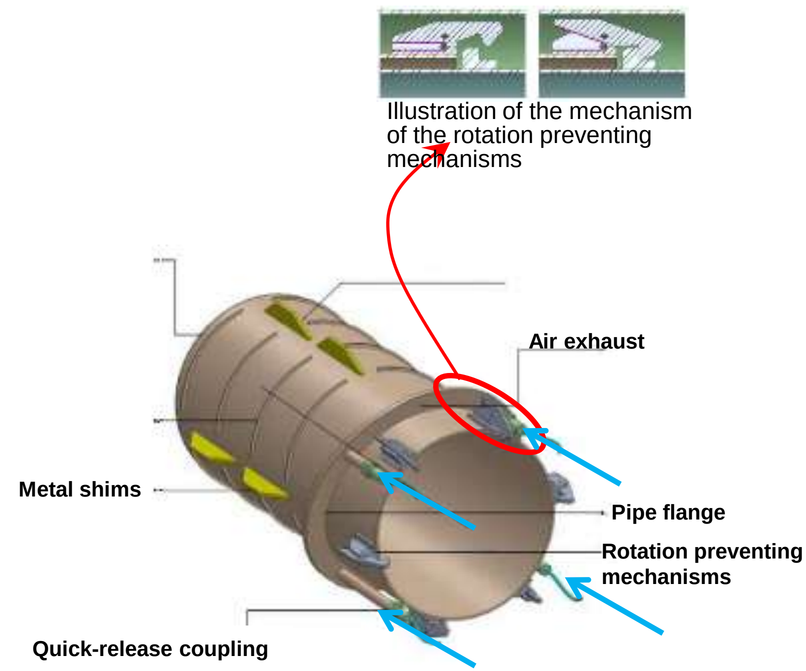
6.4.2.3 Side-opening investigation method: Boundary protection

Item	Implementation plan	Implementation items and results
Verification of the sealing performance (confinement performance) of the guide tube	· Conduct element tests to verify the feasibility of element technologies and collect basic data for equipment design, such as a leak rate.	· Element tests were conducted, and the sealing performance of the guide tube was found to satisfy the criterion (≤ 0.05 vol%/h) set in reference to the leak rate criteria of ISO10648 applicable to glove boxes, etc. (Reported)
Rationalization of the structures and construction methods in consideration of the ease of construction	· Conduct element tests to verify the feasibility of element technologies and collect basic data for equipment design.	· Element tests (joint strength tests) were conducted, and the joint of the guide tube was found to be strong enough to withstand an axial load determined to be necessary to achieve the target sealing performance through the abovementioned tests.



Drawing of a guide tube structure

Each of the guide tubes is equipped with guide rollers and rotation preventing mechanisms, so that they can be aligned in an exact concentric manner.

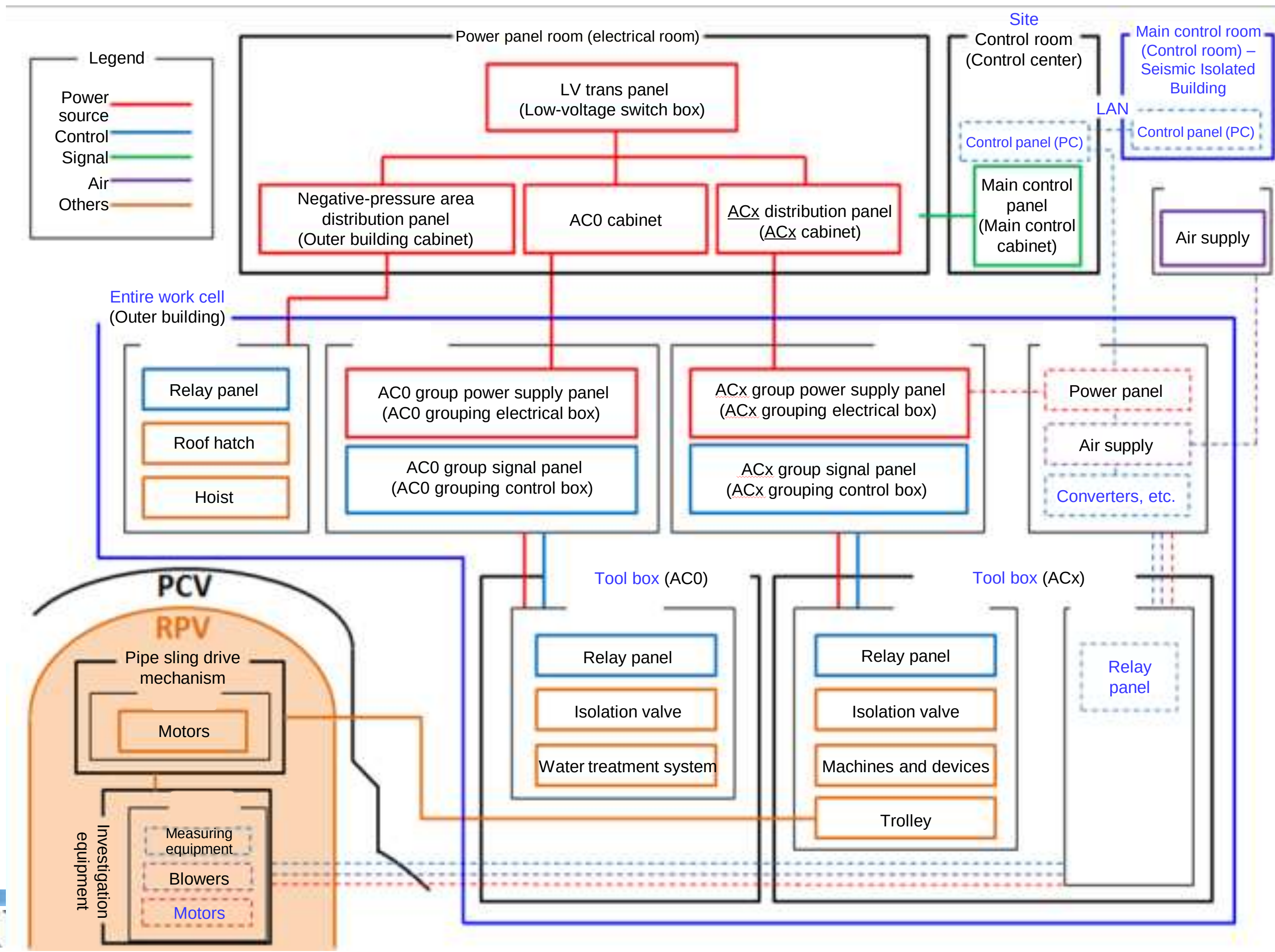


Drawing of a PCV guide tube sleeve structure

Cement milk filling ports are provided at four positions in the top edge of the sleeve to evenly fill the entire gap between the sleeve and a hole with cement.

6.4.2.4 Side-opening investigation method: Investigation equipment guiding systems

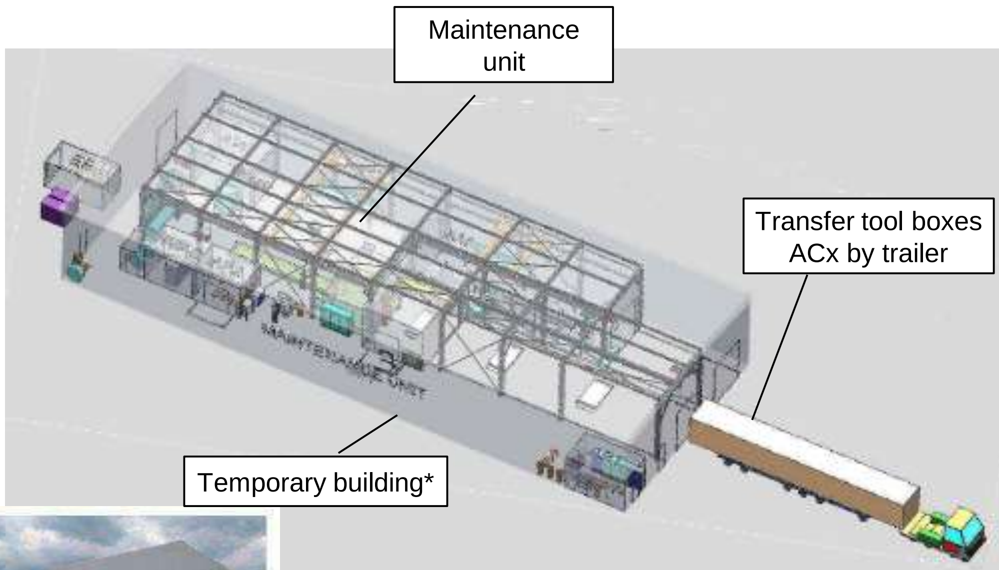
Item	Implementation plan	Implementation items and results
Investigation equipment guiding systems	· Design interface between the investigation equipment and tool boxes based on the policy that investigation equipment, including cameras, under development for the top-opening investigation method are used for the side-opening investigation method. · Design a mechanism to guide and send investigation equipment to the reactor core.	· Information on the interface required to operate the investigation equipment (such as shape, weight, electricity, and communication) was made clear as design conditions, and the interface systems and mechanisms necessary to house the investigation equipment in the tool boxes in good conditions and make them work accurately and effectively were designed. (Reported)



Power line and communication block diagram for investigation equipment (example)

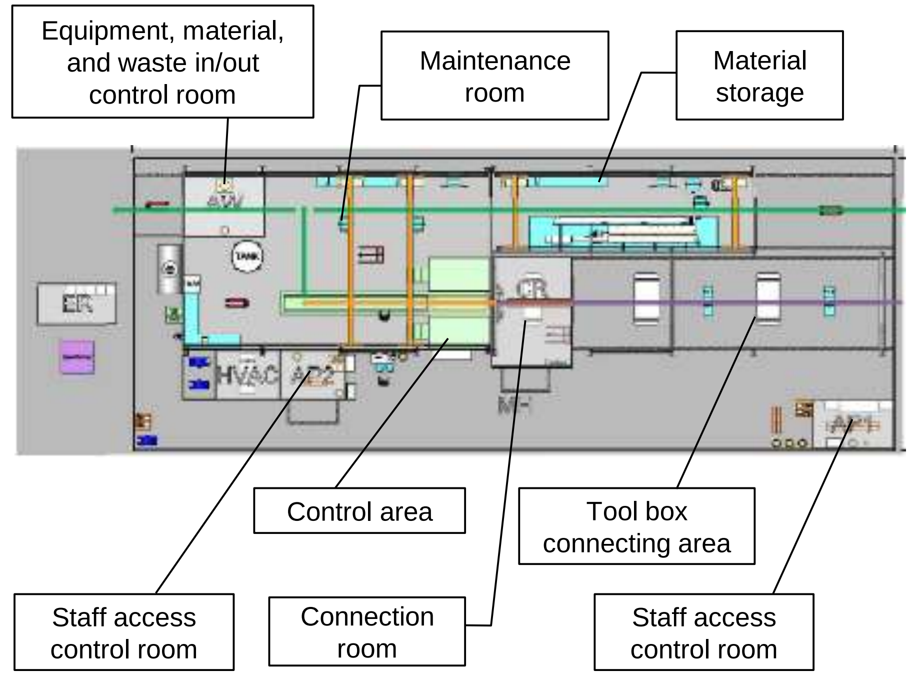
6.4.2.5 Side-opening investigation method: Maintenance unit

Item	Implementation plan	Implementation items and results
Maintenance unit	· Rationalization of the layout plans for the inside of the maintenance unit and its periphery · Development and design of the devices and systems and verification of their on-site operability	· The functions of the maintenance unit and the configuration of the equipment in it were studied, and a layout plan was created. (Reported) · A system diagram for the equipment used to control the negative pressure inside the room was created (presented in the next page), and airflow rate balance was determined according to the level of negative pressure. · The specifications of the equipment were fixed, and their strength was evaluated based on the specifications.



Bird's-eye view

*) A temporary building like a tent warehouse is used for buildings constructed outside to save cost and construction time.



Layout diagram of the temporary building inside (plan view drawing)

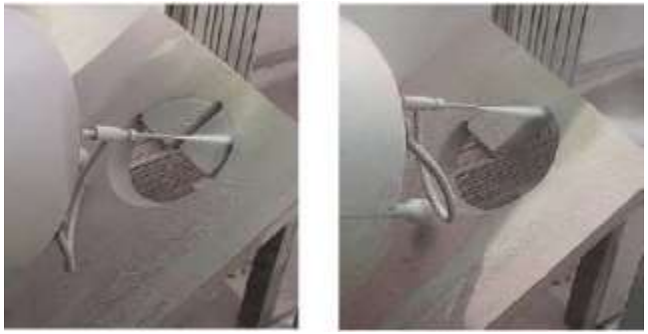
6.4.2.6 Side-opening investigation method: Operating parameters for the water volume to be used in abrasive and cutting works (rough estimate)

Structures to be cut	Required hole specifications	Construction method	Process time (Hours and minutes)	Water consumption (L)	Abrasive consumption (kg)
Biological shielding wall	φ480 mm	WJ/AWJ	176:04	83,986	4,520 (4290 + 230)*1
PCV	φ400 mm				
RPV shield wall	φ400 mm	WJ/AWJ	31:25	15,671	705
Heat-retention material	φ300 mm				
RPV	φ220 mm				
Shroud head	φ220 mm	AWJ	4:30	1,270	**163***2
Total			**211:59**	**100,972**	**5,388**
			Approx. 8.9 days	**Approx. 100,000 L**	**Approx. 5.3 t**

*1) A large part of the abrasive used for the AWJ cutting process was consumed for cutting rebars in the biological shielding wall into small pieces (see the photo below on the left). The amount of abrasive needed for penetrating the PCV itself was 230 kg. Based on this data, about 4,300 kg of consumed abrasive was estimated to be collected together with the wastewater.

*2) To ensure sub-criticality, it is important to limit the weight of a single piece of scraps 16 kg that may fall in the reactor core area during the cutting work. The shroud head is cut into four parts as shown in the photos below on the right.

Cutting the main rebars of the biological shielding wall in the element test



Cutting the shroud head into four parts in the element test

6.4.2.6 Side-opening investigation method: List of equipment and devices

No.	Name of equipment and device	Outlines
1	Entire work cell	A structure to prevent radioactive dust from spreading during the cutting and investigational works by maintaining negative pressure.
2	Support structure	Temporary storage for tool box ACx during lifting/hoisting. Used for docking and undocking with tool box AC0
3	Connection room	A structure to enclose the joint between tool boxes ACx and AC0 with the structural members of the entire work cell. Function to prevent contamination during docking and undocking if, by any chance, it occurs.
4*	Tool box AC0	A structure connected to the multi-use plate mounted on the R/B wall and equipped with a two-stage isolation valve. Equipped with a cap to block direct ray when none of tool boxes ACx are connected.
5*	Tool box AC2	A structure used to install the light guide tube, PCV guide tube, and RPV guide tube. Equipped with an expandable mandrel
6*	Light guide tube	A guide tube to cover the route from AC0 to the biological shielding wall
7*	PCV guide tube	A guide tube to cover the route from AC0 to PCV An EPDM rubber sealing is attached to its end surface to protect the boundary. Guided by guide rollers and rotation preventing mechanisms to a position that forms an exact concentric relationship with the light guide tube
8	PCV sleeve	Equipment to support the PCV guide tube by the biological shielding wall against the axial load exerted to it by filling the gap between the biological shielding wall and itself with cement milk.
9*	RPV guide tube	A guide tube to cover the route from AC0 to RPV Guided by guide rollers and rotation preventing mechanisms to a position that forms an exact concentric relationship with the light guide tube
10*	Tool box AC3	A structure to house the AWJ/WJ hybrid cutting tool head in it and cut the biological shielding wall, PCV, RPV shield wall, insulator, RPV, and shroud head

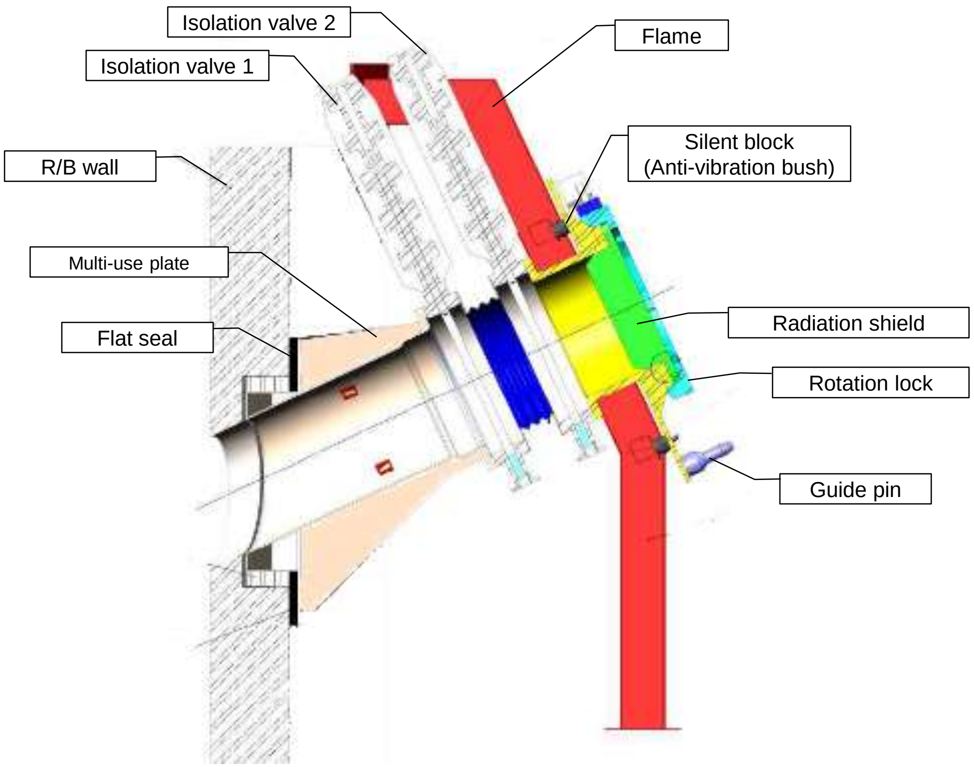
No.	Name of equipment and device	Outlines
11*	AWJ/WJ hybrid cutting tool head	Four types of cutting tool heads are prepared, each of which is capable to bore a hole with a diameter of φ480, 400, 300, and 220 mm.
12*	Crawler	A mechanism that is attached to the AWJ/WJ hybrid cutting tool head rigidly and moved forward and backward in the guide tube Guide rollers and rotation preventing mechanisms are attached to the outer surface of the crawler. They come into contact with the inner surface of the guide tube, inside which the crawler is moved, and keep it at the center of the guide tube.
13*	Tool box AC5	A structure to station a mechanism to transfer the investigation equipment developed for use in the top-opening investigation method to the reactor core area
14	Wastewater collection and discharge system	A system that is composed of three turbo-fan units and used to collect cutting scraps (concrete and rebar scraps) The collected wastewater is filtrated to separate it from cutting scraps.
15	Platform	A steel-frame structure to distribute the weight load of the entire work cell, tool boxes, and utility supply equipment installed on the roof of the air-conditioning equipment room, not only on the concrete slab roof but also on the R/B wall
16	Maintenance unit	A facility planned to be built in a ground-level area to provide an environment for the preconditioning and decontamination of the cutting tools and guide tubes that are installed on tool boxes ACx when tool change is implemented

*) Some of main equipment and devices, especially for cutting investigation holes, in this table are further explained in detail in the pages below.

6.4.2.6 Side-opening investigation method: Specifications of equipment and devices No. 4: Tool box AC0

<Outlines>
A tool box permanently installed on the entire work cell. It is fixed to the multi-use plate attached to the R/B wall with anchor bolts. A cap (radiation shield) is set to block direct ray from the reactor core when none of the tool boxes ACx are connected and no construction work is being carried out either.

<External appearance>



<Main functions and features>

[Configuration]

- The multi-use plate is fixed to the R/B wall with anchor bolts *via* flat seal.
- The frame is also fixed to the R/B wall to enable it to bear part of the weight load of the connected ACx *via* anti-vibration bushes.
- Two sets of isolation valves are provided, which contribute to the prevention of the spread of radioactive dust.

[ACx guiding function]

- The guide pin mates with the guide hole on ACx to guide it at the right position when docking tool box ACx. After docking, the rotation lock is turned and engaged to secure the connection between AC0 and ACx.

[Direct ray shielding function]

- A cap (radiation shield) is provided to block direct ray from the reactor core when none of the tool boxes ACx are connected and no construction work is being carried out either.

[Radioactive dust spread prevention function]

- Two sets of isolation valves are provided so that the opening (guide tube) is shut off and sealed airtight even if one of them fails.

<Main component specifications>

[Isolation valve]

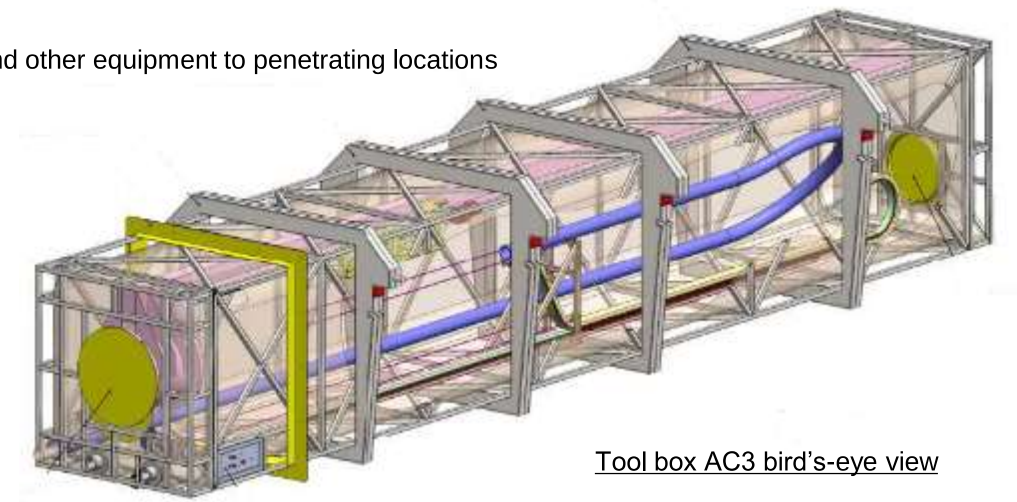
- Product of VAT, Series 192 UHV – DN 40/1000 mm (supplier ref. 19260-PE44)

[Rotation lock mechanism]

- Remotely controlled electric-driven lock mechanism

6.4.2.6 Side-opening investigation method: Specifications of equipment and devices No. 5, 10, 13: Tool boxes ACx

<Outlines>
Tool boxes to guide and transfer the AWJ/WJ hybrid cutting tool head, guide tube, and other equipment to penetrating locations



Tool box AC3 bird's-eye view

<Main functions and features>

[Configuration]

The following three types of tool boxes are prepared.

- AC2: Used to transfer guide tubes
- AC3: Used to transfer the AWJ/WJ hybrid cutting tool head
- AC5: Used to transfer the investigation equipment

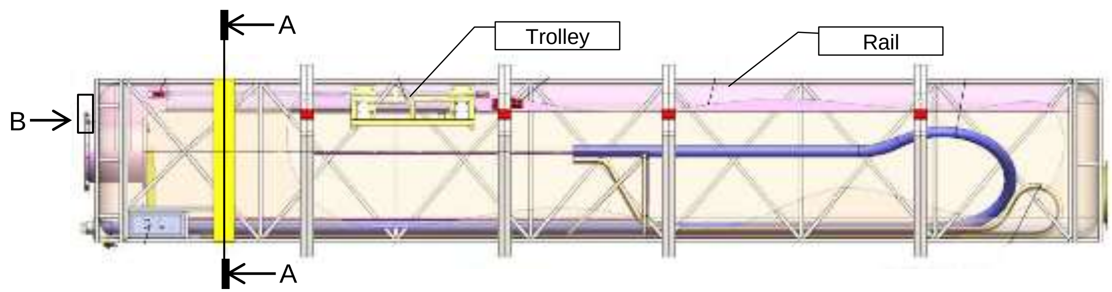
Guide tubes and other tools in each tool box are replaced with other sets in the maintenance unit.

[Function to move tools forward and backward]

- The trolley guide rail is installed on the ceiling of the tool box. The trolley moves along the rail, pushing and pulling tools between the tool box and target penetrating locations.
- Besides the trolley, a pair of winches is provided to pull the crawler if by any chance the trolley fails to function. Tools can be withdrawn by pulling a wire rope connected to the crawler by a winch.

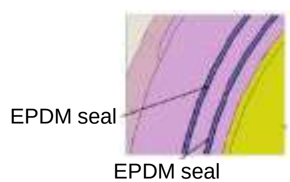
[Double-sealing function]

- Double-layer EPDM sealing is installed on the surface of the flange of ACx for connection with AC0. The sealability between AC0 and ACx is secured by pressing the flange of AC0 against the sealing.

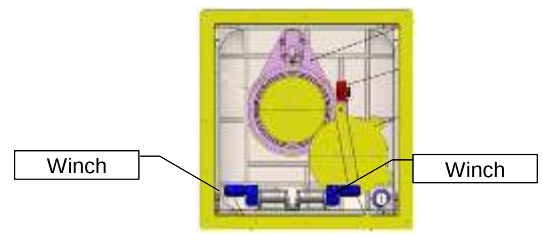


<Main component specifications>

- Main dimensions (approximate values)
  : W2200 mm × H2300mm × L18000 mm (AC2)
  : W2200 mm × H2300 mm × L15000 mm (AC3)
  : W2200 mm × H2300 mm × L11500 mm (AC5)
- Approximate weight: 30,000 kg (when equipped with the heaviest tool)



Enlarged view from arrow B



Cross section A-A

6.4.2.6 Side-opening investigation method: Specifications of equipment and devices No. 6, 7, 9: Guide tubes

<Outlines>

The light tube, PCV guide tube, and RPV guide tube are laid out in a concentric configuration in this order with the light tube placed at the outermost part. The rollers and rotation preventing mechanisms on the outer surface of the PCV guide tube contact the inner surface of the light guide tube to maintain an exact concentric relationship between the two while they are being moved. The rollers and rotation preventing mechanisms on the outer surface of the RPV guide tube work similarly. Thus, the three guide tubes are aligned in an exact concentric manner. In addition, an EPDM rubber sealing is installed on the end surface of the PCV guide tube so that the boundary is protected by pressing the PCV guide tube and the sealing against the PCV outer surface.

<Main functions and features>

[Configuration]

- Equipped with guide rollers and rotation preventing mechanisms on its outer surface
- Equipped with the anti-rotation stop on its inner surface
- EDPM rubber sealings are installed on the grooves on the end surface of the PCV guide and light guide tube.
- Mechanical sealings are installed on the other end of each guide tube and connected to the multi-use plate.

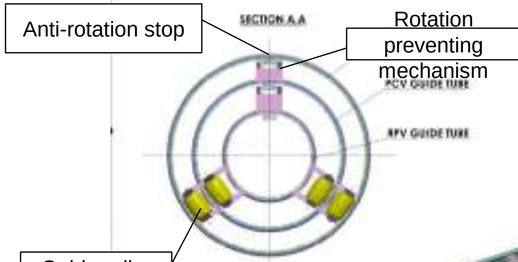
[Guiding function]

- The guide rollers keep the gap between two guide tubes constant, so that their exact concentric relationship is maintained while they are being moved. In addition, the anti-rotation stop and rotation preventing mechanisms (rotation prevention mechanism) suppress the rotational movement of the guide pipes.

[Double-sealing function]

- Pressing the end surface of the guide pipes against the PCV outer surface together with the EPDM sealings installed on it secures an airtight connection and protects the boundary.
- The gap between the light guide tube and multi-use plate and the gap between the guide tubes are sealed using mechanical seals.

Side view



Cross-sectional drawing

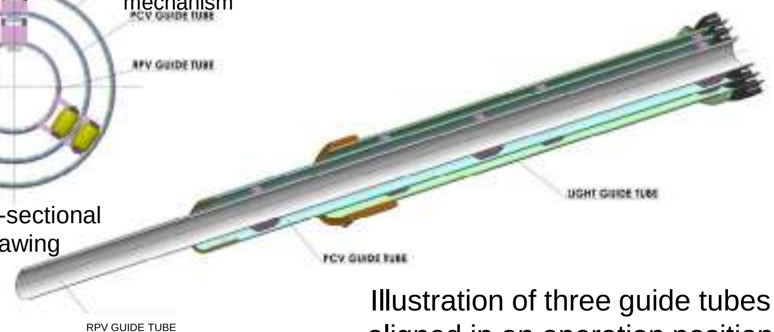
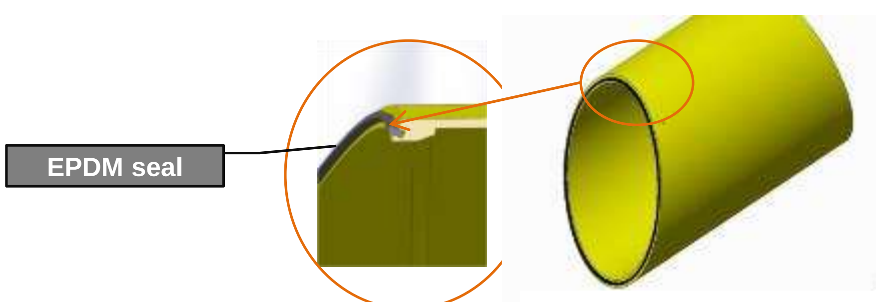


Illustration of three guide tubes aligned in an operation position

<Basic specifications>

Guide tube	Material	Outer diameter/thickness/length Unit: mm
Light guide tube	Stainless steel pipe	φ660.4/6.4t/6622L
PCV guide tube	Stainless steel pipe	φ457.2/6.4t/8741L
RPV guide tube	Stainless steel pipe	φ267.4/6.4t/11274L



PCV guide tube head

Example of mechanical seal

6.4.2.6 Side-opening investigation method: Specifications of equipment and devices No. 11: AWJ/WJ hybrid cutting tool head

<Outlines>
A penetrating head that combines a standard waterjet (WJ) mechanism and abrasive waterjet (AWJ) mechanism (hybrid configuration). It is used as the head of the processing apparatus to open holes in the structures between the biological shielding wall and PCV.

<Main functions and features>
[Configuration]
- WJ nozzle used to chip concrete layers.
- AWJ nozzle used to cut rebars and steel plates
- Cutting scrap suction port to vacuum and collect concrete and metal scraps
- Camera to monitor the condition of the holes during cutting (A microphone is embedded in the camera to check noises generated during the AWJ cutting work)
- A 3D scanner to detect the position of rebars

[Penetrating position guide]
- A 3,000-mm-long crawler is connected to the near end of the tool head rigidly, and guide rollers and rotation preventing mechanisms (rotation prevention mechanism) on the crawler come into contact with the inner surface of the light guide tube to maintain the tool head at the center of the light guide tube while the tool head advances.

[Concrete layer penetrating function]
- Chipping concrete layers with WJ. Two nozzles are installed on the WJ nozzle. They are laid out to point different directions both inclined outwardly as shown in the photo on the right so that the WJ head can bore a φ480-mm hole.

[Metal layer penetrating function]
- Penetrating steel frames and plates with AWJ to open a φ400-mm hole in them.

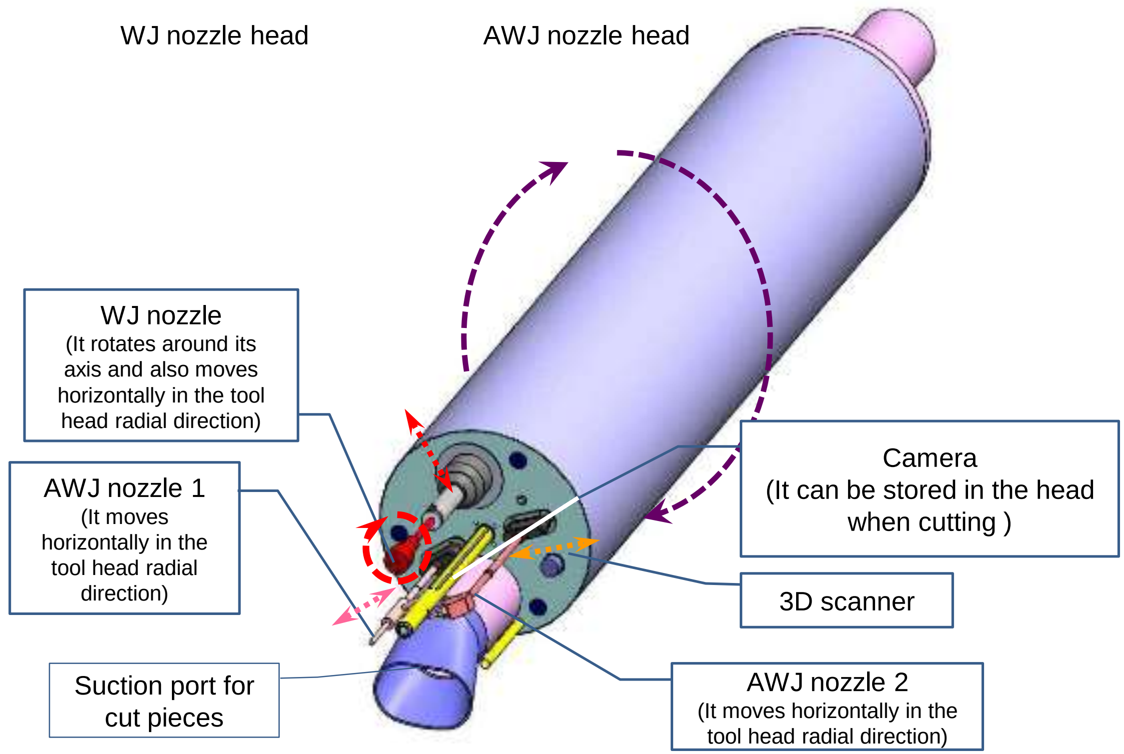
[Collection function]
- Collecting concrete and rebar scraps generated by the cutting work through the cutting scrap suction port

<Basic specifications>
[Entire machine]
- Main dimensions (approximate values): φ440 mm × L3000 mm

[Metal layer penetrating mechanism]
- Abrasive water jet with garnet abrasive


WJ nozzle head


AWJ nozzle head



6.4.2.6 Side-opening investigation method: Specifications of equipment and devices No. 12: Crawler

<Outlines>

The AWJ/WJ hybrid cutting tool head is connected to the crawler and moved forward and backward in the guide tube. Guide rollers and rotation preventing mechanisms are attached to the outer surface of the crawler 0. They come into contact with the inner surface of the guide tube, inside which the crawler is moved, and keep it at the center of the guide tube. In addition, the pipes to supply water and abrasive to the cutting tool head, pipes to collect and discharge wastewater, and cables for electric instruments are installed on the crawler.

<Main functions and features>

[Configuration]

- Crawler is equipped with guide rollers and rotation preventing mechanisms on its outer surface.

[Guiding function]

- The guide rollers keep the gap between two guide tubes or the gap between the guide tube and the crawler constant so that an exact concentric relationship of the two guide tubes is maintained while they are being moved. In addition, the rotation preventing mechanisms (rotation prevention mechanism) engage with the anti-rotation stop provided on the inner surface of the light guide tube to keep the tool head in the center of the light guide tube while it is being moved forward and backward.
- The crawler provides a passage for pipes and cables run from the tool box to the tool head to support its operation. It is constructed using a chain-drive mechanism, so that the pipes and cables can move smoothly in it when the tool head is moved forward and backward.

<Basic specifications>

Crawler	Tools to be connected	Material	Outer diameter/length Unit: mm
CR1	Cutting tool head H1 (biological shielding wall)	Stainless steel pipe	φ457/3650L
CR2	Cutting tool head H2 (PCV, reactor shield wall, insulator)	Stainless steel pipe	Φ355.6/3650L
CR3	Cutting tool head H3 (RPV, shroud head)	Stainless steel pipe	φ208/3190L
CR4	Investigation equipment	Stainless steel pipe	φ208/4600L

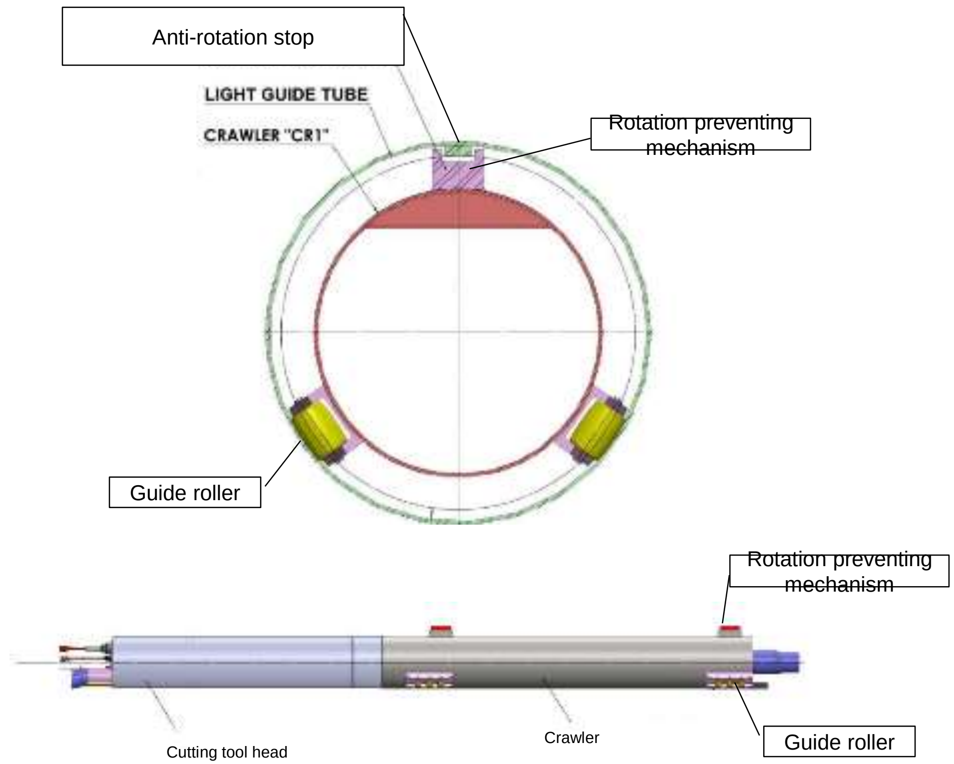
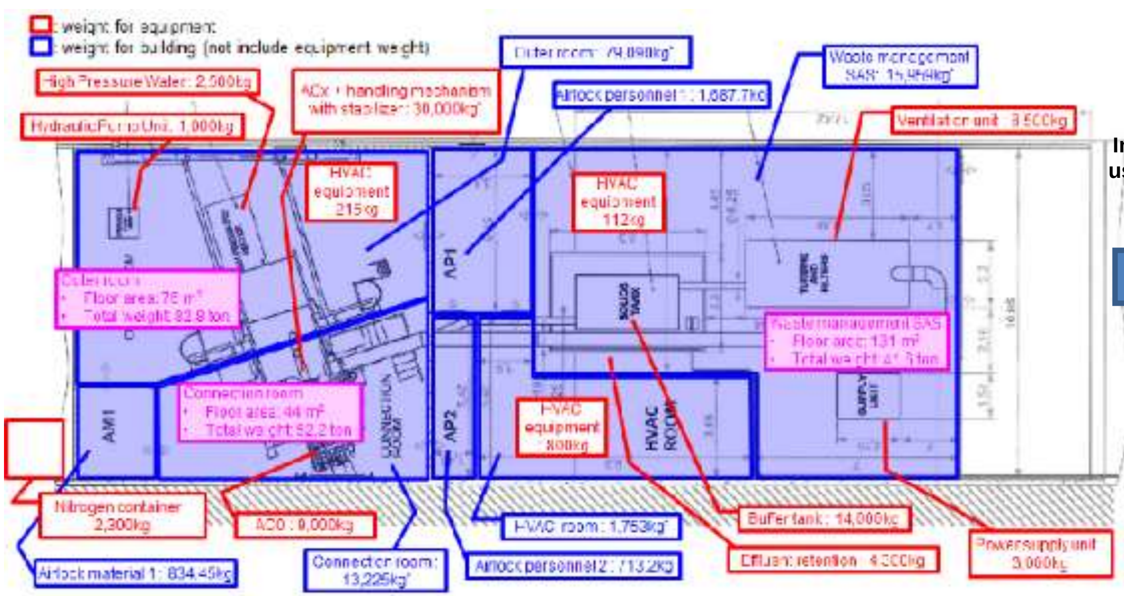


Illustration of the crawler connected to the cutting tool head

6.4.2.6 Side-opening investigation method: Layout design

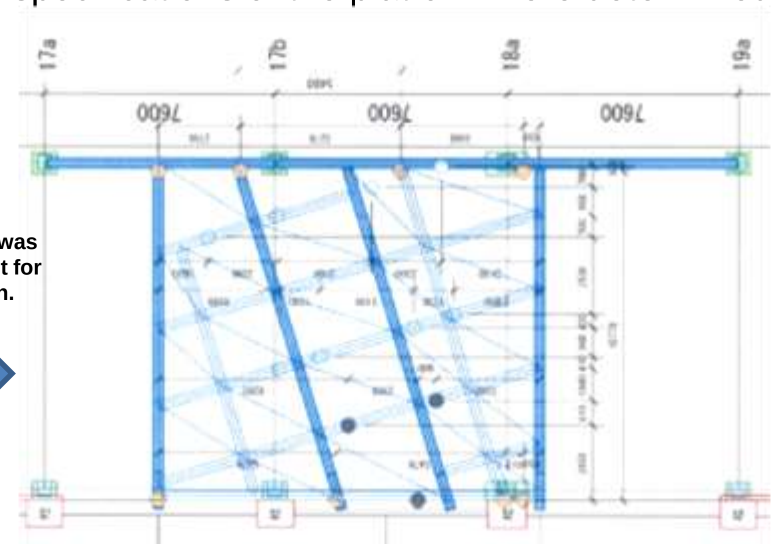
Platform for the entire work cell

- The total weight of the structures and equipment installed on the roof of the air-conditioning equipment room, including the entire work cell, was estimated to be about 140 t (80 t for those installed on the negative-pressure area). The concrete slab roof was not strong enough to bear the weight of all the structures and equipment alone. For this reason, a platform to hold the structures and equipment was designed based on the information on their weight and layout plan. A design plan to support the platform not only with the concrete slab roof (chiller mounting base) but also with the pillars of R/B on the east side and the side walls of the air-conditioning equipment room was adopted to distribute the weight load. Based on this plan, the specifications of the platform were determined.



Layout and approximate weight of the structures and equipment installed on the roof of the air-conditioning equipment room

Information was used as input for calculation.



Platform plan drawing
(Especially the platform in the negative-pressure area where the load is concentrated was designed according to the layout.)

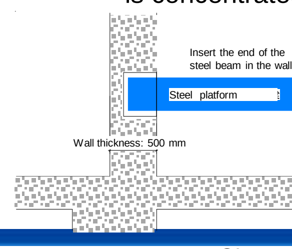
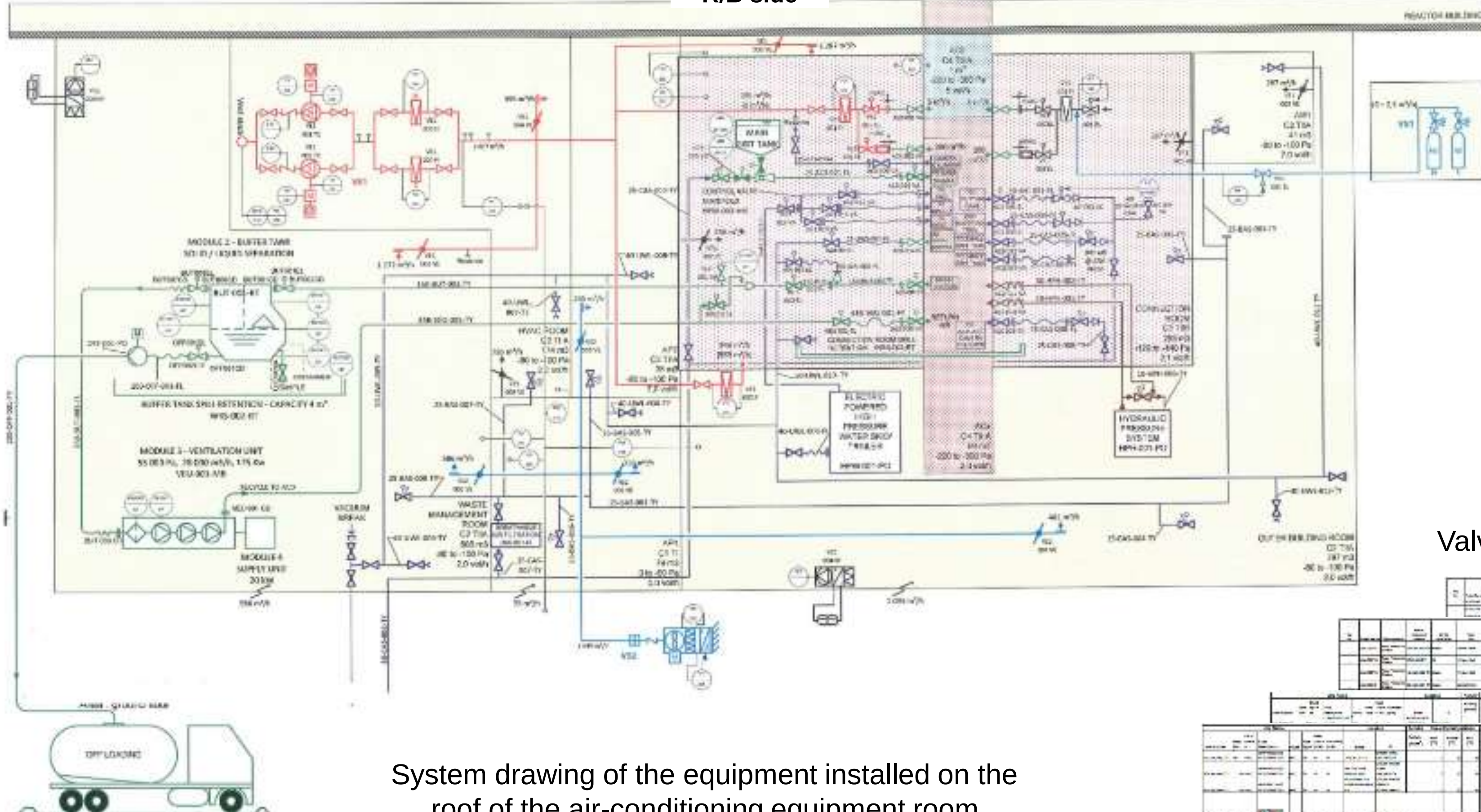


Illustration of the design to distribute the weight to the R/B pillars on the east side (Insert the end of the steel beam in the wall to hold it with the compression force of the concrete.)

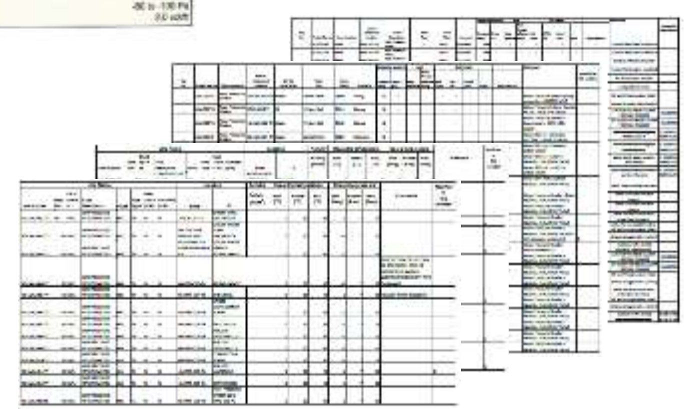
6.4.2.6 Side-opening investigation method: Overview of system configuration

A system to realize the negative-pressure control system described in the page above was designed; system diagram, piping list, and valve list were created; and information to grasp the scale of the facility was organized. Based on the results of these actions, the weight of the structures and equipment listed in the page above was estimated.



System drawing of the equipment installed on the roof of the air-conditioning equipment room
(ACx is docked with AC0)

Valve list, piping list, etc.



7. Summary

7.1 Investigation and development planning

The obtained information was similar to that from the needs research in FY2016. Schedule for investigation plan was updated, however there was no change that the data should be obtained as soon as possible. Investigation plans were updated in a step-by-step manner with the aim of reflecting them in ① the next step of the RPV inside investigation and ② the study of fuel debris retrieval methods. There was no change in the development plans.

7.2 Investigation method planning

Exposure assessment confirmed that there is no problem in the safety assessment. However, maintaining negative pressure inside the PCV will be necessary during investigation using the top-opening method as radioactivity concentration in the R/B would increase. As a result of the assessment, it was concluded that investigation of the side-opening method can be carried out in the condition of a slight positive pressure inside PCV.

7.3 Study on the investigation auxiliary system

Necessary ancillary systems were clarified and suggested as requirements based on the safety requirement list and exposure assessment result. Redundant designs were devised for radiation and dust monitoring systems as well as gas control systems in preparation for emergency.

7.4 Development of access and investigation equipment

As to element technologies required for each work step, verification tests were conducted to verify the feasibility of technologies, and the information and parameters necessary for a detailed design were obtained. In addition, the preliminary calculation of supply amount for utilities required each work step was estimated, and work steps and the specifications of the facility and equipment were determined based on the results of element tests.