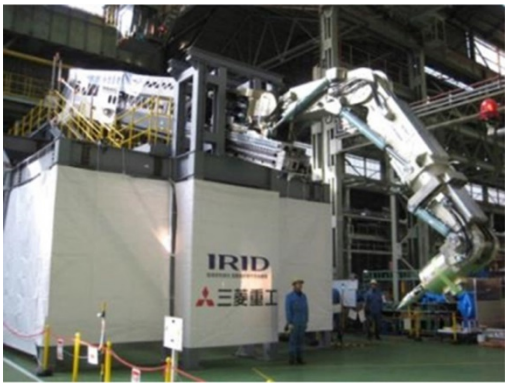
Mitsubishi Activities for Stabilization and Decommissioning of Tokyo Electric Power Company Fukushima Daiichi Nuclear Power Station

- Efforts to Unknown Territory with no Previous Experience ; Fuel Debris Retrieval –



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Mitsubishi Heavy Industries, Ltd. (MHI) has provided various forms of support for the early resolution and stabilization of the Fukushima Daiichi Accident since the initial stage by leveraging the technological capabilities of our Research & Innovation Center and other departments in active cooperation with other companies in Japan and overseas, and by utilizing our experience in the nuclear field. This report introduces our activities so far from a technological perspective. In the future, plans call for fuel debris retrieval, which is the basis for achieving early resolution and stabilization and is the highest technical hurdle. We will also actively participate in the development and promotion of various forms of support technologies to contribute to early resolution and stabilization.

1. Introduction

MHI established the “Emergency Operation Headquarters” immediately after the Great East Japan Earthquake on March 11, 2011, and we have proposed emergency supplies such as radiation shields, a modified mega-float, contaminated water treatment systems for storing large amounts of contaminated water, , etc[(1)]. The Fukushima Daiichi Nuclear Power Station is a boiling water reactor (BWR), which is different from the pressurized water reactors (PWR) our business covers. However, we have put together all the technologies of our group to carry out activities toward the resolution of the accident. This report introduces our activities so far from a technological perspective, and also describes in detail our participation in the development of various forms of support technologies related to fuel debris retrieval, which is the highest technical hurdle for future work in the decommissioning.

2. Our activities so far

2.1 Overview

Figure 1 shows the relationship between our activities so far and the medium- to long-term roadmap[(2)] established by cabinet meetings on decommissioning and contaminated water management.

As shown in this figure, we have been carrying out various activities related to resolution and stabilization measures for on-site and out-site of the nuclear power station from the initial stage of the accident to the present. Some of these activities are introduced below.

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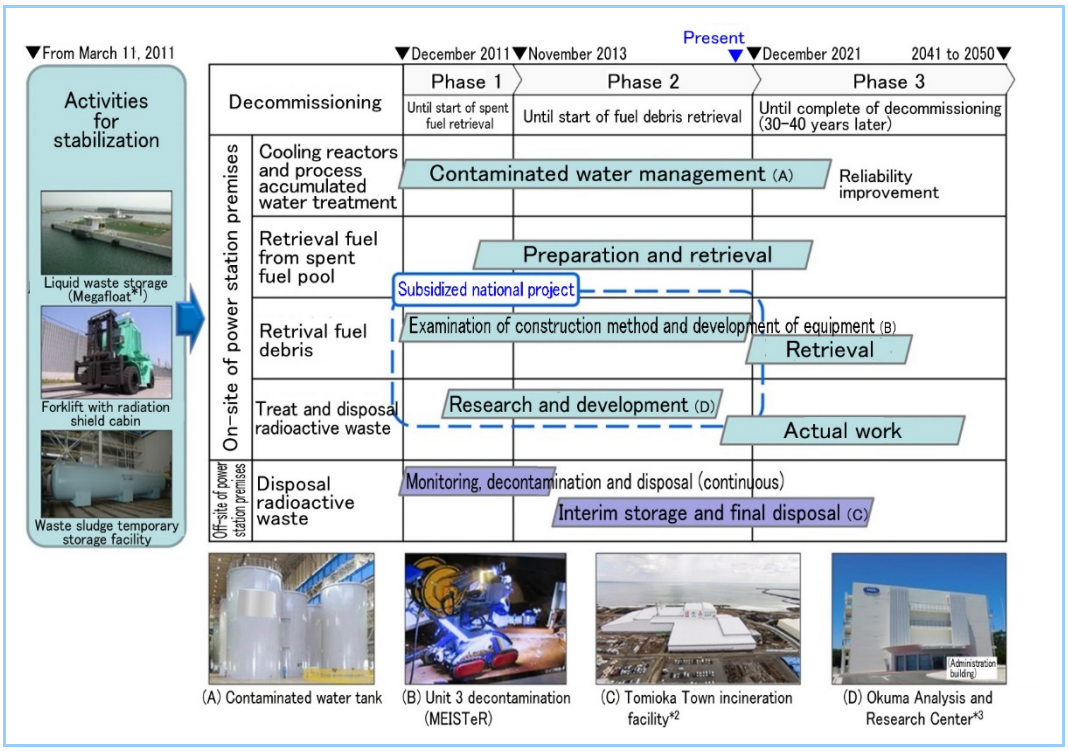

Figure 1 Mid-and-long-term roadmap and Mitsubishi's activity results
(prepared by MHI based on the government's Mid-and-Long-Term Roadmap[2])

*1 Source: Tokyo Electric Power Company Holdings, Inc.
(https://photo.tepco.co.jp/date/2011/201105-j/110521-02j.html)

*2 Source: Ministry of the Environment website
(http://shiteihaiki.env.go.jp/initiatives_fukushima/waste_disposal/tomioka/processing_tomioka.html)

*3 Source: Japan Atomic Energy Agency website
(https://fukushima.jaea.go.jp/ookuma/)

2.2 Activities for stabilization at initial stage

(1) Temporary waste sludge storage facility

(a) Facility overview

The temporary waste sludge storage facility was provided to stably store the waste sludge of the slurry-like waste liquid generated when radioactive substances are coagulated and precipitated by the decontamination equipment among contaminated water treatment facilities. This facility consists of equipment such as sludge storage tanks, off-gas (exhaust gas from sludge storage tanks) treatment equipment, ventilation and air conditioning equipment, control equipment and utility equipment installed in a concrete cell room with a wall thickness of about 1 m. **Figure 2** and **Figure 3** show the facility overview and the sludge storage tank. This equipment was established taking advantage of our comprehensive strengths and delivered after accurate implementation of the preliminary verification, while incorporating knowledge based on our experience in designing and manufacturing spent nuclear fuel reprocessing plants and high-level waste liquid storage tanks, as well as our expertise accumulated in plant construction in Japan and overseas, into the system design and construction methods, etc. Responding to the customer's request, we realized a very short construction period, with construction starting in November 2011, installation being completed on April 30, 2012, and the trial run being completed on May 10.

Figure 2 Overview of waste sludge temporary storage facility
Source: Tokyo Electric Power Company Holdings, Inc. (https://www.meti.go.jp/earthquake/nuclear/pdf/120423/120423_02nn.pdf)

Figure 3 Sludge storage tank

(b) Preliminary verification

To understand the properties of the waste liquid containing sludge to be stored , we investigated and determined the basic properties of the sludge and then carried out solidification, mixing test, stirring and temperature distribution analysis, etc., to verify the feasibility of the facility for storage. The results of the main verification items are shown below.

[1] Flow analysis and evaluation of sludge agitation property

For the purpose of preventing sludge from adhering during waste liquid storage, the optimum bubbling conditions (number and position of bubbling pipes, flow rate) were investigated by conducting a flow analysis to evaluate the bubbling-agitation property of the sludge. **Figure 4** presents part of the analysis results.

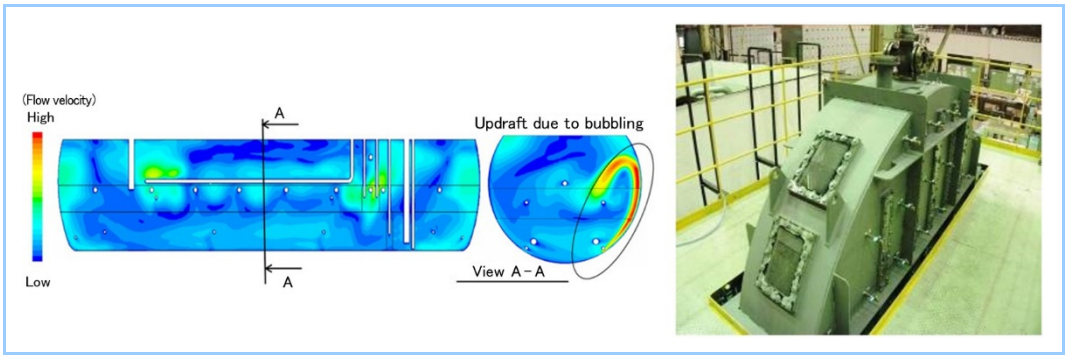

Figure 4 Flow analysis results and appearance of cut model agitation test equipment

[2] Cut model agitation test

An agitation test was conducted using simulated sludge waste liquid in a cut model of the actual tank to confirm the agitation property in the tank and the validity of the flow analysis, and then the agitation operation procedure of the actual equipment was formulated.

(c) Installation work

The installation work of the sludge storage facility started on November 14, 2011, at the Fukushima Daiichi Nuclear Power Station, installation was completed on April 30, 2012, and the trial run was completed on May 10, 2012. For this construction work, the equipment and piping were divided into blocks and packed on skids in order to shorten the construction period.

(2) Large contaminated water storage tank

(a) Facility overview

For the Fukushima Daiichi Nuclear Power Station, a large number of tanks were required to store the water used to cool the reactor vessel and the contaminated water generated by the inflow of groundwater.

For storage immediately after the accident, small tanks and large bolted tanks were

used. However, it became necessary to prepare high-quality welded large tanks in a short period of time in order to avoid the risk of leakage and store water efficiently. Therefore, we proposed a plan to manufacture and install large tanks meeting the nuclear specifications in a short period of time. Considering the amount of radiation at the site, we adopted a plan to complete the tank at the shop and transport it by sea in order to minimize the work on site. We manufactured and installed a total of 192 tanks between 2015 and 2017.

(b) Design of large tank

Table 1 lists the specifications of the tank. Since the tank is transported as a shop completed type, the tank outer diameter was determined based on transporting it on-site of the nuclear power station, the lift of the crane and the layout of the installation site. The capacity of the tank took into account the sloshing that occurs at the time of an earthquake. The maximum water level was determined so that the height of a sloshing wave would not reach the roof. In addition, this large tank was designed to have enough strength so that it can be transported and installed in a short period of time without using tools or reinforcing members for lifting (**Figure 5**). For the installation of the tank, a structure where the tank is not fixed with foundation bolts was adopted after we confirmed that it would not tip over at the time of an earthquake. The connected piping was designed to be flexible to allow sliding.

Table 1 Tank specifications

Material	Carbon steel
Tank diameter	7 to 11 m
Height	15 m
Capacity	700 to 1200 m^3
Weight (empty)	80 to 100 tons

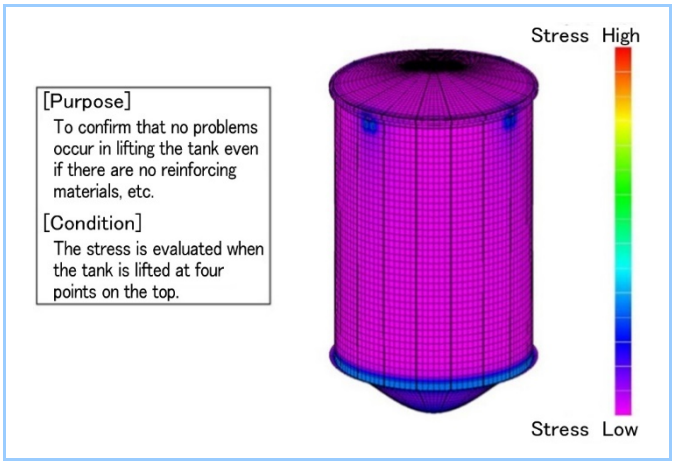

Figure 5 Example of tank stress evaluation during lifting

(c) Manufacturing completed at shop

For the manufacture of the large tank, bending and weld-assembling of large steel sheets were adopted, taking advantage of our large shop to achieve both quick delivery and high quality. For welding parts, the welding procedures and inspections used for our nuclear products were applied. The data at the time of manufacturing were recorded for each tank to provide feedback for the analysis of application of proficiency effect to improve the quality and efficiency of the manufacturing process. In addition, a tank production line was built in the outdoor yard to shorten delivery time and reduce costs.

(d) Transportation and installation

The completed tanks were transported on barges, on each of which 4 to 6 tanks were loaded and tank transportation to and from the site was carried out twice a month at its peak. Since the port of the nuclear power station was frequently used for the delivery of tanks and large structures made by other companies, we prepared a waiting area at a nearby port and performed berthing and cargo handling in a short time. On-site tank transportation was carried out at night because it requires the use of the roads on the premises. A maximum of 2 tanks were installed each day and all 192 tanks were completed in a short period of time without any accidents (**Figure 6**).

Figure 6 Contaminated water tank - Manufacturing at shop to installation
Source: Tokyo Electric Power Company Holdings, Inc.
※1（https://photo.tepco.co.jp/date/2014/201404-j/140417_01j.html）
※2（https://photo.tepco.co.jp/date/2014/201404-j/140418_01j.html）

(3) Self-propelled double-arm robot (MEISTeR*)

(a) Development history

In the reactor building, where was high-dose radiation environment after the accident, the following tasks were required from the perspective of dose reduction for various decommissioning work.

[1] Decontamination and suction: In order to carry out work inside the building continuously over a long period of time, the air dose rate in the work area and access area needs to be reduced by decontamination and suction.

[2] Core drilling and sampling: In order to examine specific dose reduction measures inside the building, the contamination properties of high-dose areas (presence or absence of the looseness, stickiness and penetrating contamination) needs to be analyzed by core sampling.

[3] Rubble retrieval: From the perspective of removing contaminants inside the building, rubble in high-dose areas needs to be removed and collected.

All the above tasks were carried out in a high-dose radiation environment, so a remote device such as a robot was required. Therefore, we carried out the remote work using a "self-propelled double-arm robot (MEISTeR)."

(b) Device overview (**Figure 7**)

[1] Decontamination and suction: Decontamination used a method of blasting abrasives onto the decontamination target to grind the surface. The abrasive consists of steel grids (square particles with sharp edges made of special steel) that are collected and separated from the contaminants by a separator and are then reused. The suction can collect dust, pebbles of about 1 cm, gravel, etc.

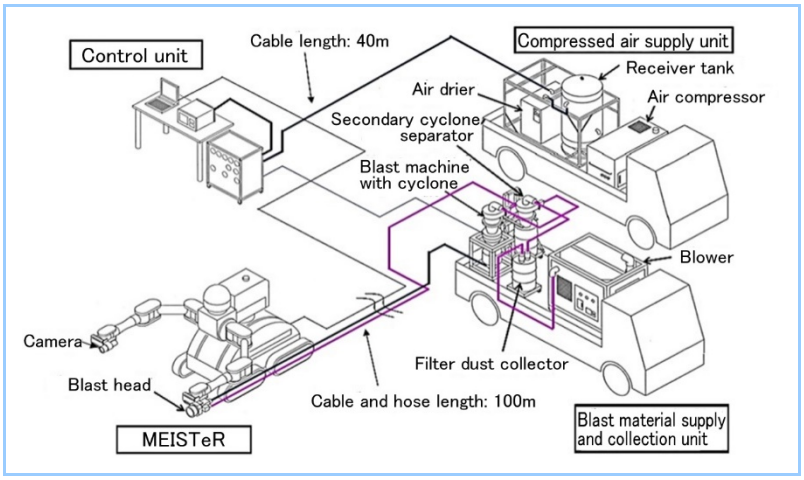

Figure 7 Overall system overview and robot tools
Source: Tokyo Electric Power Company Holdings, Inc.
(https://www.tepco.co.jp/nu/fukushima-np/handouts/2014/images/handouts_140127_06-j.pdf)

[2] Core drilling and sampling: The left side arm is equipped with a drill for drilling cores and the other side arm is equipped with a hand for pulling out the core, enabling core

boring.

[3] Rubble retrieval: The double-arm is equipped with a wire brush, spatula, dustpan, etc., for picking up rubble, etc., into a collection container.

(c) Task results

[1] Decontamination and suction: Through the decontamination of Unit 1, we checked the remote travelling ability, visibility and decontamination operation without problem, and confirmed the applicability of the robot. Suction decontamination collected dust and pebbles of 1 cm or less, and a decontamination factor (DF)* of 6.6 or greater was obtained. The DF value was not checked with the actual equipment of blast decontamination, but blast decontamination was able to remove the paint as noted in **Figure 8**. In the other test, a removal rate of 90 to 98% was confirmed for fixed contamination using simulated cesium.

(*DF value: Ratio of levels or concentrations of radioactivity before and after decontamination operations)

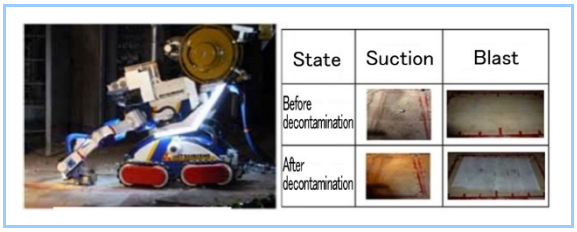

Figure 8 Decontamination state (near the southwest of Unit 1)

[2] Core drilling and sampling: In actual use on the Unit 2 operating floor, although the travelling conditions were bad and despite the fact that there were steps, the robot was able to travel without any problem and perform core drilling and Sample collecting at all four target (**Figure 9**).

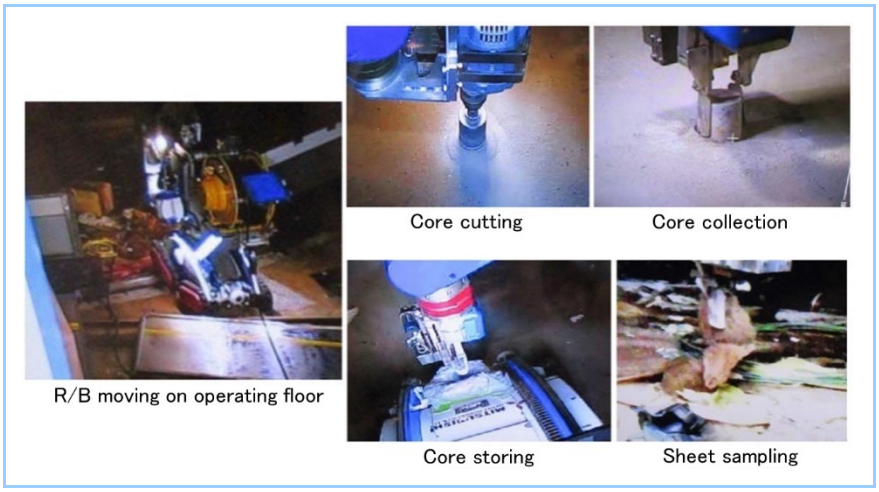

Figure 9 Core sampling state (Unit 2 operating floor)
Source: Tokyo Electric Power Company Holdings, Inc.
(https://www.tepco.co.jp/decommission/information/committee/roadmap_progress/pdf/2014/d140327_06-j.pdf)

[3] Rubble retrieval: The robot was applied to the vicinity of the southwestern part of Unit 3 and was able to collect the targeted rubble.

(d) Development of MEISTeR II

With the above achievements and based on MEISTeR, we developed MEISTeR II, which is capable of self-moving in a narrow environment and handing various tasks, and confirmed its applicability to the actual work [(3)]. The main improvements are the enhancement of ① narrow space movement ability and the ② manipulator's handling weight capacity (**Figure 10**).

(* MEISTeR : Maintenance Equipment Integrated System of Telecontrol Robot)

Figure 10 MEISTeR II

2.3 Development technology toward fuel debris retrieval

(1) Robot arm for fuel debris retrieval

(a) Overview

Figure 11 shows the system overview of large scale fuel debris retrieval including robot arms. We developed a 6-axis robot arm driven by hydraulic with high positioning accuracy in order to cut and crush fuel debris efficiently and to guide a wide variety of processing equipment (tip tools) with high accuracy.

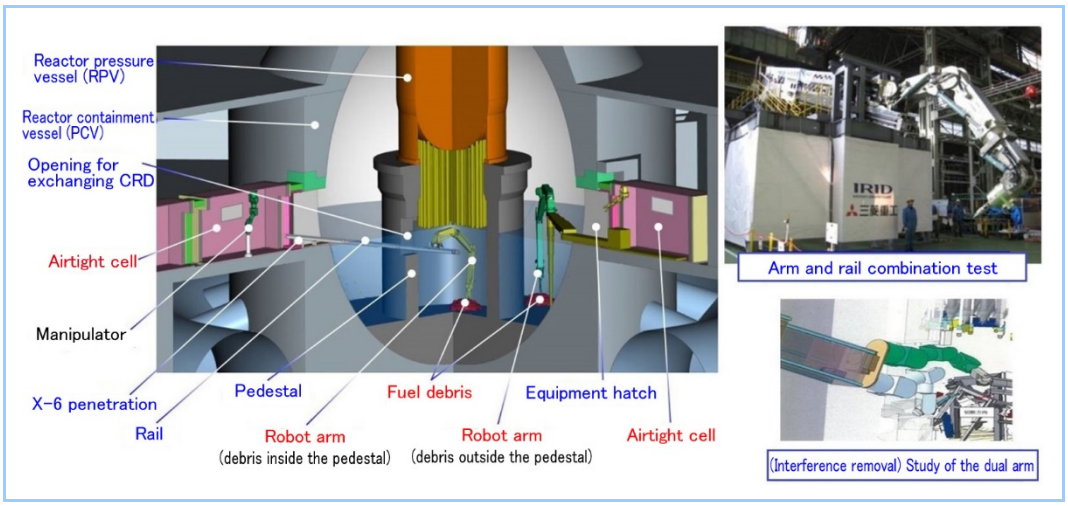

Figure 11 Large scale system overview of retrieval fuel debris

(b) Device overview

Since the robot arm works in the pedestal, it changes its posture to any other posture after passing through the opening for exchanging control rod drive (CRD). However, if the robot arm breaks down and becomes stuck, not only does fuel debris retrieval work stop, but also it may not be possible to retrieve the arm itself. Therefore, the robot arm needs to be highly reliable and to have an emergency escape ability. **Figure 12** and **Table 2** give the configuration and specifications of the prototype robot arm. The details are described below.

[1] Emergency escape mechanism that allows to escape from the pedestal in the case of breakdown

Each axis consists of two hydraulic cylinders, each of which have the ability to support axis weight and control axis by itself. As a result, even if one of hydraulic cylinder fails, the other is able to control axis so that robot arm posture can be changed to pass through the opening for exchanging CRD.

[2] Compact external dimensions

To bring the robot arm into the pedestal, it needs to pass through the 750 mm-wide opening for exchanging CRD of the pedestal. In addition, it is necessary to prevent the utility cables of tip tools and hoses of the tip tools for various fuel debris handling

method and hoses from interfering with the structures surrounding the arm. For these reasons, cables, hydraulic hoses and hydraulic equipment are housed inside of the robot arm frame, and the external dimensions are suppressed to 700 mm in width and 920 mm in height.

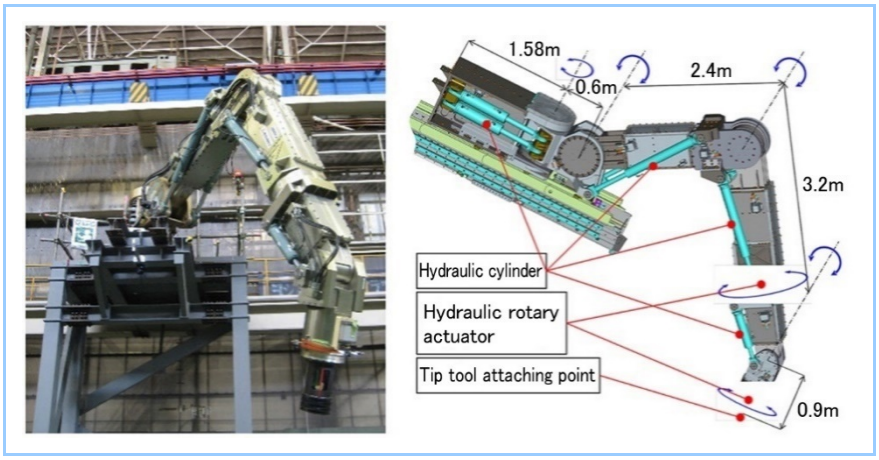

Figure 12 Configuration of prototype robot arm

Table 2 Specifications of prototype robot arm

Structure	Axis configuration: 6 axes (From the root, 1. swivel - 2. shoulder derricking - 3. elbow derricking - 4. Wrist rotation - 5. Wrist bending - 6. Hand rotation) Dimensions: Width 700 x Arm length 7100 (total length 8680) x Height 920 mm * Possible to reach up to 1.5 m below the bottom of the pedestal. * Possible to access the inside of the pedestal through the opening for exchanging CRD. * Cables and hydraulic hoses are housed in the device for compactness and the prevention of interference with external obstacles.
Maximum power at hand tip	2-ton downward pressing force * Hydraulic cylinder x 4 axes Hydraulic rotary actuator x 2 axes
Weight	Approximately 3.5 tons
Positioning accuracy	Arm tip positioning accuracy of ±5 mm
Emergency escape mechanism	Attained with the redundant hydraulic circuit. * Redundant hydraulic cylinders and pressure oil supply lines. * Each single hydraulic cylinder has enough output power to change the posture of that axis for escape.

[3] Wide range of accessibility and high positioning accuracy

With the assumption that fuel debris exists on the bottom of the pedestal and is melting into a depth of 1.5 m, the arm length is set to 7.1 m so that it can access up to 1.5 m below the bottom of the pedestal. A 6-axis arm system was adopted so that a wide variety of processing equipment (tip tools) can access, in any posture, fuel debris for which the distribution, properties and processing method are uncertain. For the angle sensor, a multi-speed resolver with high radiation resistance is used for the purpose of accurately detecting the joint angle in order to achieve high positioning accuracy with the aim of improving operability. A control method that appropriately processes joint angle information and hydraulic pressure information of the hydraulic cylinders and hydraulic rotary actuators of each axis was developed, achieving an arm tip positioning accuracy of ±5 mm or less.

[4] High output power and high-strength structure that can withstand large processing reaction force

In order to suppress the large reaction force (assumed to be a maximum of 2 tons) that is expected in processing fuel debris with a mechanical method such as boring and to realize compact external dimensions, a hydraulic drive that can be expected to be compact and provide high output power was adopted for the actuator.

(2) Analysis of fuel debris and construction of analysis facilities

(a) Positioning and purpose

It is considered that the nuclear fuel melted in the accident at the Fukushima Daiichi Nuclear Power Station exists as fuel debris inside and outside the reactor core in various

forms involving the surrounding structures. The recovered fuel debris is planned to be stored in a container, then transferred to a building, etc., with a shielding function and safely contained and stored. In order to safely and rationally perform this series of operations including fuel debris retrieval, it is necessary to understand the physical, chemical and nuclear properties of the fuel debris to be handled. For that purpose, analysis of fuel debris is important. In addition, analysis data of radionuclides that may affect the safety evaluation are important for the examination of future fuel debris treatment and disposal, making it necessary to develop such future plans.

(b) Construction of fuel debris analysis facilities

The fuel debris analysis facilities are under construction on the premises of the Fukushima Daiichi Nuclear Power Station by Japan Atomic Energy Agency as the nuclear operator. To supply high-quality analytical equipment through consistent efforts ranging from design to manufacturing, installation and verification, based on our abundant analysis experience of nuclear fuel materials and radioactive materials at a hot laboratory owned by our affiliate Nuclear Development Corporation in Tokai Village, Ibaraki Prefecture, as well as the achievements of supplying radioactive material analysis equipment to Rokkasho Reprocessing Plant, etc., we made preparations that enables the following:

[1] Safety design: Implementation of safety design such as criticality safety and radiation protection (securing shielding) necessary for handling fuel debris, which is assumed to be highly radioactive materials including nuclear fuel and the properties of which are unknown.

[2] Analysis equipment conceptual design: Planning of analyzer configuration to meet various analysis requirements including physical and mechanical properties such as shape, structure, density, hardness, etc., chemical properties of component such as U, Pu, organic substances, etc., and radiation characteristics such as activity of α, β, γ, neutron rays, etc.

[3] Containment equipment design: Planning of Iron cells that enable operation of the equipment even under high radiation, and glove boxes, hoods, etc., for the prevention of the spread of radioactive contamination.

[4] Modification of analyzer for installation in iron cell: Implementation of modification aiming at the reduction of radioactive waste and at improving maintainability for the installation of analyzers supplied by each of the specialized manufacturers in iron cells, glove boxes, etc. Arrangement for high-level coordination of the requirements of both analyzers and iron cells. **Figure 13** gives modification image of analyzer installation in iron cell.

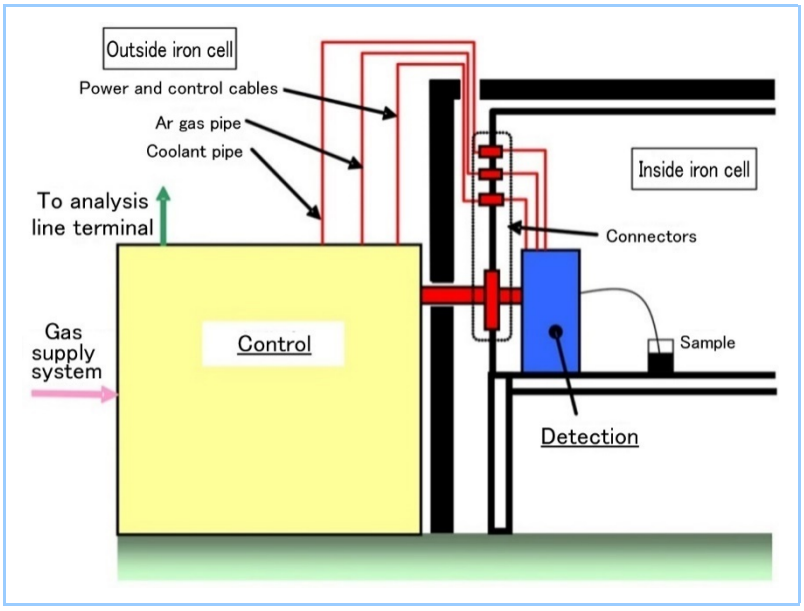

Figure 13 Modification image of analyzer installation in iron cell

[5] Future plan: Planning preliminary measures for future occurrence of analysis and research items for which the requirements are unknown at this time.

[6] Manufacturing and installation: High-precision manufacturing and installation of iron cells, which are heavy objects for shielding high radiation.

[7] Verification test: Verification of the remote operability and the maintainability of the analyzer installed in the iron cell. **Figure 14** shows remote operability verification equipment .

Figure 14 Remote operability verification equipment for analyzers

3. Activities for full-blown fuel debris retrieval in the future

Tokyo Electric Power Company Holdings, Inc. has formulated its Mid-and-Long-Term Decommissioning Action Plan 2020[5] for fuel debris retrieval in the future based on the government's Mid-and-Long-Term Roadmap[2] and The Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF)'s Technical Strategic Plan[4]. In this Mid-and-Long-Term Decommissioning Action Plan 2020, a specific process for achieving the milestones on the medium- to long-term roadmap, “Start of fuel debris retrieval from the first implementing unit (in FY2021)” and “Expand the scale of retrieval gradually” is shown. For that purpose, we are working on the development of “Reactor containment vessel (PCV) internal details investigation device” for Unit 2 and the device development toward “Trial fuel debris retrieval” and “Expand the scale of retrieval gradually” for Unit 2, as well as “Further expand the scale of retrieval” for Units 1 and 3. An overview is shown below.

3.1 Activities toward “Start of fuel debris retrieval from the first implementing unit (in FY2021)”

PCV internal details investigation device to be introduced into Unit 2 is a device for acquiring information such as the state of the internal structure (shape and dimensions), fuel debris distribution, γ dose distribution, etc[6]. We are planning to carry out trial fuel debris retrieval utilizing this device after replacing the tip tool of its investigation arm with a retrieval tool when the internal details investigation is completed. **Figure 15** gives appearance of investigation device and trial fuel debris retrieval device

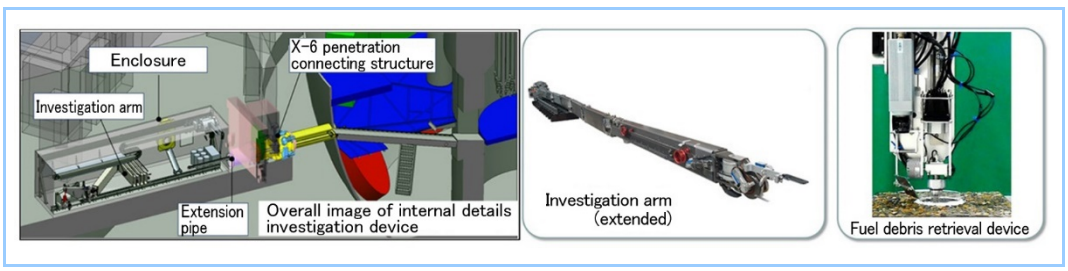

Figure 15 Appearance of PCV internal details investigation device and trial fuel debris retrieval device

3.2 Activities toward "Expand the scale of retrieval gradually (Unit 2)"

For the gradual expansion of the scale of retrieval, we are developing an arm and tip tool with payload (load capacity) increased from 10 kg to 20 kg by shortening the PCV internal details investigation arm and improving the rigidity[6][7]. **Figure 16** shows Concept of arm and tip tools.

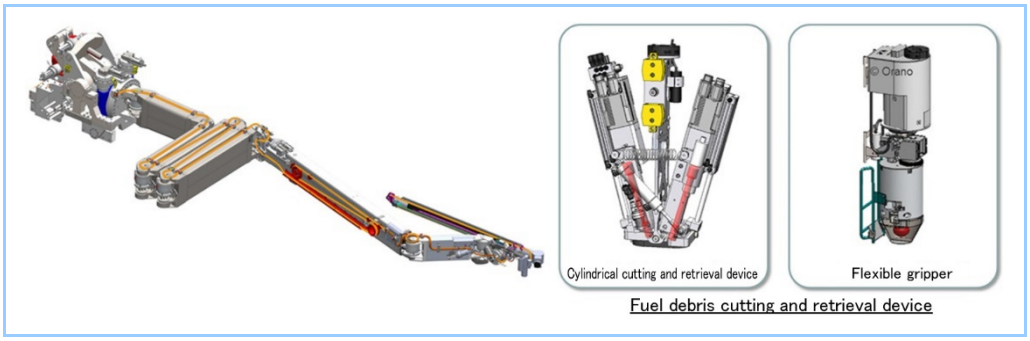

Figure 16 Concept of arm and tip tools for "Expand the scale of retrieval gradually"

3.3 Activities toward "Further expand the scale of retrieval (Units 1, 3)"

At the initial stage of the large-scale technological development of fuel debris retrieval methods, we devised an aerial-horizontal access method utilizing the opening for exchanging CRD that allows for shortest-distance access to fuel debris, and have been developing that technology since then for a subsidized project (Figure 11). So far, we have been working on various technological developments related to fuel debris retrieval in general including the safety design, safety system, cell structure, access device (presented in the previous chapter), etc[8][9]. We plan to further enhance this method in the future based on various knowledge to be obtained from the fuel debris retrieval of Unit 2.

4. Conclusion

We recognize that the early resolution and stabilization of the Fukushima Daiichi Nuclear Power Station is an important issue for Japan's nuclear power business and have provided various forms of support since the initial stage of the accident leveraging the comprehensive technological capabilities of the other departments inside MHI in active cooperation with other companies in Japan and overseas and by taking advantage of our experience in the nuclear field. This report introduced our activities so far from a technological perspective. In the future, plans call for proceeding to fuel debris retrieval, which is a difficult unknown that has never been experienced. We will continue to do our best while further enhancing and refining the related technology development that we have been promoting.

Some of the contents of this report are a result of development that was carried out by MHI as a member of the International Research Institute for Nuclear Decommissioning (IRID) with a subsidy for the project of decommissioning and contaminated water management of the Ministry of Economy, Trade and Industry.

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