# Subsidy Project of Decommissioning and Contaminated Water Management commenced in FY2021

# Development of Technology for Gradually Increasing the Scale of Fuel Debris Retrieval

## Final Report
## (Report Documents)

**October 2023**

**International Research Institute for Nuclear Decommissioning (IRID)**

# Table of Contents

# 1. Research Background and Purpose
# 1.1 Reasons why this research is necessary

- Information on fuel debris properties is needed for equipment development and criticality evaluation to retrieve fuel debris from Units 1 through 3 of the Fukushima Daiichi Nuclear Power Station. Until now, values estimated from the accident data or analysis results of TMI or Chernobyl accidents have been used. However, for appropriate development of the equipment, the on-site fuel debris needs to be retrieved and analyzed so as to verify whether or not the estimated values are valid (including whether or not the values are on the conservative side).

- Hence, in continuation from FY2021, in FY2022 as well, mainly the following work has been implemented.
  - Creation and update of the development plan of retrieval technology for gradually increasing the scale of fuel debris retrieval, and the retrieval plan.
  - Detailed designing, prototype manufacturing, and various verification tests of the devices and systems for fuel debris retrieval
  - Development of equipment for fuel debris retrieval and combination tests (Test on passage of the arm for retrieval through the X-6 penetration)

- Based on the outcomes of the above-mentioned work, newly found challenges and the recent circumstances at the Fukushima Daiichi Nuclear Power Station, retrieval technology for gradually increasing the scale of fuel debris retrieval needs to be developed while reviewing the positioning or objectives of fuel debris retrieval, which is being implemented through this research.

# 1.2 Reflection of results and contribution thereof



**Project for Development of Technology for detailed Investigation inside PCV*1**
(Development of technology for detailed investigation inside PCV)

**Results of the investigation inside PCV*1 will be reflected.**

**Project for Development of Technology for Detailed Investigation inside PCV*1**
(On-site demonstration for detailed investigation inside PCV through X-6 penetration)

**The development progress of investigation equipment will be reflected.**

***1: PCV = Primary Containment Vessel**

Project for "Development of Technology for Gradually Increasing the Scale of Fuel Debris Retrieval" (This project)

Creation of the retrieval technology development plan for gradually increasing the scale of fuel debris retrieval, and the retrieval plan

Development of equipment and systems for gradually increasing the scale of fuel debris retrieval

Gradually increasing the retrieval scale of fuel debris and analysis

**Physical property data such as hardness, etc., cutting speed, status of dust scattering**

**Component data such as U, Pu, Gd, etc.**

**Fuel debris distribution data**

**Component data such as amount of hydrogen generated, etc.**

**Waste inventory data**

**Project for Development of Technology for Further Increasing the Scale of Retrieval of Fuel Debris and Reactor Internals (including criticality control)**

Upgrading of approach and systems for retrieval of fuel debris and internal structures,
Upgrading of fundamental technology for retrieval of fuel debris and internal structures,
Upgrading of criticality control technology for fuel debris

- **Reflection into the system design of the retrieval cell**
- **Designing and improvement of fuel debris retrieval tools**
- **Validity check of criticality evaluation**

**Project for Development of Analysis and Estimation Technology for Fuel Debris Characterization**

Advancement of understanding of the in-core conditions through accident progression analysis and actual equipment data, etc.

**Verification of the reliability of the in-core analysis results**

**Project for Development of Technology for Containing, Transfer and Storage of Fuel Debris**

Development of technology for collection, transfer and storage of fuel debris

**Verification of canister safety**

**Project for R&D for Treatment and Disposal of Solid Waste**

Research and development for treatment and disposal of solid waste

**Reflection in the overall plan for waste**

Research projects concerning detailed designing of the fuel debris retrieval methods and equipment, etc.

**Gradually Increasing the Scale of Fuel Debris Retrieval**
(Planned to be implemented at TEPCO HD)

Detailed designing of equipment for gradually increasing the scale of fuel debris retrieval

# 2. Project Goals

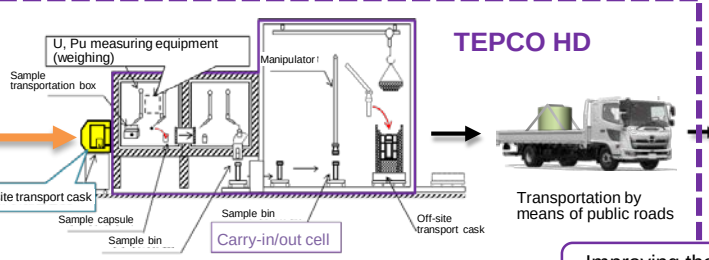


| Project details | Target Technology Readiness Level (TRL) at the end of the research |
|---|---|
| **Update of the retrieval technology development plan** | The retrieval technology (equipment, systems, etc. for retrieval) development plan for gradually increasing the scale of fuel debris retrieval, designed as part of preceding projects (projects commenced in FY2019), based on the information obtained from investigation, etc. inside Unit 2 PCV, is updated as necessary, and the improvement and verification items expected from development carried out in the next phase, and their background are clearly specified.<br>Besides, latest findings, etc. are reflected and updated as needed into the scenarios related to gradually increasing the scale of fuel debris retrieval.<br><br>(This is not included in setting the Technology Readiness Level (TRL) to organize information.) |
| **Development of the retrieval equipment and combination tests** | Development of the access equipment for retrieval (arm and enclosure, etc.)<br>Manufacturing know-how is accumulated by manufacturing the access equipment for retrieval (arm and enclosure) based on detailed designing of the access equipment for retrieval (arm and enclosure, etc.) carried out during preceding projects (projects commenced in FY2020), and the manufactured prototype demonstrates the required functions and properties through in-factory verification tests, etc.<br>(Target TRL at completion: Level 5) |
| | Combination tests of the access equipment for retrieval with the entire system<br>The manufactured access equipment for retrieval (arm and enclosure) and the equipment developed until FY2021 during the preceding projects (projects commenced in FY2019) are combined, and it is ensured that matters of concern or mutual mechanical and electrical impact, etc. in interfaces where verification is difficult through in-factory verification tests of the stand-alone equipment, do not hinder their required functions and properties as a system, or their impact and resulting technical issues are ascertained.<br>(Target TRL at completion: Level 5) |

# 3. Implementation Items, their Correlation and Relations with Other Research



TEPCO HD




Transportation by means of public roads

Fuel Debris Characterization PJ

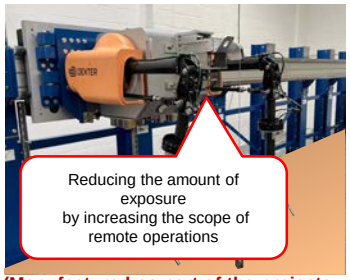
Existing analysis facility

*The carry-in/out cell and the scope of cell work needs to be coordinated with TEPCO

Improving the environment in which manipulator is operated

Fuel debris collection scenario

Dual arm type manipulator

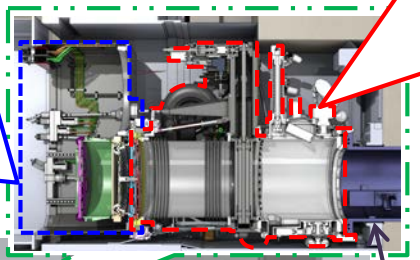


Reducing the amount of exposure by increasing the scope of remote operations

(Manufactured as part of the projects commenced in FY2019)

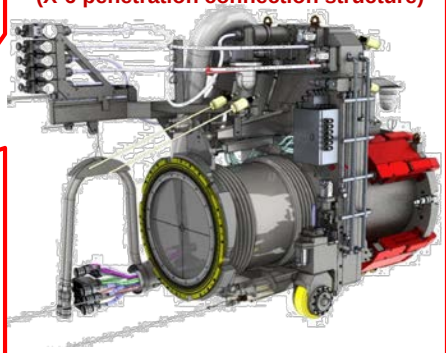
Double door mechanism (Developed as part of the projects commenced in FY2020)

Avoiding exposure of contaminated surfaces while equipment are being removed, by developing a double door with a large diameter



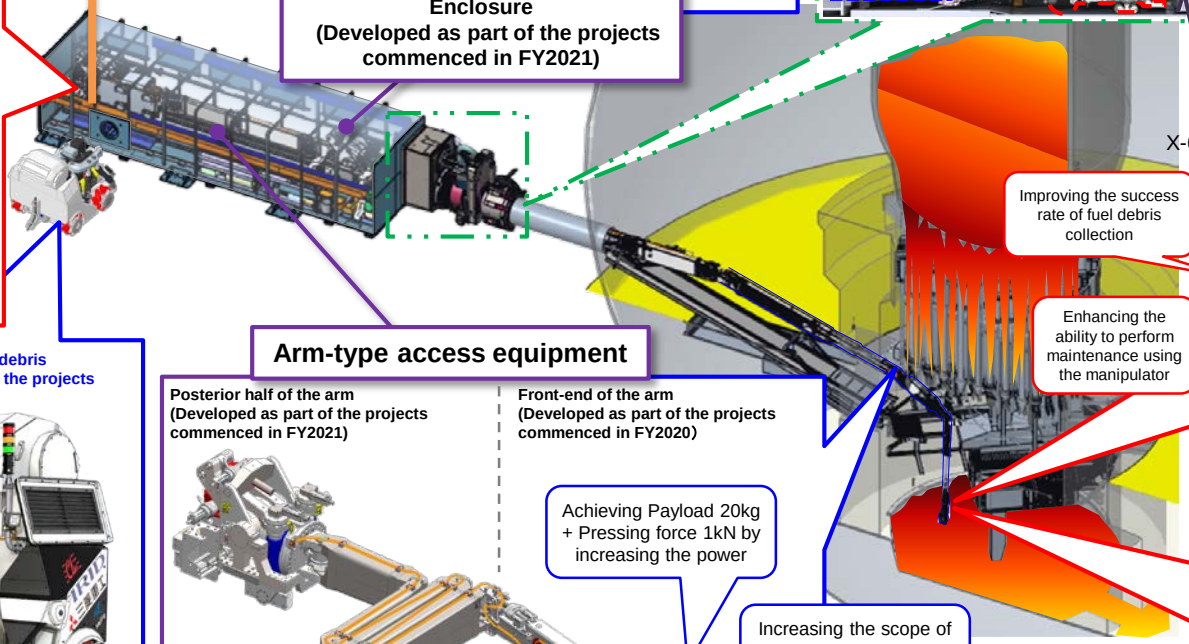
Reducing the time required for work involving exposure by reducing the total length and enhancing remote operability

Equipment for constructing access route (X-6 penetration connection structure)



(Manufactured as part of the projects commenced in FY2019)

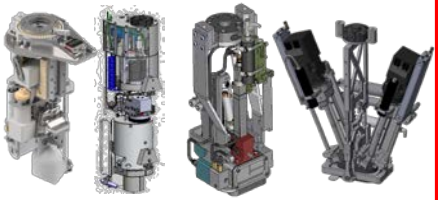
Enclosure (Developed as part of the projects commenced in FY2021)



X-6 penetration

Improving the success rate of fuel debris collection

Fuel debris cutting and collection equipment



Enhancing the ability to perform maintenance using the manipulator

(Manufactured as part of the projects commenced in FY2019)

Arm-type access equipment

Posterior half of the arm (Developed as part of the projects commenced in FY2021)

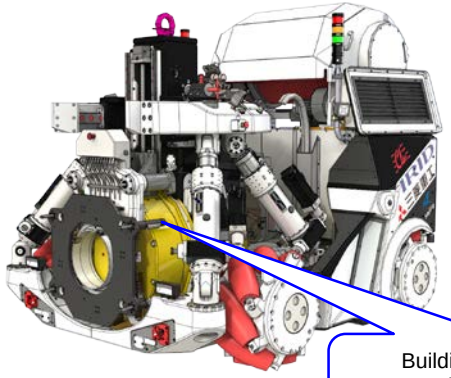
Front-end of the arm (Developed as part of the projects commenced in FY2020)



Achieving Payload 20kg + Pressing force 1kN by increasing the power

Increasing the scope of access by means of the horizontal offset link

Remotely controlled transport cart for fuel debris canisters (PADIRAC) (Developed as part of the projects commenced in FY2020)

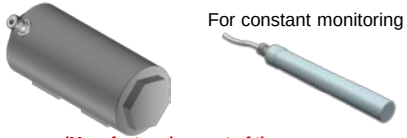


Building a safe fuel debris transportation system through remote transportation of the 4 ton PADIRAC

Neutron monitor (for monitoring approach to criticality, etc.)

For predictive monitoring

For constant monitoring



Verifying downsizing, reducing the weight and the new technology

(Manufactured as part of the projects commenced in FY2019)

3. Implementation Items, their Correlation and Relations with Other Research

## 3.1. Implementation items of this research

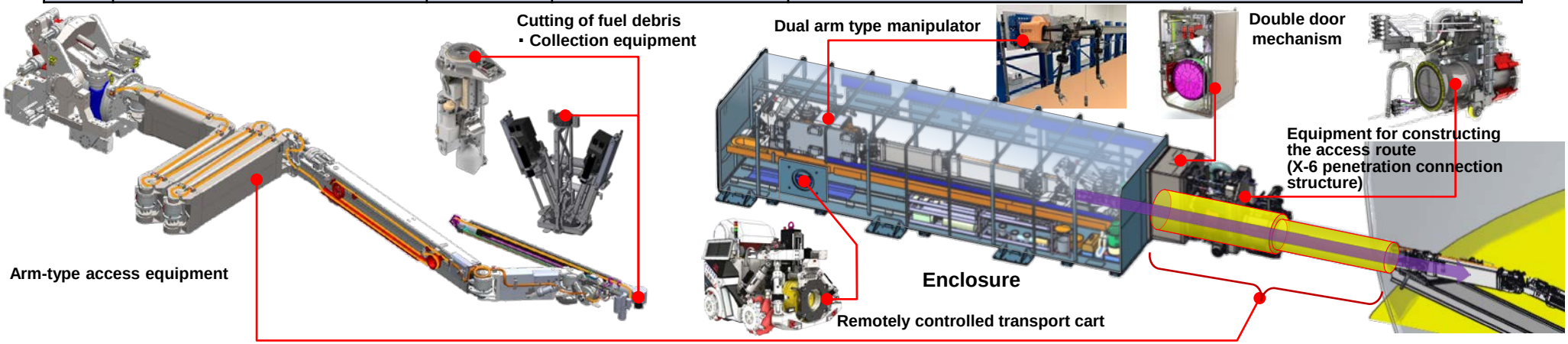
| Implementation items | | Scope of implementation in FY2022 + FY2023 | Page |
|---|---|---|---|
| Update of the retrieval technology development plan | | • Updating the development plan at the time of commencement in FY2021 (examination of the timing of reflecting the results of the verification tests of the arm for detailed investigation inside PCV and the points to be focused on during the reflection, and examination of the contents of the combination tests conducted by combining various developed equipment)<br>• Reflecting technical issues identified during the combination tests implemented in FY2022 into the development plan for the next phase. | 11-16 |
| Development of the retrieval equipment and combination tests | Development of the access equipment for retrieval (arm and enclosure, etc.) | • Designing and manufacturing of the posterior half of the arm and integrating it with the front-end of the arm.<br>• Designing and manufacturing of the enclosure | 17-21 |
| | Combination tests of the access equipment for retrieval with the entire system | • Study of the combination test plan<br>• Combination tests<br>✓ Combination test of the front-end of the arm and the tip tools<br>✓ Combination tests related to the enclosure<br>✓ Combination test of the entire arm | 22-30 |

Black: Desk study  Red: Manufacturing  Blue: Testing

# 3. Implementation Items, their Correlation and Relations with Other Research

## 3.2 Correlation between implementation items and with other research (1/2)

| Implementation items | | Related items | Details of collaboration | Relationship |
|---|---|---|---|---|
| A<br>Update of the retrieval technology development plan | | B<br>(Input) | Reflection of technological challenges in the development plan | The plan is updated with the new technological challenges that became evident through the in-factory verification test of the prototype, as part of this project. |
| | | C<br>(Input) | Same as above | The plan is updated in response to the new technical issues related to coordination between systems that became evident through the combination tests as part of this project. |
| Development of the retrieval equipment and combination tests | B<br>Development of the access equipment for retrieval (arm and enclosure, etc.) | C<br>(Output) | Setting up of an interface keeping combination tests in mind<br>(Refer to the figure below) | The interface is appropriately set considering the system as a whole, and is reflected while designing and manufacturing the equipment. |
| | C<br>Combination tests of the access equipment for retrieval with the entire system | B<br>(Input) | Delivery of the access equipment for retrieval (arm and enclosure, etc.) | The equipment is received at an appropriate time, and the test procedures and test facility are arranged for considering the method of handling the equipment. |



# 3. Implementation Items, their Correlation and Relations with Other Research

## 3.2 Correlation between implementation items and with other research (2/2)

**Work flow for fuel debris retrieval from inside PCV**

Equipment related to fuel debris retrieval from inside PCV

Enclosure

Double door mechanism

Dual arm type manipulator

Equipment for constructing the access route

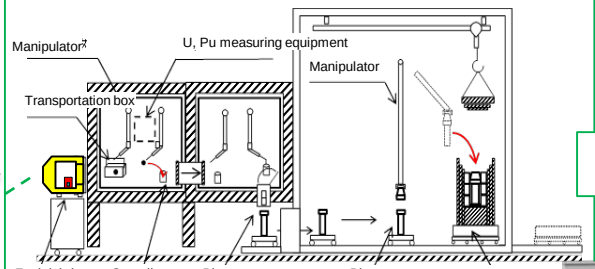
Fuel debris collection equipment

Arm-type access equipment

Neutron monitor

Remotely controlled transport cart

Equipment related to the carry-in/out cell




Existing analysis facility

Off-site transportation

Project for Development of Technology for Gradually Increasing the Scale of Fuel Debris Retrieval

TEPCO HD

Fuel Debris Characterization PJ

**Main connections with related PJs**

[PCV Detailed Internal Investigation PJ] **(Input)**
・Reflection of the image of the condition inside PCV into the design
・Sharing of information on development of the arm for investigating inside PCV
・Sharing of development challenges pertaining to the detailed investigation inside PCV

[PCV Detailed Internal Investigation PJ] **(Input)**
・Sharing of information on development of enclosure for investigating inside PCV
・ Sharing of remote operation procedures to be followed during the investigation inside PCV
[TEPCO HD]
・ Reflection of related technologies into fuel debris retrieval, the scale of which is gradually increased

[Fuel Debris Characterization PJ] **(Input)**
・Fuel debris acceptance interface coordination
[Fuel Debris Retrieval PJ]
・ Fuel debris sampling requirements
・Fuel debris cutting technology related information sharing
・Criticality prevention measures at the time of fuel debris cutting

[TEPCO HD] **(Input)**
・ Coordination of the maintenance area in the Reactor Building

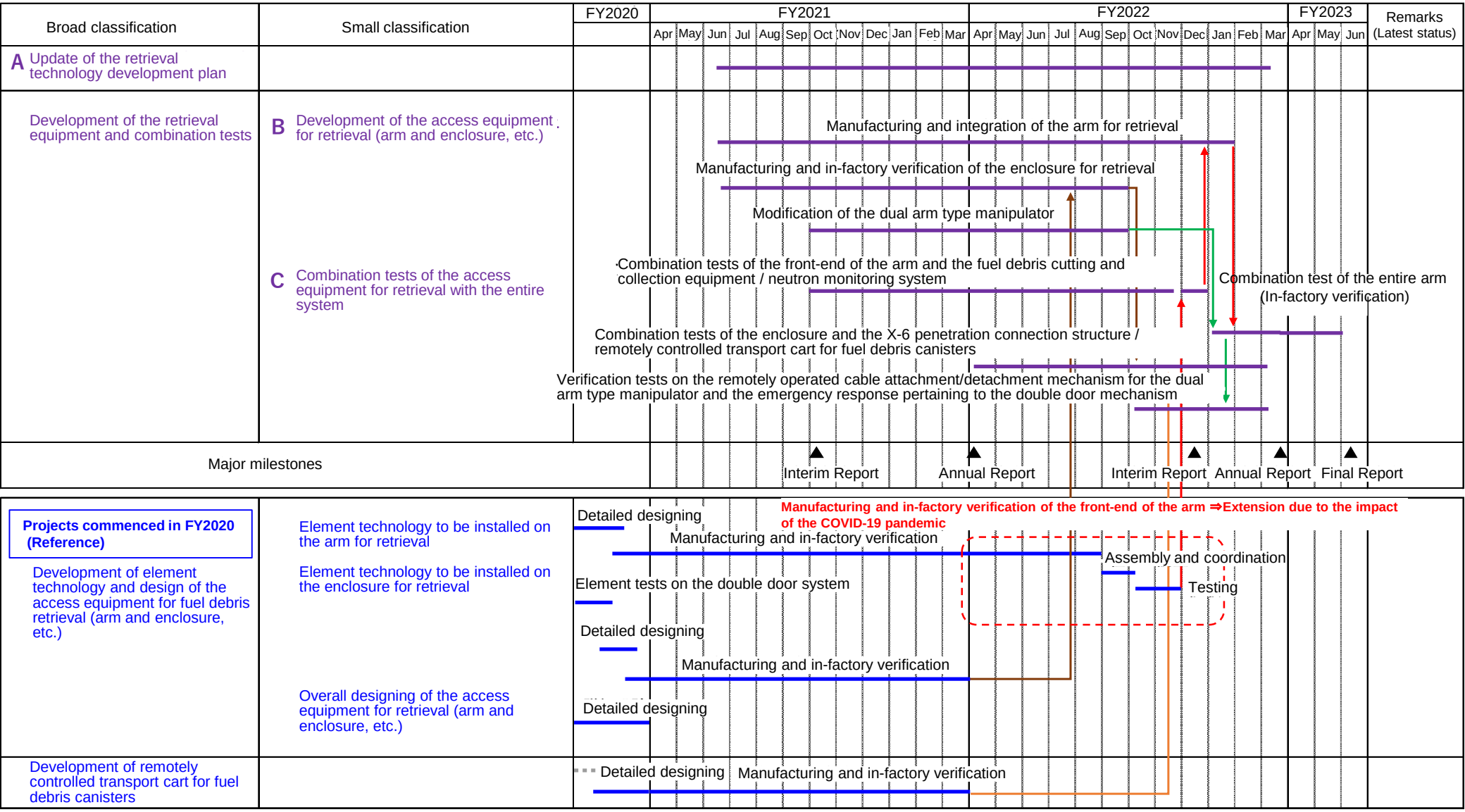
[TEPCO HD] **(Input)**
・Sharing of information on fuel debris canister (PADIRAC)
・Coordination with the transfer area in the Reactor Building
・ Reflection of needs pertaining to technologies to be utilized for fuel debris retrieval, the scale of which is gradually increased

Fuel debris retrieval plan

[Fuel Debris Characterization PJ] **(Input)**
・ Questioning about analytical capabilities of the existing analysis facilities and its reflection in the fuel debris retrieval plan
[TEPCO HD]
・ Discussion on fuel debris transfer route and its reflection in the fuel debris retrieval plan

# 4. Implementation Schedule






**Since the process of manufacturing and in-factory verification of the front-end of the arm got prolonged, the front-end of the arm was handed over to this project at the end of November 2022, and the combination tests of the entire arm (in-factory verification) were completed in May.**

# 5. Project Organization Chart



**Tokyo Electric Power Company Holdings, Inc.**

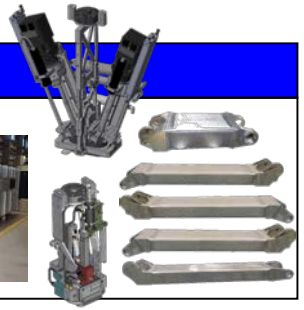
○ Various coordination for site application

**International Research Institute for Nuclear Decommissioning (Headquarters)**

○ Coordination of overall planning and technology management
○ Coordination of technology administration including technology development progress management

**Mitsubishi Heavy Industries, Ltd.**

Update of the retrieval technology development plan
Development of the retrieval equipment and combination tests
- Development of the access equipment for retrieval (arm and enclosure, etc.)
- Combination tests of the access equipment for retrieval with the entire system
- Development of equipment for collecting cutting swarf and cylindrical debris

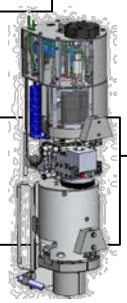


Project teams to cooperate for technological development

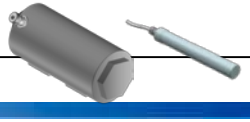
- Development of technology for detailed Investigation inside PCV (On-site demonstration for detailed investigation inside PCV through X-6 penetration)
- Development of technology for further Increasing the scale of retrieval of fuel debris and reactor internals
- Development of technology for containing, transfer and storage of fuel debris
- Research and development for treatment and disposal of solid waste
- Development of analysis and estimation technology for fuel debris characterization

**Jacobs**:
- Preparation for the combination tests on pebble-shaped and sandy debris collection equipment (bucket type)
- Combination tests of the front-end of the arm and the tip tools

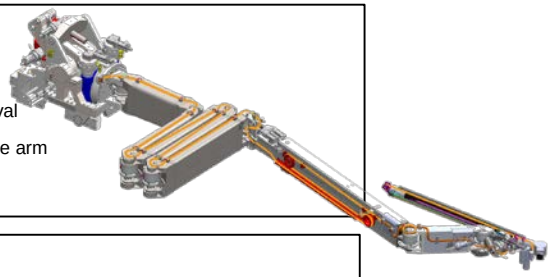
**ORANO**:
- Preparation for the combination tests on pebble-shaped and sandy debris collection equipment (flexible gripper type)



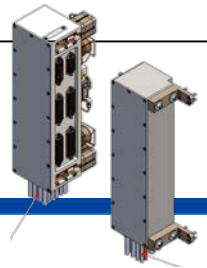
**Innovative Physics Limited**:
- Preparation and assistance for the combination tests on neutron monitors



**VEOLIA NUCLEAR SOLUTIONS**:
- Test manufacturing of access equipment for retrieval
- Combination tests on the access equipment for retrieval
- Assistance for combination tests of the front-end of the arm and the tip tools



**Sojitz Machinery Corporation CLEO:**
- Test manufacturing of the remotely operated cable attachment/ detachment mechanism for the dual arm type manipulator
- Preparation and assistance for the combination tests on the double door mechanism
- Preparation and assistance for the combination tests on remotely controlled transport cart for fuel debris canisters



# 6. Implementation Details

## 6.1 Update of the retrieval technology development plan

**[Achievements for FY2022 1/5)**

✓ **Based on the information obtained from the manufacturing tests and combination tests of the access equipment carried out during the Project for Development of Technology for Detailed Investigation inside PCV, the time period of reflection into the development plan of this project, the reflection items and specific details were updated. [Achieved]**

| Information planned to be acquired | Time period of acquisition Time period of reflection | Items to be reflected in the development | Specific implementation details and implementation method | Status of reflection |
|---|---|---|---|---|
| Operating speed of the arm for investigation inside PCV | September 2022 | Review of the expected performance of the arm for retrieval, study on the possibility of improving speed, study on the possibility of changing the operating method | As a result of reviewing the expected performance of the telescopic arm considering the disparities in the weight, gear ratio and motor torque of the arm for retrieval, it was determined that there are prospects of achieving the target speed.<br>A high-torque motor with specifications identical to that used for the arm for retrieval was used for the arm for investigating the PCV as well, and the speed was improved by modifying the control method. | The target telescopic arm extension speed was achieved by collecting data pertaining to motor properties and modifying the control method.<br>The forward and reverse speed of the carriage is planned to be improved by adopting a similar approach. |
| Attenuation properties of the arm for investigation inside PCV | November 2021 to November 2022 | Review of the expected behavior of the arm for retrieval, study on the possibility of reducing vibrations, study on the possibility of changing the operating method | The expected behavior in terms of the vibrations is reviewed considering the disparities in the length and weight of the arm for retrieval.<br>If the expected vibrations of the arm have a negative impact on the ease of passing through the X-6 penetration or the platform opening, or if the vibrational amplitude when the tip tool approaches fuel debris exceeds 100mm, the possibility of reducing vibrations by means of low speed operation is studied.<br>If it is evaluated that there isn't sufficient room for reducing vibrations, the possibility of controlling vibrations by reviewing the operating procedures, is studied. | Was 4% or more horizontally. Was less than 1% vertically. However, as stabilization of the vibrations required time, it is determined that the arm needs to come to a resting position inside the pedestal.<br>The acquired data will be utilized in the future for mechanism analysis. |
| Workability of removing the external cable using the dual arm type manipulator | November 2022 | Review of the cable fixing structure or the cable drum structure of the arm for retrieval, study on the necessity of special tools for the installation work, study on the possibility of improvement in the external cable | The cable fixing structure or the cable drum structure was reviewed for improving the workability of remote operation by means of the dual arm type manipulator, and an electric cable winding equipment was developed. | The workability of remote operations improved due to electric cable winding.<br>The procedure for winding the cable by efficiently using the space inside the enclosure will be reflected. |
| Improvement of the external cable cutter | January 2023 | Review of the external cable cutting mechanism and the margin for improvement in the external cable | Since the Kevlar fiber, which is a reinforcement member of the external cable, hinders the emergency response function of the cutting mechanism, the cutter blade was modified.<br>The cable cutting function of 3 types of blades test manufactured for the arm for PCV investigation was compared, and the specifications of the blade that did not leave a stub behind were selected. | The specifications and method of operation of the cutter blade selected for the arm for PCV investigation will be reflected. |

# 6. Implementation Details

## 6.1 Update of the retrieval technology development plan

**[Achievements for FY2022 2/5)**

- ✓ **The positioning, verification items and goals to be achieved as indicated in the chart below, pertaining to the combination tests implemented during this project were crystallized, and in addition, the status of achievement after the tests was evaluated. [Achieved]**
- ✓ **New technological challenges were identified, and the development plan was updated. [Achieved]**

| Combination test items | Positioning | Items to be verified | Goals to be achieved | Achievement status |
|---|---|---|---|---|
| ① Combination tests of the front-end of the arm and the fuel debris cutting and collection equipment | The method and procedure for operating inside the pedestal to bring the fuel debris collection and cutting equipment and the neutron monitor in close proximity to the target location in the designated position, is verified.<br>Until now, the study was conducted using VR simulation, but verification is required considering the vibrations arising from acceleration/deceleration and rigidity of the arm. | Vibrational amplitude of the arm and deceleration time<br>Visibility of the camera installed on the fuel debris collection equipment<br>Operability of the wand<br>Method of getting closer to the target location in the designated position | Vibrational amplitude: 100mm or less<br>Deceleration time: less than 5 minutes<br>The camera image recording must prove beneficial for arm operation.<br>There must not be any steps wherein it is difficult to operate the arm.<br>Must be able to get closer to the target location in the designated position. | The vibrational amplitude was small enough and had almost no impact on the fuel debris collection work.<br>For the above reason, deceleration time did not cause any issues.<br>It was difficult to detect whether or not the camera on the equipment for collecting cutting swarf and cylindrical debris was seated, however, it was determined that this can be resolved by adding a load monitor.<br>The equipment was able to get closer to the target location in the designated position without hindering arm operation, and was able to collect the fuel debris. |
| ② Combination tests of the arm and the simulated X-6 penetration | The ability of the arm for retrieval to pass through the X-6 penetration is verified by spreading out the boom link and forward movement of the carriage.<br>The vibrating properties are verified by operating the front-end arm beyond the telescopic arm while the boom link is spread out. | Verification of the ability of passing through X-6 penetration<br>Measurement of the deflection of the arm<br>Vibration properties of the telescopic arm by operating the wand while the arm is extended | Must be able to pass while maintaining a clearance of 10mm or more. (including vibrations)<br>Arm deflection must be equivalent to or under the value assumed in the design.<br>Amplitude must be within 30mm. | .<br>The test contents and criteria were crystallized.<br>The in-factory verification test was conducted in April 2023, and it was verified that the arm can pass through the X-6 penetration while leaving a gap of approx. 9mm on each side, by developing a control system in accordance with the deflection characteristics of the arm, by adjusting the zero point using the rail as reference, and by using chaining when there are multiple axles. |

**Table continued on the next slide**

## 6.1 Update of the retrieval technology development plan

### [Achievements for FY2022 3/5)

Table continued from the previous slide

| Combination test items | Positioning | Items to be verified | Goals to be achieved | Achievement status |
|---|---|---|---|---|
| ③ Combination tests of the enclosure (double door mechanism) and X-6 penetration connection structure | It is verified that docking of the double door mechanism and the X-6 penetration connection structure can be performed as per the design, while installing the enclosure on site. Emergency drive by remote operation and layout of the camera are verified, particularly since workers are unable to access the narrow space inside the sealed door where the double door connection is performed. | Whether or not docking of the double door mechanism and the X-6 penetration connection structure can be performed, and the relevant procedures<br>Sealing efficiency of the connector<br>Efficacy of the emergency drive<br>Visibility of the camera | Docking of the double door mechanism and the X-6 penetration connection structure must be performed remotely and accurately and the connector must be properly sealed.<br>Emergency drive by remote operation must be possible using the manipulator.<br>It must be possible to monitor the status with the help of a camera with sufficient field of vision. | It was verified that docking of the double door mechanism and the X-6 penetration connection structure can be performed accurately in line with the on-site installation work. It was verified that docking by remote operation can be efficiently monitored with the camera, and the efficacy of the emergency separation work anticipating a breakdown of the motor during removal work was verified as well. |
| ④ Combination tests of the enclosure and the remotely controlled transport cart | Work of docking the fuel debris canister (PADIRAC) in the enclosure is verified, and the rescue method in the event of an accident is verified. | Whether or not docking of the fuel debris canisters can be performed, and the relevant procedures<br>Efficacy of the rescue method in the event of an accident | It must be possible to perform docking of the fuel debris canisters according to the procedures.<br>It must be possible to perform the emergency rescue operation in accordance with the procedures. | The PADIRAC was docked into the enclosure and it was verified that there were no issues in the surrounding area. Issues were identified during maintenance verification and rescue verification. |
| ⑤ Combination tests of the dual arm type manipulator and the double door mechanism | A double door mechanism equipped with a rescue interface is placed in the enclosure that is test manufactured, and it is verified that the operation of restoring the double door mechanism using the dual arm type manipulator and special auxiliary tools can be performed. | Efficacy of the rescue interface<br>Efficacy of the special auxiliary tools of the dual arm type manipulator | It must be possible to perform the operation of restoring the double door mechanism using the dual arm type manipulator and the special auxiliary tools. | The verification was carried out using alternative means as the import of the dual arm type manipulator got postponed. The operation of manually restoring the double door mechanism using the special auxiliary tools was verified. It was verified that this operation is possible using the alternative manipulator. |
| ⑥ Combination tests of the dual arm type manipulator and the remotely operated cable attachment/detachment mechanism | The operation of the cable attachment/detachment mechanism of the dual arm type manipulator is verified inside the test manufactured enclosure. Test is conducted with the dual arm type manipulator, its dedicated cart and its rail combined. | Operation of the cable attachment/detachment mechanism in loaded condition | The cable attachment/detachment mechanism must be able to perform the attachment/detachment operation while the dual arm type manipulator is loaded. | It was possible to perform the attachment/detachment operation as per the design although it was important to align the dual arm type manipulator rail and dedicated cart inside the enclosure. |

# 6. Implementation Details

## 6.1 Update of the retrieval technology development plan

**[Achievements for FY2022 4/5)**

✓ **The measures in response to the technical issues identified during the in-factory verification test of the front-end of the arm were reflected into the development plan. [Achieved]**

| Classification | Issues | Response measures added |
|---|---|---|
| This equipment | Improving the extension speed of the telescopic arm to 2mm/s or more | The voltage-torque correlation data of the motor should be acquired, and the system should be changed to a feedforward control system. |
| | Preventing the wrist camera from coming in contact with the platform | It is expected that contact can be avoided by changing to a Mirion radiation tolerant camera. This should be verified separately using a simulated pedestal. |
| | Improving the speed of unfolding of the boom link to 0.56deg/s or more. | The unfolding speed should be enhanced by revising the safety limit. It should be ensured that the effect that the increase in speed has on the vibrational amplitude of the arm tip does not cause any issues in its ability to pass through the X-6 penetration. |
| | Slimming down the protrusion to improve the ability to pass through the X-6 penetration | The shape of the protrusions such as the main body of the wrist camera, the wrist camera bracket, cable holder, etc. should be reviewed. Also, ensuring the workability of carrying out maintenance using the the dual arm type manipulator should be considered. |
| Connections with other equipment | Preventing the external cable from sagging | The sliding of the cart of the movable pulley and the cable cladding should be improved. |
| | Eliminating the stub left behind by the external cable cutting mechanism | An external cable without Kevlar fiber should be manufactured, or the blade of the external cable cutting mechanism should be improved. The improved blade results of the Project for Detailed Investigation inside PCV should be followed. |
| | Mitigating the impact while positioning the tip tool | The control panel should be adjusted to further reduce the lowest wand unfolding speed. |
| | Lowering the wand from the slit opening | The length of the wand should be reduced to about 315mm. |
| On-site application | Specifying the factors causing load fluctuation while positioning the foot | Data should be acquired during the mock-up verification considering the rigidity of the platform as the parameter. |
| | Specifying the factors causing fluctuations in pressing force of the tip tool | Whether fluctuations are due to the structure of the arm or due to the rigidity on the side of the platform should be specified by conducting tests or performing analysis. |
| | Ascertaining the temporal change in long-term control accuracy | The change in positioning accuracy due to long-term operation should be ascertained by repeating the action multiple times. Mock-up verification should be carried out. |
| | Ascertaining the pressing behavior of the tip tool without positioning the foot | The correlation of the lateral motion of the foot when the tip tool is pressed, with the seating load should be ascertained. |
| | Automatic control of the arm | The function that enables simultaneous operation of multiple axles and performing multiple steps in a row, should be added. |

**Table continued on the next slide**

# 6. Implementation Details



## 6.1 Update of the retrieval technology development plan

### [Achievements for FY2022 5/5)

**Table continued from the previous slide**

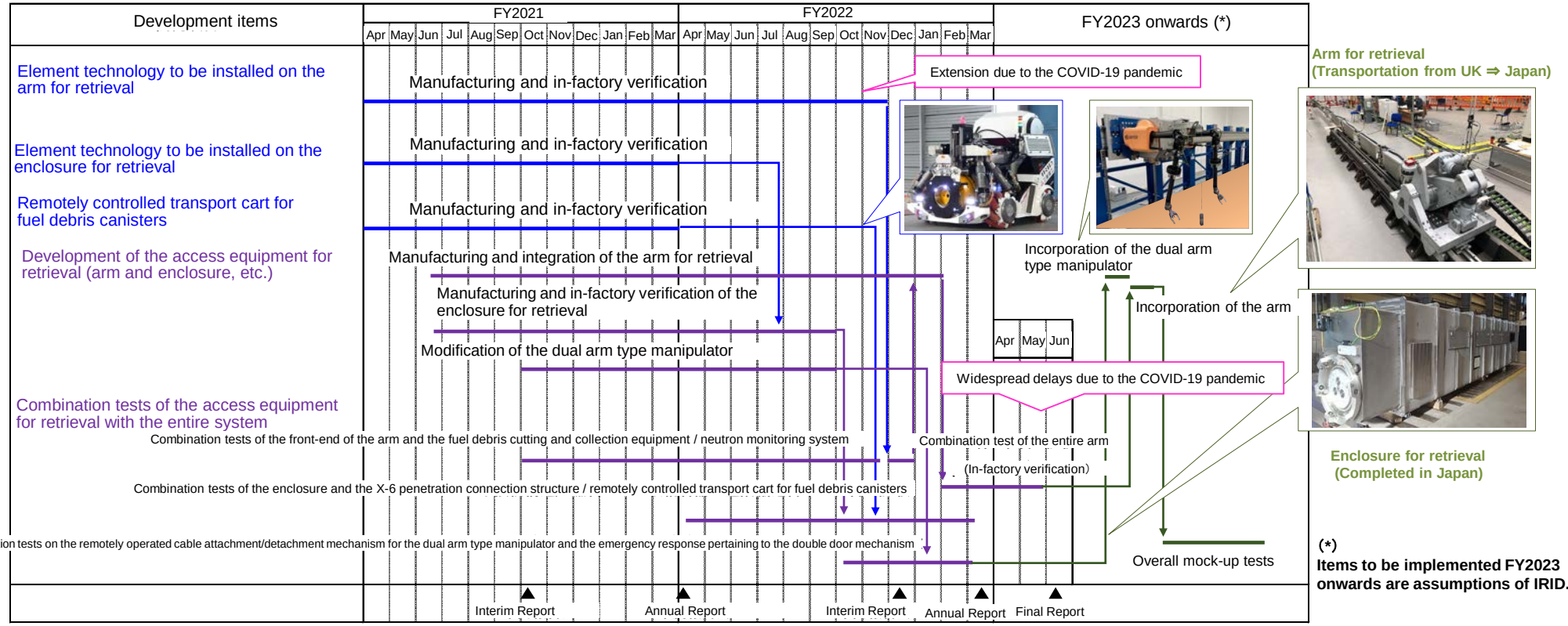
| Classification | Issues | Response measures added |
|---|---|---|
| Arm | Reducing the wand unfolding speed | The lowest speed should be lowered further so that the pressing force (approx. 50N) of the cutting swarf fuel debris collection equipment can be easily adjusted. |
| | Modifying the external cable | The neutron monitor control signal cable should be changed to a thicker cable to prevent generation of noise. |
| Double door mechanism | Verifying long-term impact on the environment | Since the double door mechanism requires highly precise control, decrease in reliability due to long-term impact under the site environment should be studied. |
| | Adding interlocks for enhanced safety | Interlocks should be added for protecting the workers and the double door mechanism during manual operations such as maintenance work or while taking actions in response to failures, etc. |
| | Enhancing the reliability of the system | Since there have been several instances of automatic shutdown as a result of detecting an abnormality in the electrical system, the threshold of the monitoring system should be relaxed to the extent that does not affect its functioning. Also, procedures for system restoration by remote operation should be incorporated into the system specifications. |
| Remotely controlled transport cart | Reducing the duration of PADIRAC locking / automation of operation | The work of installing and removing the PADIRAC is complex and requires time (1 hour or more). Hence the structure for fixing it on to the remotely controlled transport cart should be modified to simplify the work of installing and removing it and thereby reduce the duration of on-site work. The load on remote operation should be reduced by automating the operation of passing through narrow spaces. |
| | Preventing mistakes in coordination between the site and the control room | Driving of the remotely controlled transport cart and on-site work needs to be carried out from the control room alternately during the work on installing and removing the PADIRAC. As a result, the duration of work is likely to increase in the process of coordination, and mistakes are likely to happen while coordinating. Hence a simple auxiliary system for operating the remotely controlled transport cart on site should be developed. |
| | Adding interlocks for enhanced safety / modifying the maintenance method | Interlocks should be added for protecting the workers and remotely controlled transport cart during manual operations such as maintenance work or while taking actions in response to failures, etc. Also, maintenance work carried out very close to the floor should be reduced to the extent possible. |
| Remotely operated cable attachment/detachment mechanism | Verifying the impact on the operability of the dual arm type manipulator | In this project, instead of the dual arm type manipulator, a simulated weight that simulates the weight and and center of gravity of the manipulator was used. During the mock-up verification, the cable of the dual arm type manipulator should be connected and operation through the remote attachment/detachment mechanism should be verified. |
| | Verifying the workability of transferring the dual arm type manipulator from the enclosure for maintenance | Remote attachment/detachment on the dual arm type manipulator rail has been verified in this project. However, in order to perform maintenance of the dual arm type manipulator, the dual arm type manipulator and the carriage need to be transferred outside the enclosure together. The compatibility with equipment required for that work should be verified through mock-up verification. |
| | Verifying the accuracy of the repetitive operation of remote attachment/detachment | The reliability of the stand-alone remote attachment/detachment mechanism has been verified for 50 or more rounds of attachment/detachment. However, misalignment due to the gap between the carriage and rail of the dual arm type manipulator should be verified, and the extent to which the gaps can be eliminated on a regular basis should be evaluated. |
| Tip tool | Adjusting the length of the cable | The cable length and the casing of the 2 types of pebble-shaped debris collection equipment should be modified to secure extra cable length and prevent protrusion. |
| | Adding load meter | Load meters should be added to the cutting swarf fuel debris collection equipment and the cylindrical debris collection equipment for detecting positioning and pressing force. |

# 6. Implementation Details

## 6.1 Update of the retrieval technology development plan

**[Issues]**

- ✓ **Since the arm for retrieval is completed in UK and the enclosure for retrieval is completed in Japan, verification through overall mock-up test needs to be considered after the completion of this project.**
- ✓ **The measures in response to technical issues identified during the combination tests of the arm for retrieval with the simulated X-6 penetration need to be reflected separately.**
- ✓ **When the outline of the system design becomes clear, the safety design of the system needs to be updated and the safety related explanations need to be compiled.**



# 6. Implementation Details

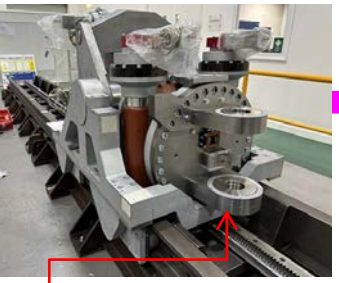


## 6.2 Development of retrieval equipment and combination tests

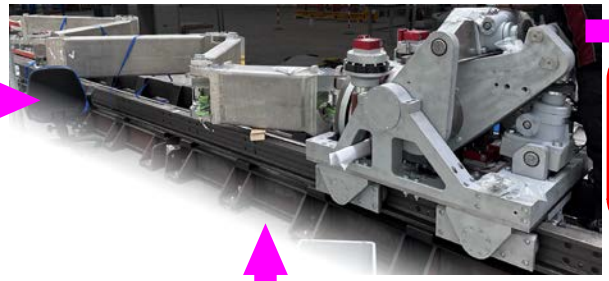
### 6.2.1 Development of access equipment for retrieval (arm and enclosure, etc.)

**[Achievements for FY2022 (arm) (1/2)]**

- ✓ **Knowhow about the boom-links 1 - 5 designed by VNS (UK) was obtained and these were them manufactured in Japan. [Achieved]**
- ✓ **The boom links were assembled on to the rail and the carriage, and the front-end of the arm was connected. [Achieved]**
- ✓ **It was verified through combination tests (test on ability to pass through the simulated X-6 penetration) that the assembled structure can pass through the penetration. [Achieved]**

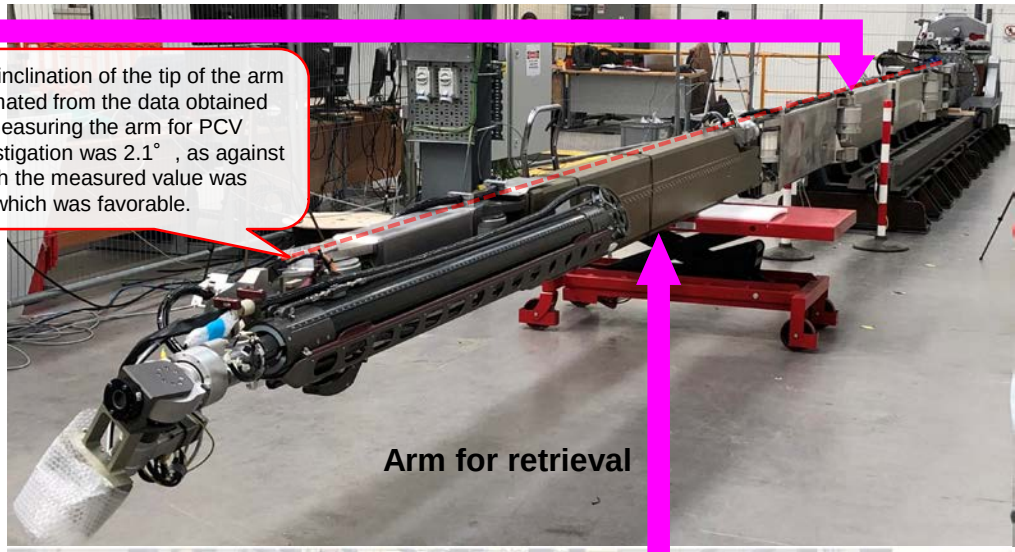


Carriage



Posterior half of the arm

The inclination of the tip of the arm estimated from the data obtained by measuring the arm for PCV investigation was 2.1˚ , as against which the measured value was 1.8°which was favorable.



Arm for retrieval

Link 1

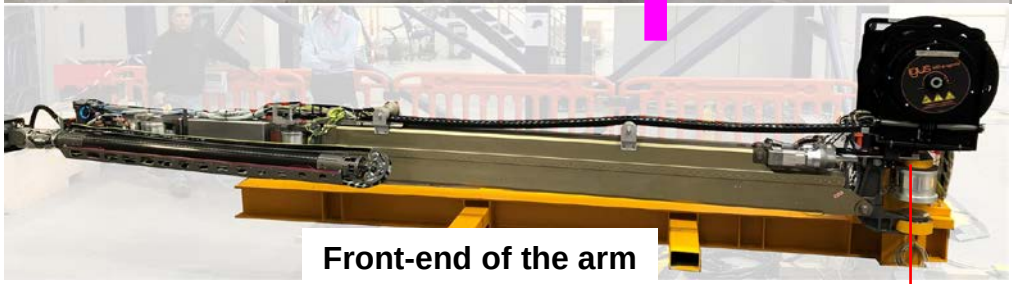
Boom link

Link 2

Link 3

Link 4

Link 5



Front-end of the arm

# 6. Implementation Details

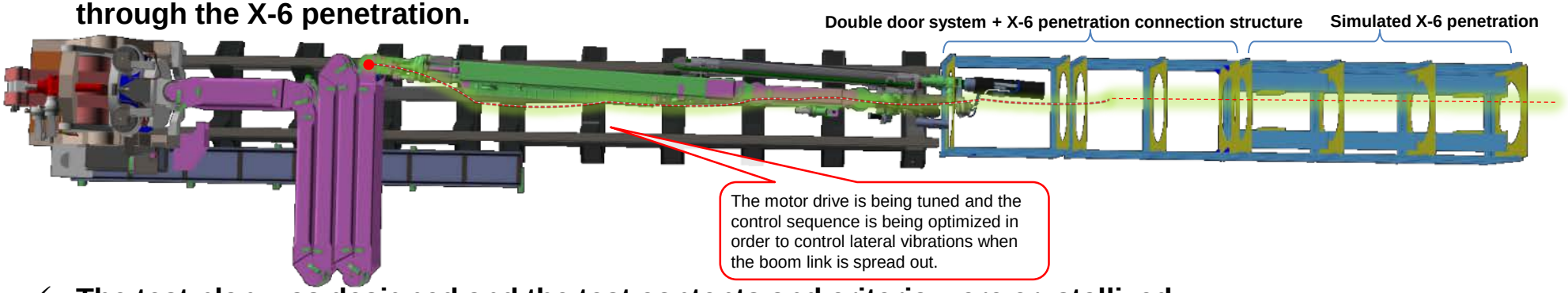


## 6.2 Development of retrieval equipment and combination tests

### 6.2.1 Development of access equipment for retrieval (arm and enclosure, etc.)

**[Achievements for FY2022 (arm) (2/2)]**

- ✓ **The position of the arm and the structure of the protrusions were corrected so as to reduce the risk of contact based on structural analysis and VR simulation of the movement of the arm for retrieval to pass through the X-6 penetration.**




- ✓ **The test plan was designed and the test contents and criteria were crystallized.**

| No. | Name | Details | Material used | Criteria |
|---|---|---|---|---|
| 1 | Operating range verification test | Angle of rotation of each joint of the boom links, the carriage tilting and lifting range are measured.<br>The range of forward and reverse movement of the carriage is measured | In-built resolver, retractable measuring tape, etc. | Must have an angle of rotation that enables unfolding of the arm from the folded state to the completely spread out state.<br>Must have a tilting range (-0.5 to +1.0˚ ) and lifting range (-0 to +50mm) enough for correcting the deflection and tilt angle of the front-end of the arm for retrieval.<br>The forward and backward stroke of the carriage must be 6.6m or more. |
| 2 | Simulated X-6 penetration passing test | The arm for retrieval is unfolded in the direction of the simulated access route and passed through it.<br>After passing, the arm for retrieval is moved in the opposite direction and withdrawn from the simulated access route. | Camera, laser pointer, etc. | The displacement of the central axis of the dummy tip tool must be within a 25mm radius circle.<br>A gap of 10mm or more must be secured at places where the arm is expected to come close to the inner surface of the X-6 penetration according to the VR simulation. |

# 6. Implementation Details

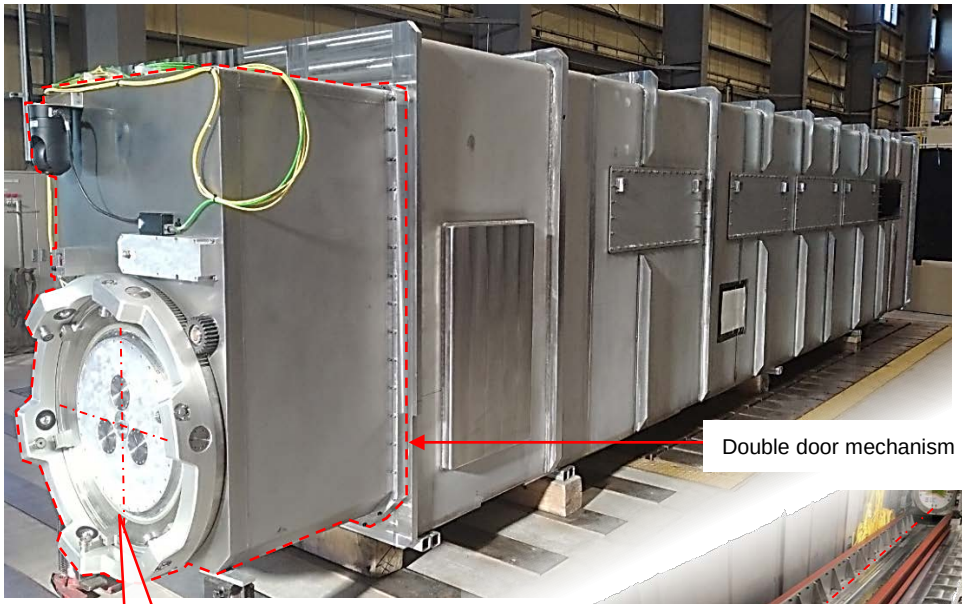


## 6.2 Development of retrieval equipment and combination tests

### 6.2.1 Development of access equipment for retrieval (arm and enclosure, etc.)

**[Achievements for FY2022 (Enclosure 1/3)]**

✓ **The enclosure (main body and accessories) for the verification test was manufactured according to the plan.**

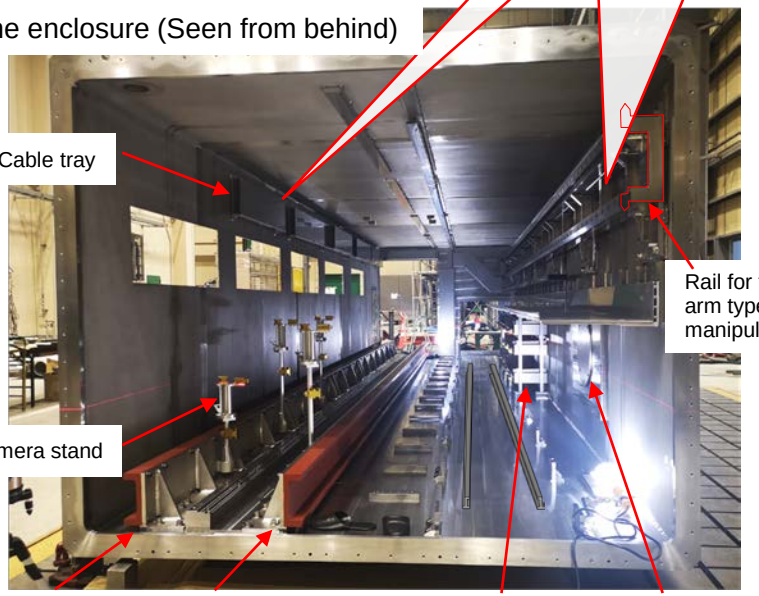



Precise adjustments within ±2mm were made to align the opening of the double door mechanism and the rail.

Rail for the arm for retrieval

Inside the enclosure (Seen from behind)

The rail of the dual arm type manipulator was streamlined and the arrangement of the cable tray was reviewed in order to increase the workspace for the dual arm type manipulator.




The tool rack of the enclosure for detailed internal investigation of PCV was modified and sliding was extended to make it easier to put in and take out storage items.

Tool rack

# 6. Implementation Details



## 6.2 Development of retrieval equipment and combination tests

### 6.2.1 Development of access equipment for retrieval (arm and enclosure, etc.)

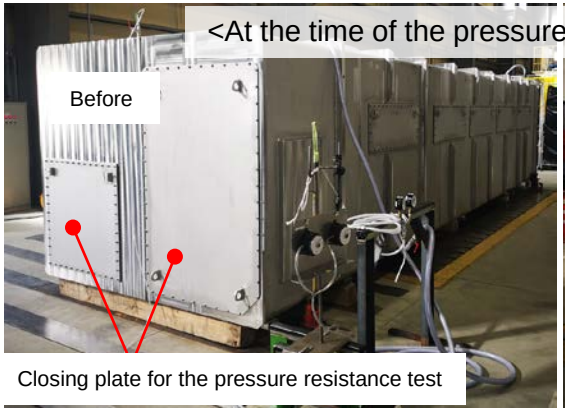
**[Achievements for FY2022 (Enclosure 2/3)]**

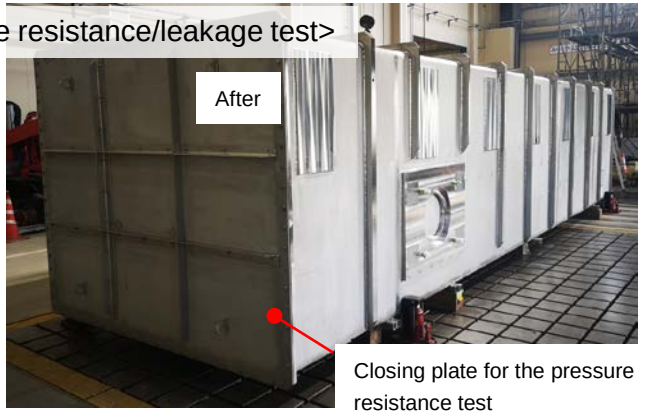
✓ **Factory inspection of the enclosure as a stand-alone unit was conducted, and it was verified that the requirements with respect to all the inspection items were fulfilled. [Achieved]**

| No. | Item | Implementation Details | Results | Judgment |
|---|---|---|---|---|
| 1 | Visual inspection | Visually checking whether or not there are any harmful defects, deformations on the surface of the product with appropriate lighting, etc. | It was verified that there are no harmful defects, deformations on the surface of the product. | Pass |
| 2 | Dimensional check | Verifying that the external dimensions, layout dimensions of the equipment are within the acceptable range using measuring instruments that are appropriately calibrated. | It was verified that all dimensions are within the acceptable range. | Pass |
| 3 | Pressure resistance test | Decompressing the design pressure 5.2kPa x 1.2 times, and verifying that there is no harmful deformation. Also, the holding time is 30 minutes or more. | It was verified that there are no harmful deformations after the holding time elapsed. | Pass |
| 4 | Leakage test | Testing pressure 5.2kPa x 1.2 times was applied, and after foaming agent was applied to the weld seam between the flange part and the airtight boundary, it was visually checked whether or not air bubbles are formed. | It was verified that air bubbles were not formed until the holding time elapsed. | Pass |

<At the time of the dimensional check>

<At the time of the pressure resistance/leakage test>



# 6. Implementation Details

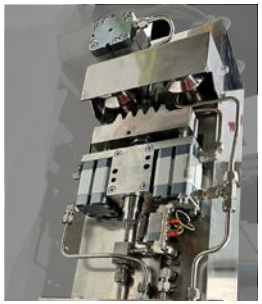


## 6.2 Development of retrieval equipment and combination tests

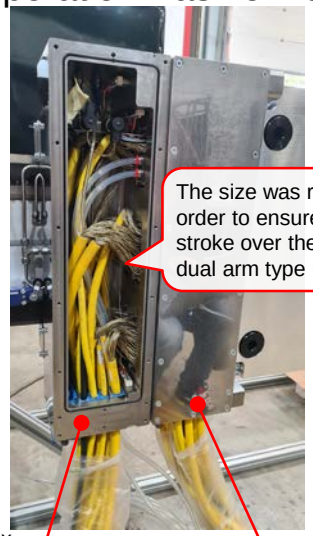
### 6.2.1 Development of access equipment for retrieval (arm and enclosure, etc.)

**[Achievements for FY2022 (Enclosure 3/3)]**

✓ The remotely operated cable attachment/ detachment mechanism for the dual arm type manipulator was manufactured, and the attachment/detachment operation was verified through factory testing. **[Achieved]**

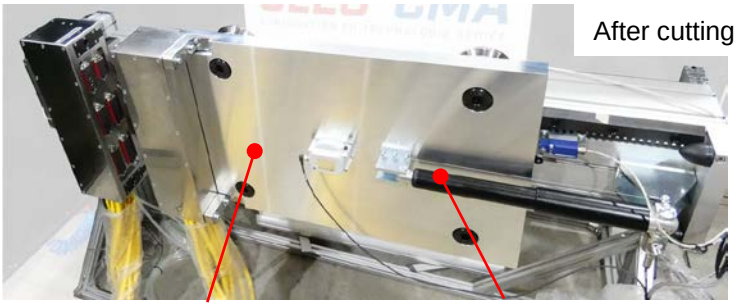


Dual arm type manipulator side terminal box being assembled



The size was reduced in order to ensure a travel stroke over the rail of the dual arm type manipulator.

Before cutting



After cutting

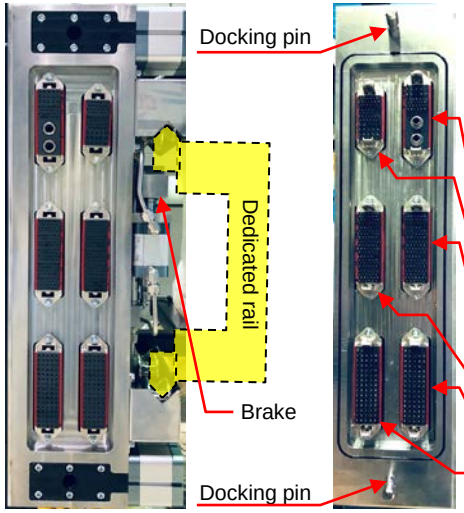
Back side of enclosure side terminal box

Enclosure side terminal box

Dual arm type manipulator side terminal box

Simulated dedicated cart for the dual arm type manipulator

Actuator for the test






Camera + N2 purge gas
Dedicated cart (signal line + power line)
Right hand (signal line)
Left hand (signal line)
Right hand (power line)
Left hand (power line)

The signal line and power line of the dual arm type manipulator were separated to prevent noise.

Enclosure side terminal

Dual arm type manipulator side terminal

✓ It was verified that 539 contact pins were connected by repeating the the attachment and detachment task 50 times over. **[Achieved]**

# 6. Implementation Details

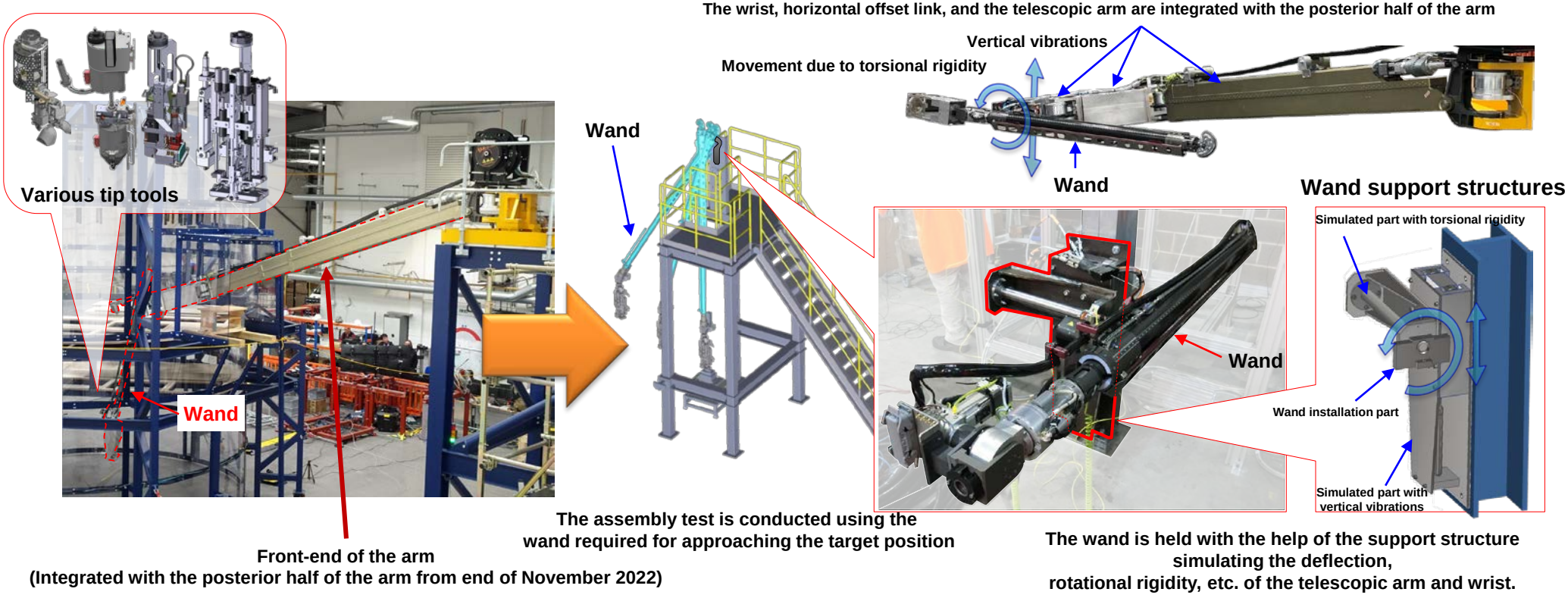


## 6.2 Development of retrieval equipment and combination tests

### 6.2.2 Combination tests of the access equipment for retrieval with the entire system

**[Achievements for FY2022 (Combination tests of the front-end of the arm and the tip tools 1/2)]**

- ✓ **A test plan was created for ascertaining the issues related to connecting the tip tools such as the fuel debris cutting and collection equipment or the neutron monitor, their behavior when they approach fuel debris, and remote workability, using the front-end of the arm.**
- ✓ **The wand which is mainly required while approaching the target position and the tool pan & tilt were used in the test while avoiding any impact on the work of assembling the arm for retrieval. The structure for simulating vibrations, etc. inflicted upon the wand by the telescopic arm was used to support the wand.**



# 6. Implementation Details

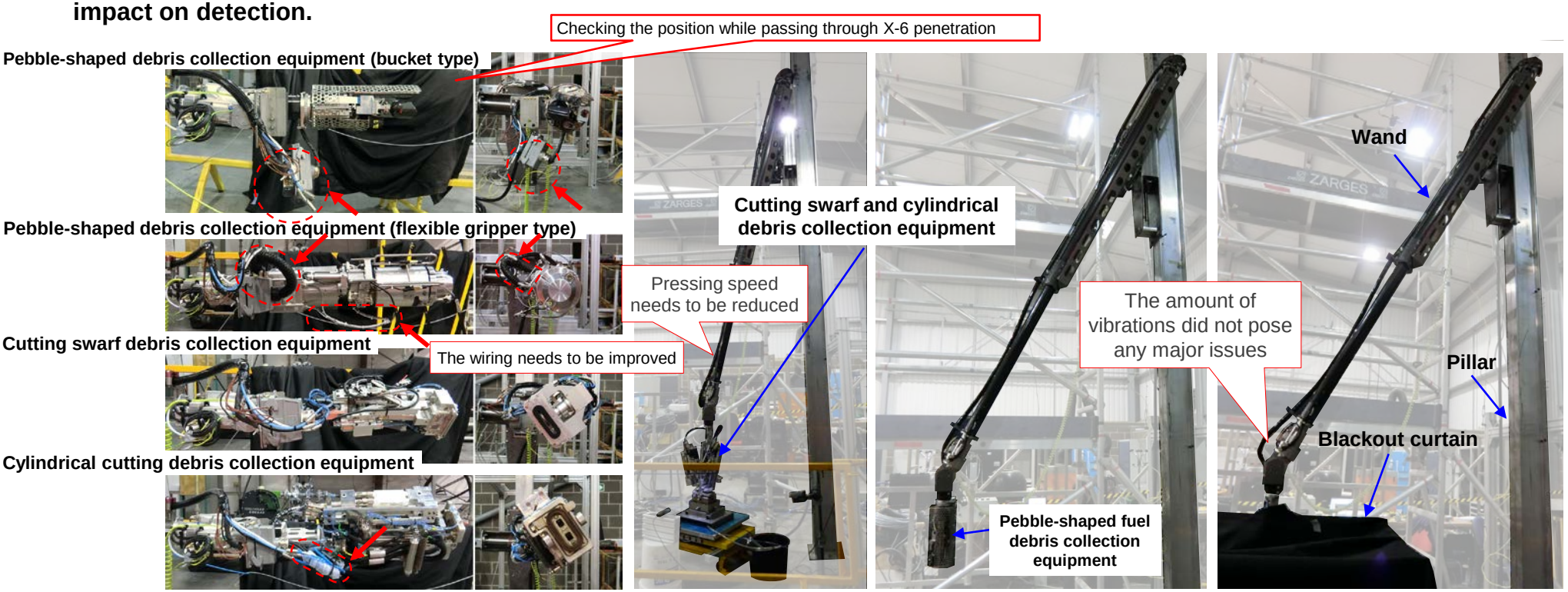


## 6.2 Development of retrieval equipment and combination tests

### 6.2.2 Combination tests of the access equipment for retrieval with the entire system

**[Achievements for FY2022 (Combination tests of the front-end of the arm and the tip tools 2/2)]**

- ✓ **Combination tests were conducted with the tip tools (4 types of fuel debris cutting and collection equipment) and the front-end of the arm, and improvements to be made in the interface were identified. Also, it was confirmed based on the status of vibrations and the camera images that are important for remote operation that fuel debris can be collected in the current condition.**
- ✓ **The noise level of the neutron monitor while the fuel debris cutting and collection equipment is in operation was measured. It was verified that the level of noise was 1/10 or less with respect to the neutron detection signal and thus it did not have an impact on detection.**



# 6. Implementation Details

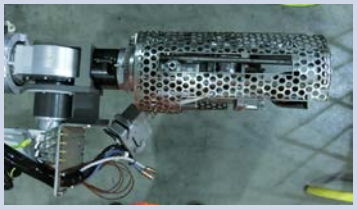
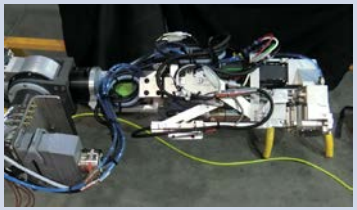
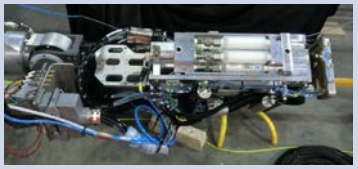
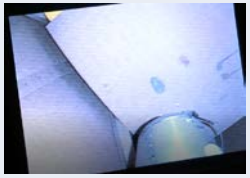
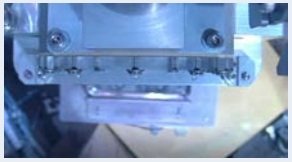


## 6.2 Development of retrieval equipment and combination tests

### 6.2.2 Combination tests of the access equipment for retrieval with the entire system

**[Summary (Combination tests of the front-end of the arm and the tip tools)]**

✓ **Areas for improvement in the functions and interface of the 4 types of fuel debris cutting and collection equipment and the neutron monitor were identified using the wand of the front-end of the arm. The rigidity and vibrations of the front-end of the arm did not have any adverse effect on the fuel debris cutting and collection performance. The signal-to-noise ratio of the neutron monitor was 10 or more. Thus the impact of noise was not an issue. [Achieved]**

| Evaluation items | Pebble-shaped debris collection equipment (Bucket) | Pebble-shaped debris collection equipment (Flexible gripper) | Cutting swarf debris collection equipment | Cylindrical cutting debris collection equipment |
|---|---|---|---|---|
| Cable connection<br>Cable noise<br>Fixed condition | Cable short and difficult to connect<br>No issues with noise<br>  | Cable run-out and sagging<br>No issues with noise<br>  | No issues with connection<br>Noise in the camera images during cutting<br>  | Cable sagging<br>Noise in the camera images during cutting<br>  |
| Fuel debris collection time | Within 15 minutes | Within 15 minutes | Approx. 30 minutes | Approx. 5 hours (cast iron) |
| Impact of vibrations | No impact | Slight vibrations while deploying the camera | Slight vibrations while deploying the camera | Slight vibrations during V-shaped deployment |
| Approach towards fuel debris | Good camera visibility<br>  | Good camera visibility<br>  | Difficult to determine contact with ground using the camera<br>  | Difficult to determine contact with ground using the camera<br>  |
| Pushing towards fuel debris | Not applicable | Not applicable | The wand moves fast. Pushing adjustments with low load are difficult. | Adjustments with load meter |
| Response in the event of a failure | Can be folded with the stand-by motor | Response in the event of motor failure is an issue | Can be folded with the return spring | Can be folded with the return spring, etc. |

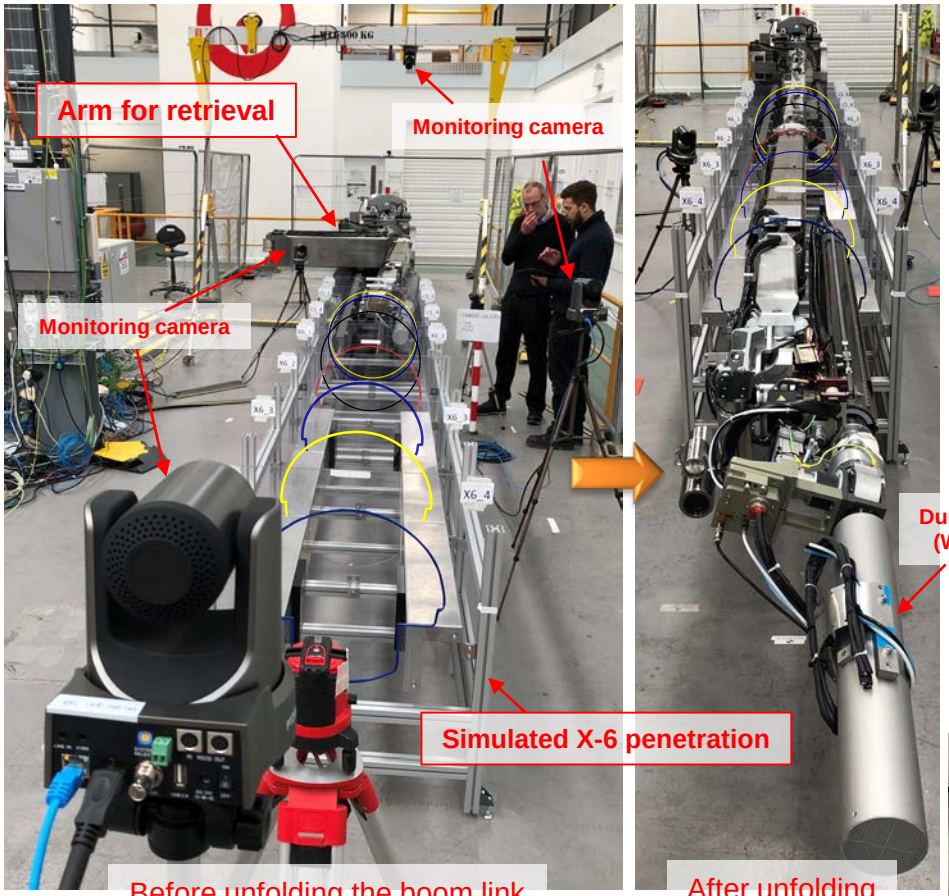
# 6. Implementation Details

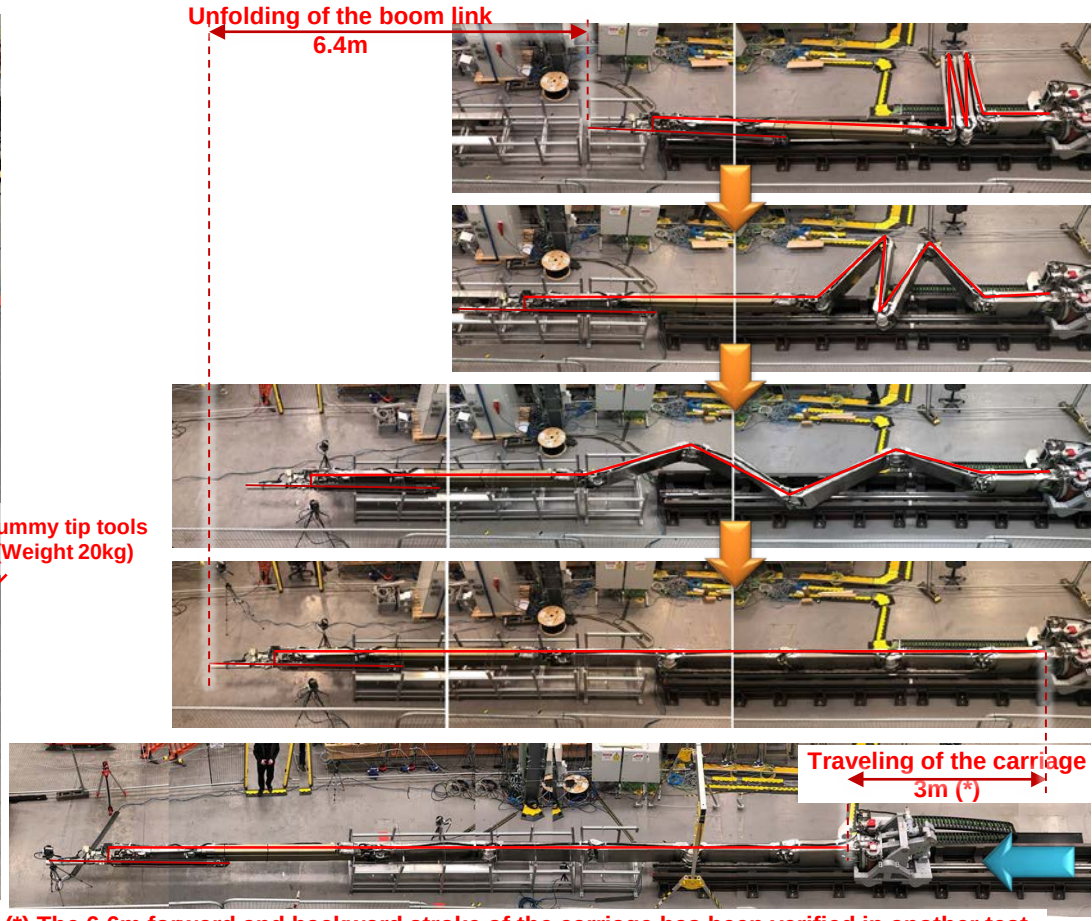
## 6.2 Development of retrieval equipment and combination tests

### 6.2.2 Combination tests of the access equipment for retrieval with the entire system

**[Achievements for FY2023 (Combination tests of the entire arm）1/2]**

- ✓ **The X-6 penetration passing test was conducted, and it was verified that the arm can pass inside the X-6 penetration by building a control system required for passing through the X-6 penetration, adjusting the zero point using the rail as reference and using chaining when there are multiple axles. [Achieved]**




**(*) The 6.6m forward and backward stroke of the carriage has been verified in another test.**

# 6. Implementation Details

## 6.2 Development of retrieval equipment and combination tests

### 6.2.2 Combination tests of the access equipment for retrieval with the entire system

**[Achievements for FY2023 (Combination tests of the entire arm) 2/2]**

✓ **Since there is a gap of 25mm on each side vertically and horizontally in the X-6 penetration, it is ensured that the arm can pass through the X-6 penetration as follows. [Achieved]**

Horizontal vibrational amplitude + Variations in horizontal positions + Impact of multi-axle drive + Error in three-dimensional measuring instrument + Alignment error < Gap on one side

5mm(*1) + 4mm(*2) + 5mm(*3) + 0.1mm(*4) + 2mm(*5) < 25mm

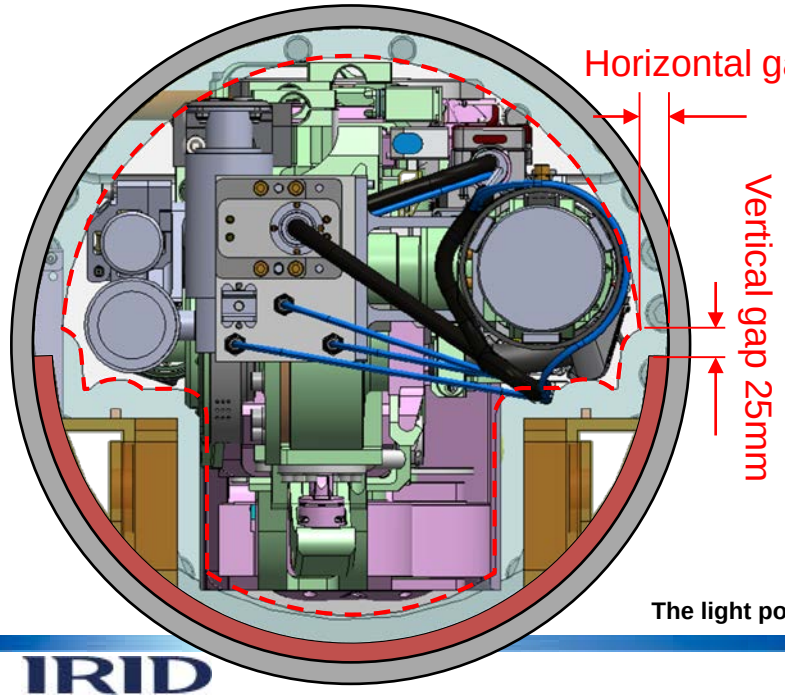
*1 Horizontal vibrational amplitude: Result of observation using the laser pointer (Refer to the bottom right picture)

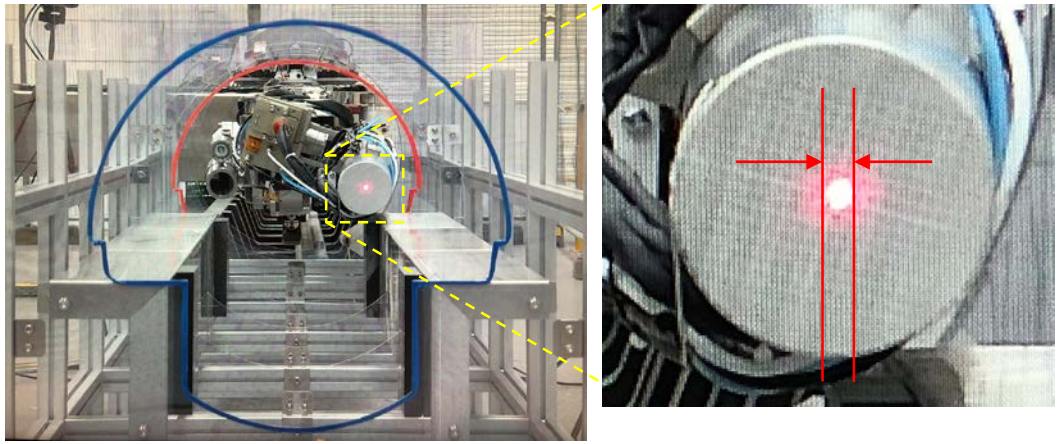
*2 Variations in horizontal positions: Since the total length up to the measurement point at the tip of the horizontal offset link increases from 8.7m to 12.3m when the arm is completely unfolded, variations in the horizontal direction give rise to an offset of about 4mm at the tip of the arm

*3 Vibrational amplitude in the horizontal direction due to lack of synchronization at the time of simultaneous operation of multiple actuators

*4 Error in the measurement conditions of the Faro Vantage Laser Scanner used for measuring the position of the arm during the test

*5 Misalignment of the carriage rail and double door mechanism of the test manufactured enclosure (the misalignment of the enclosure and X-6 penetration is not considered)



**The light point of the laser pointer was within a range of 10mm (5mm on each side) even when there were vibrations.**

# 6. Implementation Details

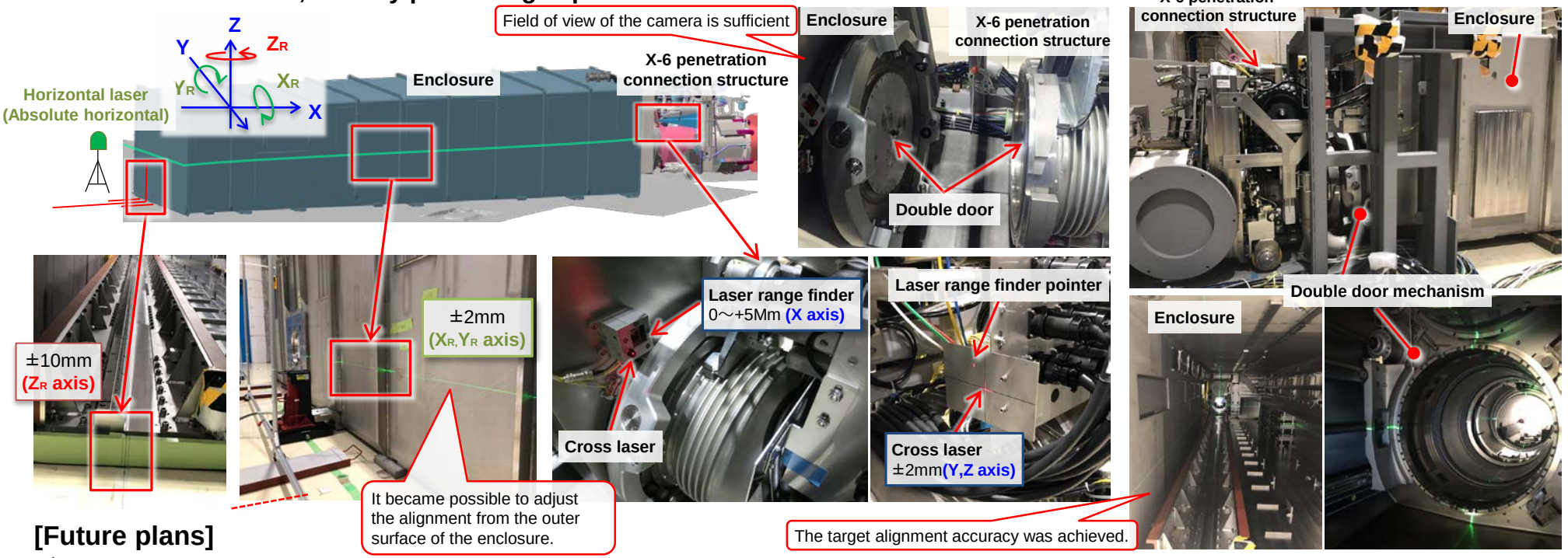


## 6.2 Development of retrieval equipment and combination tests

### 6.2.2 Combination tests of the access equipment for retrieval with the entire system

**[Achievements for FY2022 (Combination tests related to the enclosure 1/4)]**

- ✓ **Combination tests with the enclosure (double door mechanism) and the X-6 penetration connection structure were conducted, and it was verified that installation is possible within the accuracy required for the X-6 penetration connection structure, and that connection is possible.**
- ✓ **It was verified that the double door mechanism can open and close while connected to the X-6 penetration connection structure, and when it is detached the x-6 penetration connection structure side and the enclosure side are closed by means of the double door, thereby preventing exposure of the contaminated inner surface.**




**[Future plans]**

- ✓ **Since the series of functions in the combined state and the work procedures have been verified, in the future, the compatibility with the actual equipment will be enhanced such as enhancing the maintainability, etc., and risks will be investigated further.**

# 6. Implementation Details

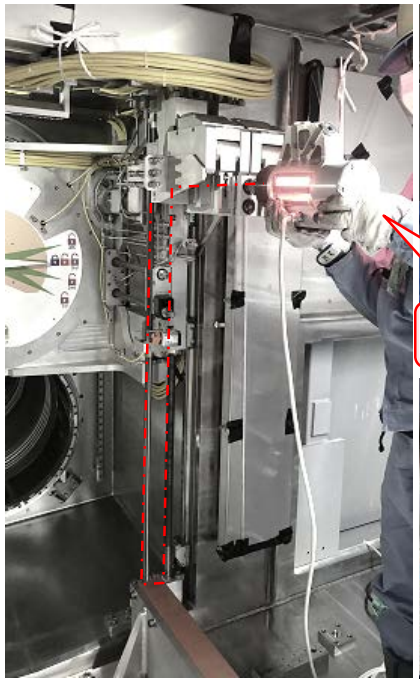


## 6.2 Development of retrieval equipment and combination tests

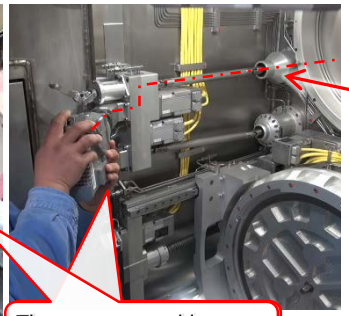
### 6.2.2 Combination tests of the access equipment for retrieval with the entire system

**[Achievements for FY2022 (Combination tests related to the enclosure 2/4)]**

- ✓ **It was verified that air-tightness (required value: 0.1vol%/h) can be ensured by closing the double doors with the help of the emergency drive tools, and closing the shielding door (air-tight door) of the X-6 penetration connection structure as an emergency response (motor failure) of the double door mechanism.**
- ✓ **The handleability of the manipulator for testing was verified using the emergency drive tools.**

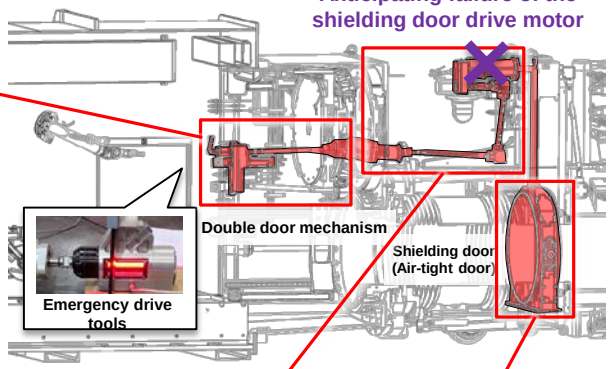


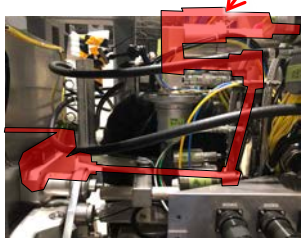
Emergency closing of the double door mechanism using the emergency drive tools



The emergency drive tools were handled well.

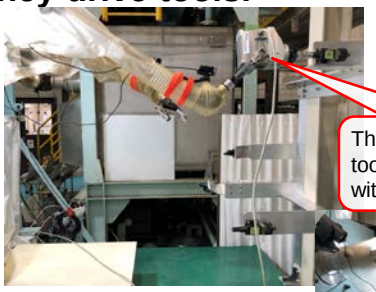
Emergency drive tools operation panel (Transfer of the control program of the double door mechanism)



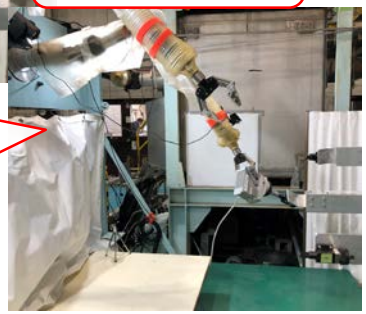



Emergency drive shaft

Shielding door (Air-tight door)



There were no issues in installing the emergency drive tools with the help of the manipulator or in the reaction force at the time of driving.



The emergency drive tools was handled well with the manipulator.

The shielding door was closed with the emergency drive tools.

**Verification of the handleability of the emergency drive tools using the manipulator for testing**

View from the camera installed on the manipulator

# 6. Implementation Details

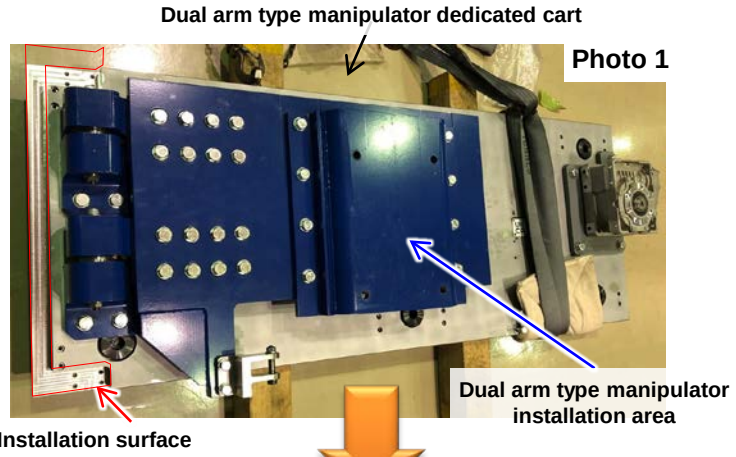


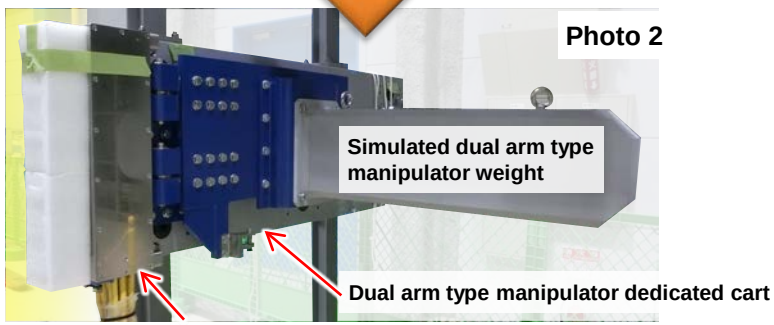
## 6.2 Development of retrieval equipment and combination tests

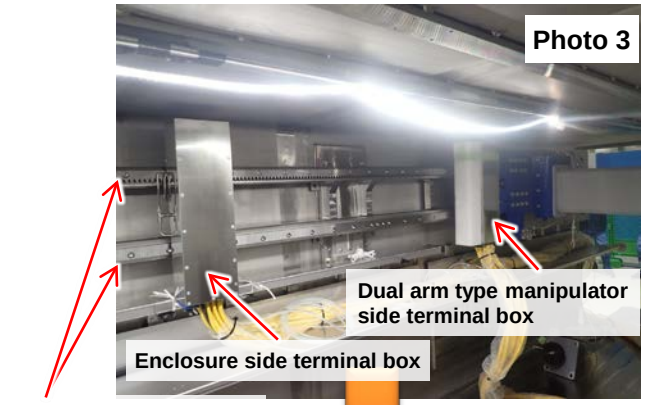
### 6.2.2 Combination tests of the access equipment for retrieval with the entire system

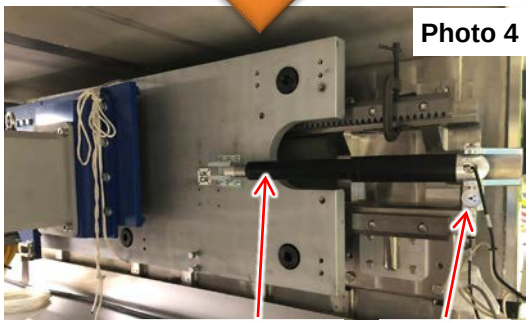
**[Achievements for FY2022 (Combination tests related to the enclosure 3/4)]**

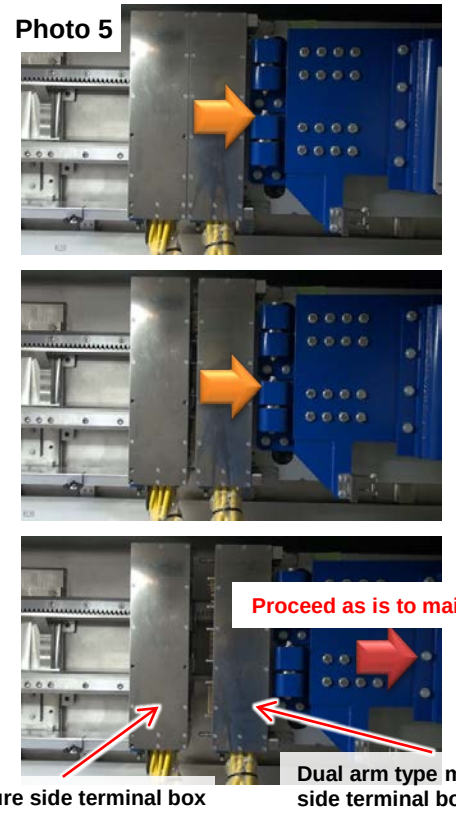
- ✓ **A dual arm type manipulator dedicated cart was processed and the dual arm type manipulator side terminal box was installed. (Photo 1, 2)**
- ✓ **The enclosure side terminal box and the manipulator side terminal box (dedicated cart) were installed on the rail inside the enclosure (Photo 3).**
- ✓ **The actuator for the test was installed (Photo 4), and it was confirmed that the attachment/detachment operation can be performed with a force that is 2000N or less (Photo 5).**



# 6. Implementation Details

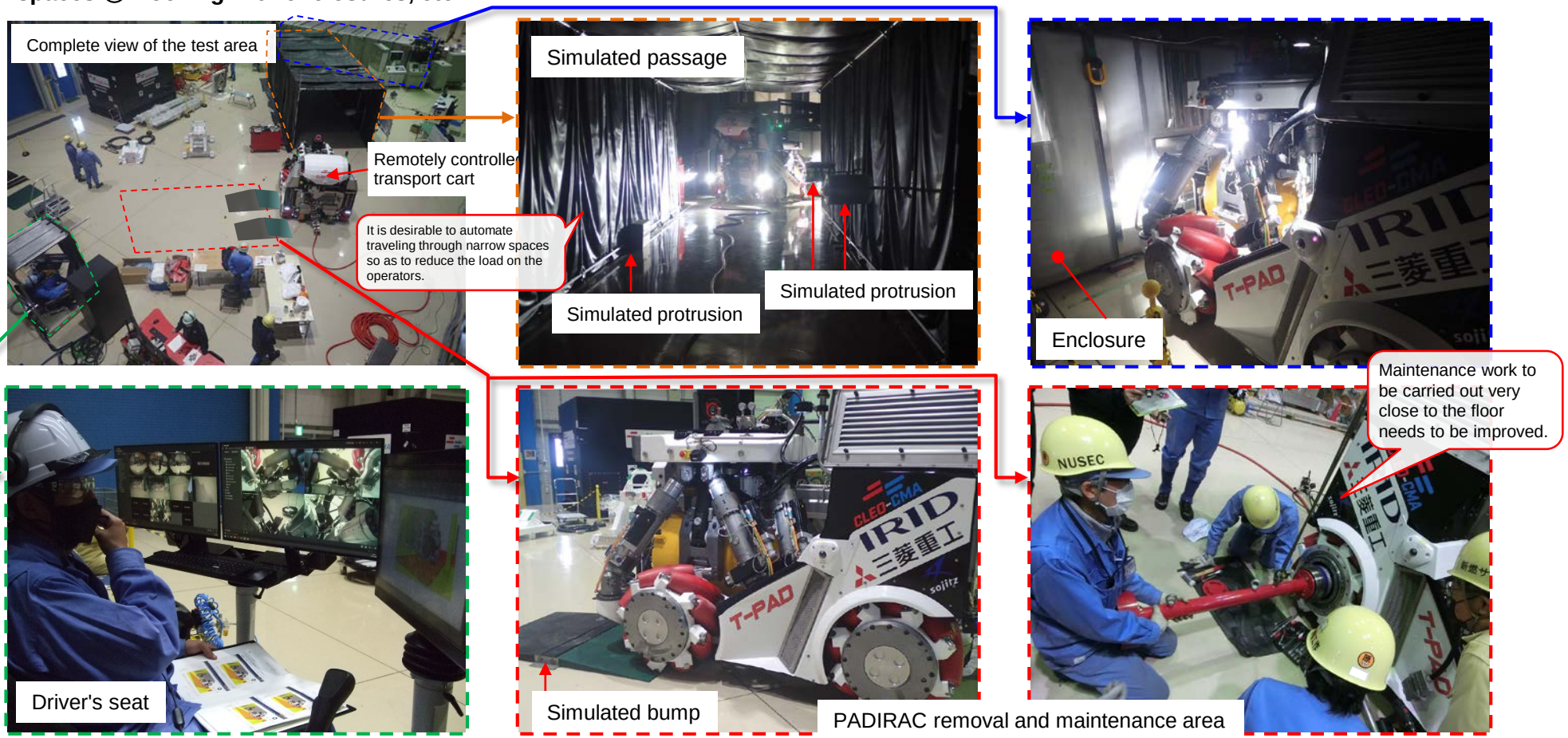


## 6.2 Development of retrieval equipment and combination tests

### 6.2.2 Combination tests of the access equipment for retrieval with the entire system

**[Achievements for FY2022 (Combination tests related to the enclosure 4/4)]**

- ✓ **Workers were provided training on operation and maintenance of the remotely controlled transport cart, and the work procedures were developed.**
- ✓ **It was verified that there are no issues in the functions and operability such as ① Crossing over bumps ② Traveling through narrow spaces ③ Docking with enclosures, etc.**



# 7. Summary and Future Action



- ✓ **During the next phase of development, the series of fuel debris retrieval tasks are expected to move on to simulated mock-up verification.**
- ✓ **Actions are expected to be taken for making improvements in response to the technical issues identified during the verification tests so far.**

| Implementation items | | Summary of the scope of implementation | Achievement status | Remarks |
|---|---|---|---|---|
| Development of the access equipment for retrieval (arm and enclosure, etc.) | Arm | The arm for retrieval was completed. | Achieved | |
| | Enclosure | The enclosure for retrieval was completed, and the workability of the dual arm type manipulator was enhanced by making various improvements. | Achieved | |
| Combination tests of the access equipment for retrieval with the entire system | Combination test of the front-end of the arm and the tip tools | It was verified that the stand-alone performance of each tip tool can be demonstrated, and points of improvements in the interface were identified. | Achieved | |
| | Combination test of the entire arm | The ability of the arm for retrieval to pass through the simulated X-6 penetration was tested. | Achieved | Improvement in the boom link speed and streamlining of the front-end of the arm are expected to be accomplished during the next phase of development. |
| | Combination tests of the enclosure and X-6 penetration connection structure | It was verified that the rail for the arm inside the enclosure can be docked into the X-6 penetration with the required alignment accuracy (±2mm). | Achieved | Since the double door mechanism abnormality detection is overly sensitive, there is room for improvement in the next phase of development. |
| | | A system was established for preventing exposure of contaminated surfaces by means of the double door mechanism. | Achieved | |
| | | It was verified that even if the motor fails while separating the enclosure, the task can be accomplished with the help of the manipulator and the emergency drive tools. | Achieved | Verification using the actual manipulator needs to be carried out in the next phase of development. |
| | | The workers in Japan were trained on rescue tasks anticipating the rare occurrence of failure of the remotely controlled transport cart, maintenance tasks, and normal operation tasks, and were made proficient to the extent that they can perform these tasks within a realistic time frame. | Achieved | |
| | Test for verifying the remotely operated cable attachment/detachment mechanism for the dual arm type manipulator | With the development of the remotely operated cable attachment/detachment mechanism, it has become possible to attach and detach 539 connectors and 2 gas lines at once, thus enhancing maintenance workabilty of the manipulator inside the enclosure. | Achieved | During the next phase of development, it is important to move on to verifying maintenance work itself by connecting the actual manipulator. |
| | Combination tests of the enclosure, remotely controlled transport cart and the fuel debris canister (PADIRAC). | It was confirmed that the traveling performance and the docking performance were according to the design requirements by verifying the work of transfer of fuel debris from the enclosure. | Achieved | |