Completion of "Joyo" Experimental Fast Reactor Upper Core Structure Replacement - Development of Fast Reactor Core Internal Equipment Replacement method -

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In the "Joyo" experimental fast reactor of Japan Atomic Energy Agency, the upper core structure was damaged due to an accident with the experimental equipment in the reactor vessel. Under high radioactive atmosphere (with fuel loaded) and with the inert gas boundary of about maximum of 160°C, the old upper core structure was extracted through a gap of millimeters by remote control and was replaced with a new upper core structure. Such unprecedentedly difficult operation was successfully completed after a prior study of the risks, design validation using a full-scale mock-up and operational training. This replacement contributed to the development of the fast reactor core internal equipment replacement method.

1. Introduction

In the "Joyo" experimental fast reactor (sodium-cooled fast reactor: hereinafter called "SFR," thermal output: 140 MWt) of Japan Atomic Energy Agency (hereinafter, "JAEA"), a problem occurred in the extraction of the Material Testing Rig with Temperature Control (hereinafter "MARICO-2") that was conducted in May 2007, and part of the testing rig (hereinafter "test subassembly") was damaged and deformed onto the in-vessel storage rack, disabling access to the reactor core fuel in some areas. It was also confirmed that the contact with the MARICO-2 test subassembly caused damage to the bottom of the upper core structure (hereinafter "UCS") (See **Figure 1**)(1).

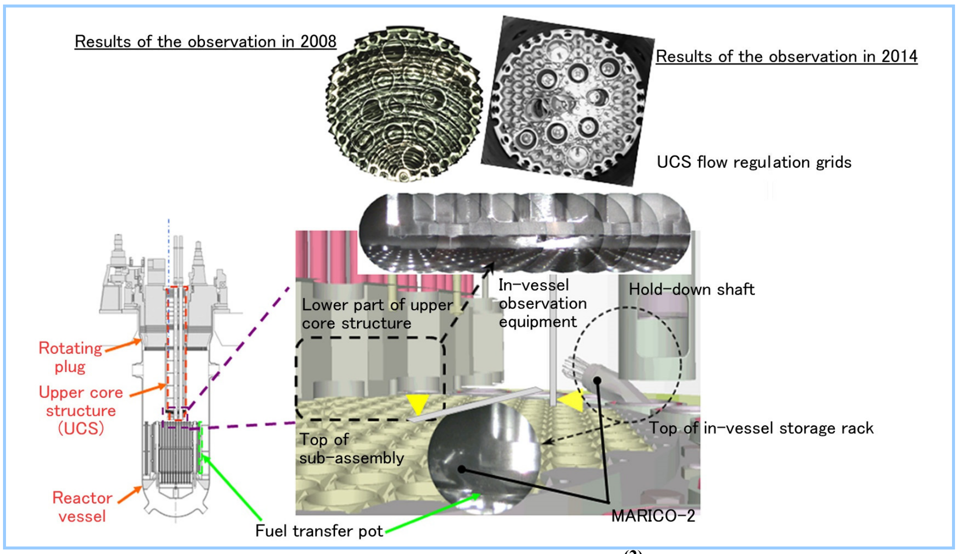

Figure 1 State of damage of core internal equipment(2)
By observing the inside of the core, damage of MARICO-2 was found.
Through the observation of the underside of the UCS, damage of the UCS was also confirmed.

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JAEA decided that to recover from this problem, the MARICO-2 test subassembly should be retrieved and the UCS should be replaced with a new one. Under a commission from JAEA, Mitsubishi Heavy Industries, Ltd. (MHI) cooperated in the development of techniques and a construction method utilizing those techniques, both are required for this UCS replacement work, and designed and manufactured the UCS for replacement as well as the equipment used to carry out the work, which was conducted over May to December 2014. This report describes the achievements in the development of techniques and the methods for the replacement of UCS.

2. Outline of UCS replacement work

2.1 Overview of UCS

An outline structure of the reactor vessel, the rotating plug and UCS of “Joyo” are shown in **Figure 2**. The reactor vessel has a cylindrical container structure with inside diameter of about 3.6m and height of about 10m, and contains the core internals, sub-assemblies, etc. In addition, it has sodium filled inside it to cool sub-assemblies, and its temperature is kept at about 200°C during reactor shutdown. The sodium in the reactor vessel has a free liquid level, and inert gas (argon gas) is filled in the space above the liquid level as cover gas. The rotating plug (including the UCS) installed on top of the reactor vessel defines the boundary of this cover gas.

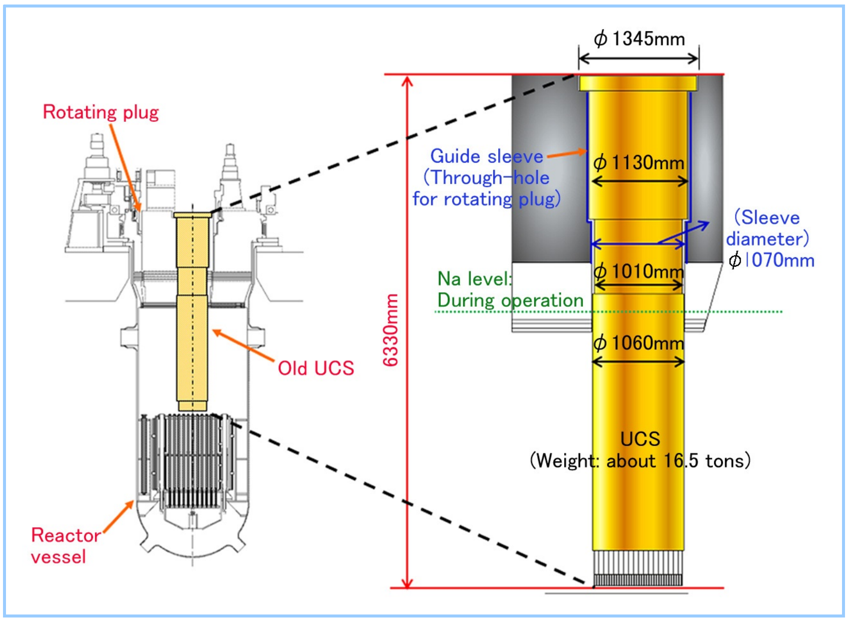

Figure 2 Outline structure of the reactor vessel, rotating plug and UCS of “Joyo”[2]

The UCS, which forms a part of the rotating plug, has a cylindrical structure, as shown in Figure 2, with the maximum diameter of about 1345 mm and a height of about 6330 mm. Its bottom is provided with a flow-regulating grid and thermocouples for measuring the coolant temperature at each sub-assembly outlets. The UCS is also structured to have a large diameter at its lower part, specifically, with the outside diameters of the body being ϕ1130 mm, ϕ1010 mm and ϕ1060 mm from the top.

2.2 Purpose of UCS replacement work

For the purpose of recovering the fuel exchange function and restoring the reactor to a normal state, the UCS replacement work was conducted using the following procedure: (1) the damaged old UCS was extracted; (2) the MARICO-2 test subassembly interfering with the UCS was retrieved (MARICO-2 retrieval work, under control of JAEA), and (3) a newly manufactured UCS was loaded (new UCS installation work).

2.3 Constraint conditions and special conditions for UCS replacement work

In the study of the UCS replacement work method, the constraint conditions and special conditions described below were considered, the risks in the work were extracted and the work procedure for avoiding the risks and the specifications of jigs and devices used in the work were examined.

(1) Constraint conditions

(a) Sub-assemblies in the reactor: Since the Sub-assemblies are loaded inside the reactor, the consideration must be given to radiation.

(b) Liquid sodium in the reactor: Chemically active liquid sodium is present in the reactor, and it is necessary to keep the inert gas atmosphere and take measures against high temperature.

(2) Special conditions

(a) The structure of UCS: Since the UCS was designed without assuming it would be replaced, it has never been extracted in more than 30 years since the reactor was constructed. Therefore, it is necessary to study the avoidance of interference and extraction force at the time of extraction.

3. Efforts by MHI toward the completion of the replacement work

UCS replacement work is broadly divided into two tasks: the "old UCS removal work" in which the existing damaged UCS is extracted, put in a storage cask and transferred to a storage place; and the "new UCS installation work" in which a newly manufactured UCS is loaded into the removal hole (guide sleeve). Taking into consideration the previously described constraint conditions and special conditions, MHI studied the work procedure and the specifications of jigs and devices used in the work and manufactured them. Then, using these jigs and devices, a full-scale mock-up test was conducted for the validation of the work method, and training was provided before the field work.

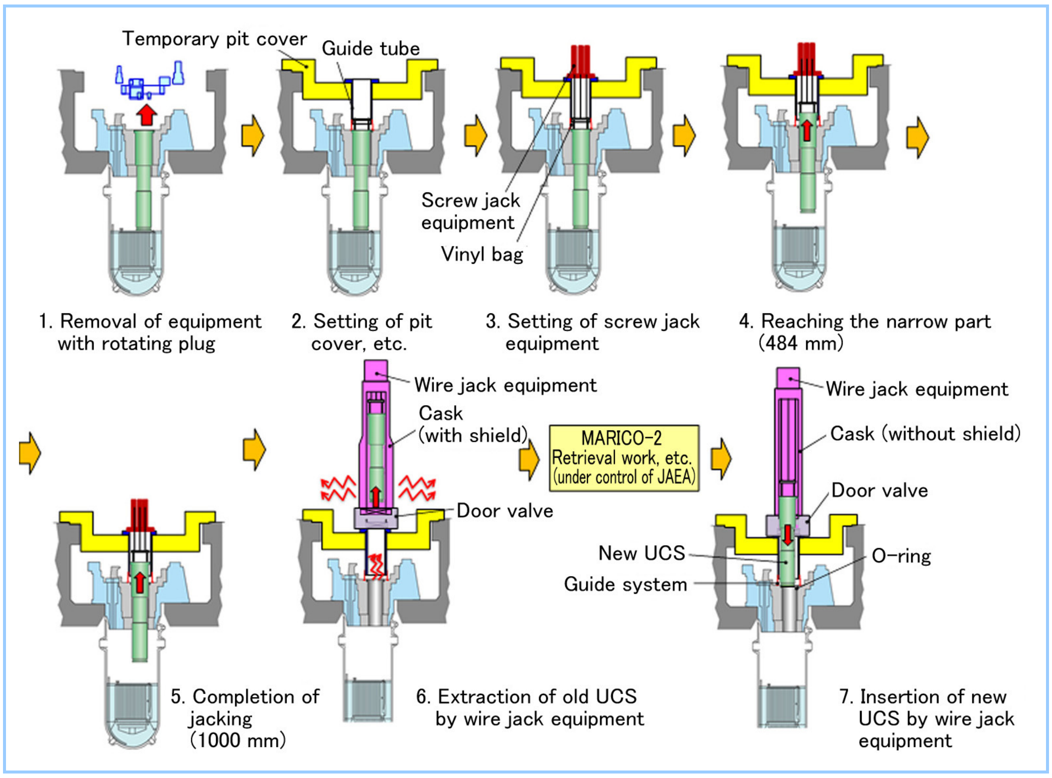

Figure 3 Outline of UCS replacement work procedure
The damaged old UCS was extracted using screw jack equipment and wire jack equipment, and the new UCS was inserted using the wire jack equipment.

3.1 Work procedure and problems and countermeasures

An outline of the UCS replacement work procedure is shown in **Figure 3**. In addition, the major problems and countermeasures in the replacement work are described below.

(1) Problem such as interference in the old UCS extraction work

The UCS of "Joyo" was designed as an eternal structure, as were the reactor vessel and rotating plug, and it was not assumed that the UCS might be replaced during the lifetime of the plant. In fact, it had never been replaced. Therefore, before the old UCS extraction work was conducted, the risks described below were considered. The concept of the risks is shown in **Figure 4**.

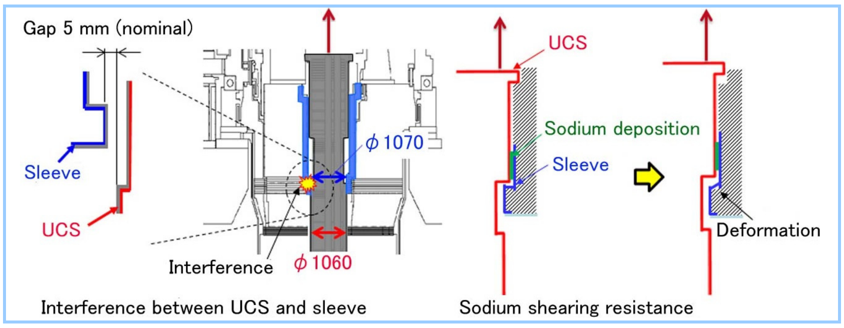

Figure 4 Concept of risks during extraction of UCS
At the time of the extraction of the UCS, there is a risk of damage to the UCS caused by sodium shearing resistance or interference.

(a) When the gap between the old UCS and the guide sleeve is obstructed by sodium deposited during over 30 years of use, resistance is produced by the sodium being sheared during extraction of the old UCS. The guide sleeve in which the old UCS was inserted is a thin structure with a wall thickness of 5 mm. If the sodium shearing resistance becomes excessively large, the guide sleeve may be deformed or damaged.

(b) The design value of the outside diameter of the old UCS large-diameter part is ϕ 1060 mm, while the design value of the inside diameter of the guide sleeve small-diameter part is ϕ 1070 mm. During extraction of the old UCS, the gap becomes 5 mm at one side. The UCS is positioned with reference to the central axis of the core internals (core support plate), and the UCS has been set up being displaced from the central axis of the guide sleeve. As such, the gap may become lopsided. Therefore, if the large-diameter part of the old UCS is largely inclined during extraction, the old UCS and the guide sleeve interfere or come into contact with each other, producing resistance (hereinafter, “interference resistance”). If the interference resistance becomes excessively large, the old UCS may be deformed or damaged.

To prevent the above (a) and (b), it is effective to monitor the inclination (levelness of the top face) and load of the old UCS during the extraction work and to stop the work by interlocking if the inclination or load becomes large.

(2) Establishment of method using vinyl bag

The O-ring replacement and its associated O-ring groove cleaning work before the installation of the new UCS had to be conducted manually, in the state of the cover gas boundary being secured, while being visually checked. Therefore, a gas boundary made from a transparent vinyl bag with work gloves attached thereto was adopted. This work must be conducted via the vinyl bag in a very confined space above the rotating plug (See **Figure 5**.) The O-ring replacement and O-ring groove cleaning method were established after the verification of work through the full-scale mock-up test and changes in the design, such as the positioning of the gloves, were based on the verification results.

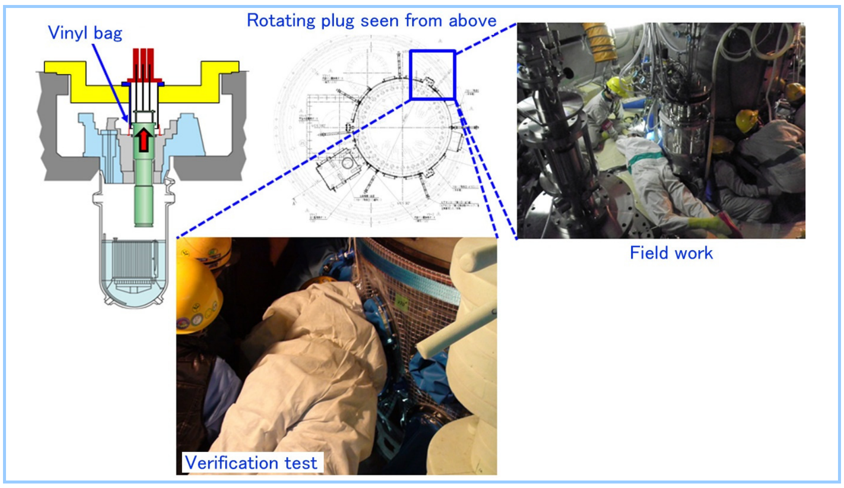

Figure 5 Work via vinyl bag
Through the full-scale mock-up test in the closely simulated field work environment, the problems in the work were identified and improvements were made, resulting in success in the work.

(3) Ascending of high-temperature cover gas

In the period from the old UCS extraction work to the completion of new UCS installation, the high-temperature cover gas in the reactor vessel will ascend while top of the UCS guide sleeve is opened, and the ability of the boundary formed by the vinyl bag which is set up on the rotating plug cannot be ensured. To prevent this, the cover gas circulating system was constructed, so that low-temperature argon gas was blown down from upper side of the argon gas boundary to prevent the high-temperature cover gas from ascending from the reactor vessel. This system was planned and provided by JAEA (See **Figure 6**)(3).

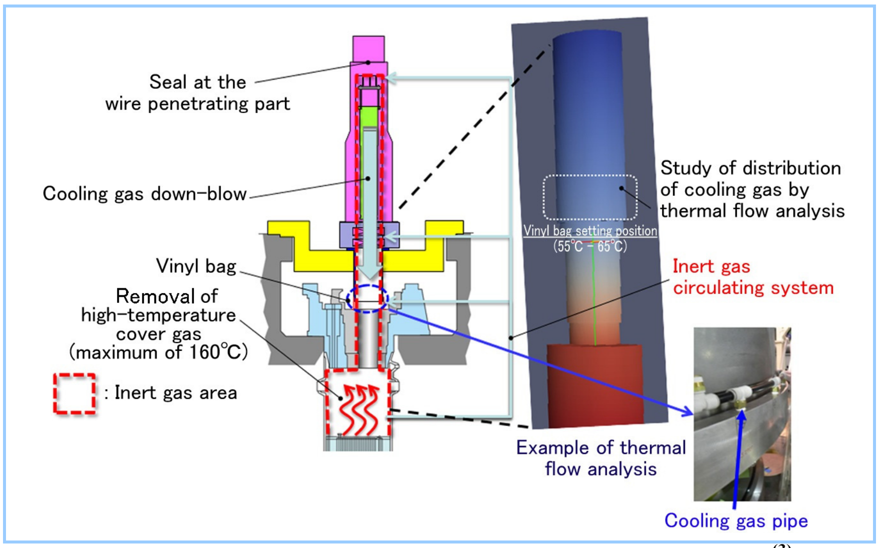

Figure 6 Concept of the measures for high-temperature cover gas(3)
An inert gas circulating system was constructed, so that the down blow of cooling gas prevents the high-temperature cover gas from ascending. (By JAEA)

3.2 Full-scale mock-up test

Prior to the UCS replacement work, a full-scale mock-up test was conducted using the equipment used in the actual work and mock-ups with the same sizes as those of the actual devices, the work procedure and operational methods of jigs and devices were checked and the obtained results were reflected in the work procedural manuals. In the full-scale mock-up test, mock-ups with the actual dimensions of the small rotating plug, guide sleeve and UCS were set up on a test stand with dimensions of about 12m × 12m × 8m, and the working conditions of the actual work were simulated. The lower body of the guide sleeve mock-up was designed so that part of the gap between the guide sleeve mock-up and the UCS mock-up would be smaller than the design value, in consideration of the manufacturing tolerance in the actual guide sleeve and any distortion created during its installation. The UCS mock-up was designed to simulate the weight and the position of the center of gravity of the actual equipment.

The outlines and results of the “jacking work procedure test” and the “extraction and insertion performance check test” in the full-scale mock-up test, which were implemented to obtain data on the UCS removal and insertion work, are described below.

(1) Jacking work procedure test

All the operations from the installation to the removal of the screw jack equipment were simulated and the setting data for parameters (extraction height, extraction speed, allowable loads thereto, etc.) required for extraction by the screw jack equipment were obtained. Through the simulation, the prospect was obtained that the work for jacking from the state of being placed on the bottom to the position at 1000 mm could be conducted without any problems, while the load and levelness were maintained within the allowable values. Furthermore, to check the procedure of O-ring removal work that will be conducted after the jacking work of the old UCS in the actual equipment and the handling ability of jigs, training for removing O-rings via the vinyl bag in the same way as in the actual work was conducted.

In the old UCS jacking work and the new UCS insertion work, there is an especially high risk that the UCS and the guide sleeve may interfere or come into contact with each other, resulting in difficulty in continuing the work. To reduce these risks, the interference simulation test was conducted using a mock-up for the purpose of estimating the position where interference occurs and establishing a procedure for avoiding interference. The results of the interference simulation test are shown in **Figure 7**. In this test, an interference plate with a width of 50 mm was set up on the guide sleeve mock-up, and the data on the loading behavior in the directions from 0 to 360 degrees when it interferes with the UCS mock-up was obtained. If the UCS interferes or comes into contact with the guide sleeve during the extraction of the UCS, the loads applied to the three jacks become unbalanced due to the resistance at the interfering position. In the old UCS jacking work, etc., the position where interference occurred was calculated or estimated based on the obtained offset load data. As shown in Figure 7, the offset load data obtained when the mock-ups were directly interfered with generally agrees with the load value obtained when the interference plate was set up, which shows that this procedure is effective(2).

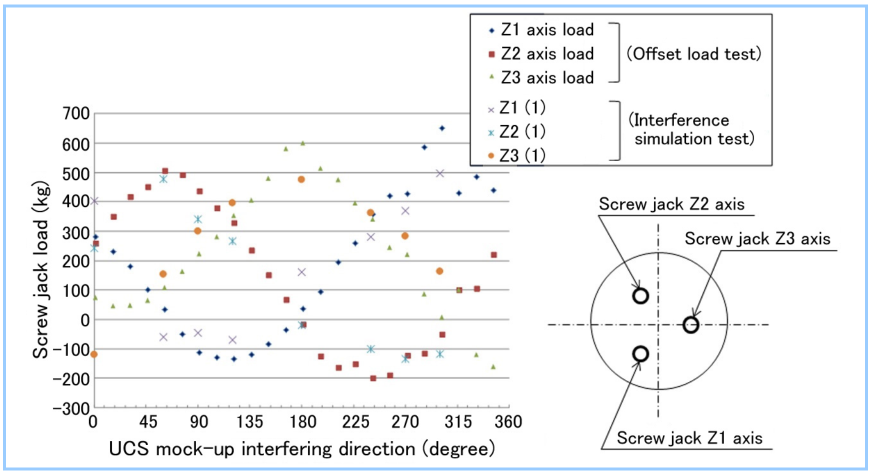

Figure 7 Results of the interference simulation test using the mock-up
In the mock-up test, interference was intentionally produced, so that a method of identifying the interfering direction could be established.

Next, the procedure for avoiding interference is described. The screw jack equipment has a high rigidity and is integrally structured with the old UCS so that precise level control is realized. Therefore, as shown in **Figure 8**, the screw jack equipment was set up on the top face of the guide tube, the guide tube was slid in horizontal and right-angled two directions by the push bolt for the adjustment of the horizontal position provided on the guide tube, thereby correcting the eccentricity of the old UCS to avoid interference between the old UCS and the guide sleeve, and the UCS mock-up was extracted up to the position of 1000 mm. Thus, it was confirmed that by using the same method, the old UCS could be extracted in the actual field work(2).

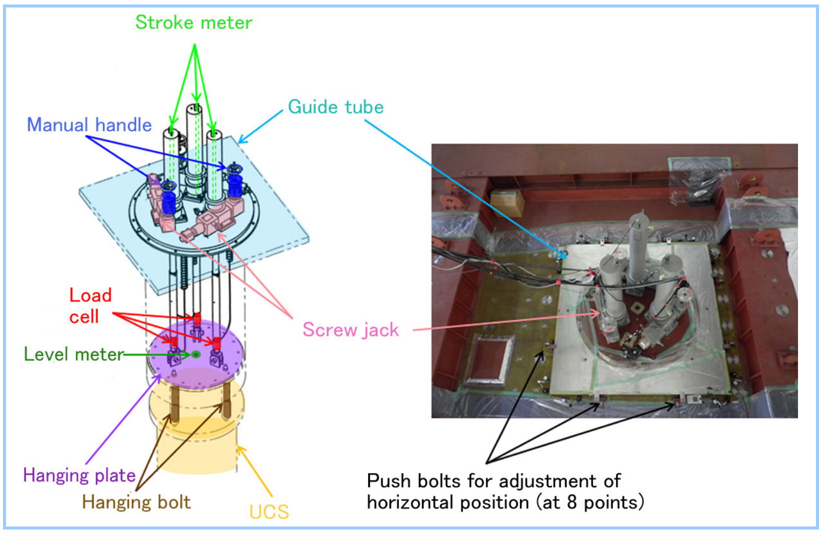

Figure 8 Screw jack equipment
Three screw jacks are placed in a circle, with each of them equipped with a load meter and a stroke meter. They are set up on the guide tube so that horizontal adjustment can be made.

(2) Extraction and insertion performance test

In the extraction and insertion performance test, the UCS test body was visually checked from above and from the lateral side, and all the operations of the old UCS extraction and housing work and the new UCS insertion work using the wire jack equipment were simulated while checking the run-out state of the UCS test body occurring during extraction and insertion, and the setting data for the necessary parameters (extraction/insertion height, extraction/insertion speed, allowable loads thereto, etc.) were obtained. Thus, the prospect was obtained that the housing work (1000 mm to about 11400 mm) and the insertion work (about 11400 mm to 0 mm) could be conducted without any problems, while the load and levelness were maintained within the allowable values[2].

Next, concerning the means of avoiding interference, since the wire jack equipment has a flexible structure, the eccentricity of the new UCS was corrected by the guide system provided at three points in the circumferential direction on the top face of the rotating plug, so that interference between the new UCS and the guide sleeve could be avoided.

Furthermore, in the preparatory work for the extraction and insertion performance test, the procedure for setting the large, heavy devices, such as the door valve and cask, in alignment with the central axis of the UCS was verified, and through the measurement of the deformation, etc., of the shield floor associated with the setting-up of the large, heavy devices, the data required for securing the verticality during the installation of the cask, etc., in the actual field work and for preventing eccentricity, etc., of the UCS and the guide sleeve lifted up by the wire jack equipment was also obtained.

In addition to the above operations, in the full-scale mock-up test, a series of tasks including the removal and attachment of bolts were implemented. Through this work, the installation positions and connection of devices, installation procedures, handling methods,, etc., were clarified, the data contributing to the development of work procedural manuals was obtained, and the skills of workers were enhanced, toward the actual field work.

4. UCS replacement work in the field

The UCS replacement work implemented in the field based on the previously described full-scale mock-up test results is described below.

4.1 Old UCS removal work

In the old UCS removal work, the monitoring of levelness with high precision and the load control of the jacking equipment and the wire jack equipment effectively functioned and the work was completed as planned.

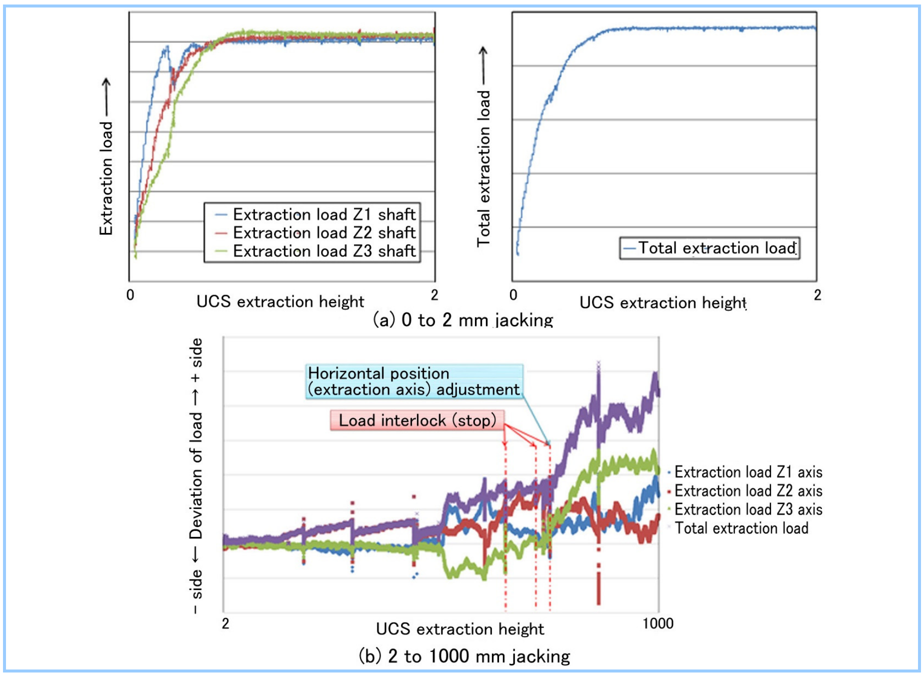

Figure 9 Changes of load during jacking of UCS
During the extraction of the UCS, no sodium shearing resistance was observed.
Interference during the extraction was avoided by horizontal movement.

(1) Old UCS jacking work

At the position of 0 to 2 mm, to check for the presence or absence of sodium shearing resistance and its behavior, the old UCS was jacked up by manual handle operation (with a jacking speed of about 2 mm/h). The load measurement results at the position are shown in **Figure 9**(a). The extraction load increased with the movement of the jack, but it became almost constant at about 16.8 tons, and resistance associated with sodium shearing was not observed. However, in the observation after 1000 mm jacking, adherence of porous sodium with fine particles that had aggregated or deposited on the side face of the upper body of the old UCS was observed[2].

At the position of 2 to 1000 mm, the old UCS was jacked up by automatic operation with interlocking triggered by levelness and load restriction. The load measurement results at this position are shown in Figure 9(b). Here, the load value was set by canceling the weight of the old UCS, etc. to make it easy to determine the load produced by interference. During jacking, load equalization measures (level adjustment only by screw jack operation) were conducted as appropriate, so that the unbalanced load produced by the offset between the center of gravity of the old UCS and the center of jacking was corrected. As shown in Figure 9(b), at the position of about 750 mm, it was detected that interference was produced between the old UCS and the guide sleeve. According to the prepared procedure for avoiding interference, the extraction position was moved by about 0.7 mm using the push bolt for the adjustment of the horizontal position on the guide tube, resulting in the avoidance of interference. It was confirmed that the procedure for avoiding interference was appropriate[2]. Thus, the prospect was obtained that in the old UCS jacking work, after the old UCS was jacked up to the position of 1000 mm, the subsequent old UCS removal and containing work could be conducted without any problems as initially planned.

(2) Old UCS removal and containing work

In the old UCS removal and containing work using the wire jack equipment, the total initial load was about 18 tons as shown in **Figure 10**, but while the removal work was being conducted, the resistance which may be caused by the contact between the old UCS and the guide sleeve gradually decreased, and it became almost stable at about 17.3 tons in the position between about 4000 mm and the upper limit, where the removal and containing work could be completed. The storage cask in which the old UCS was contained was transferred from the reactor containment vessel to the old waste treatment building, an additional shield body for storage was mounted, and the storage cask was put into storage.

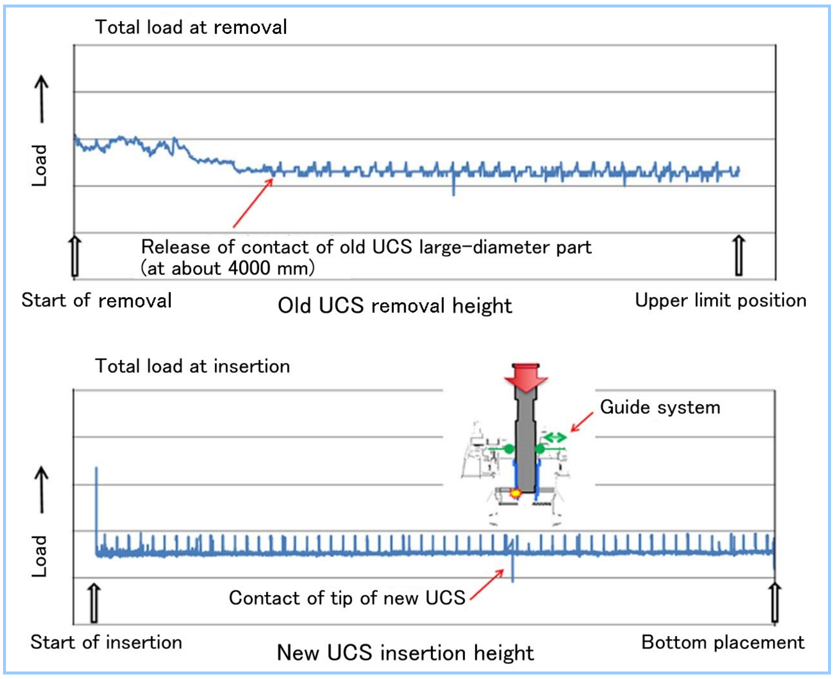

Figure 10 Changes of load during removal and insertion of UCS
During the removal of the UCS, the load fluctuated until the UCS completely passed through the small-diameter part of the guide sleeve. During the insertion of the new UCS, the load was stable except when the fore-end came into contact.

4.2 New UCS installation work

The new UCS installation work could also be completed as planned, because a detailed work plan was prepared and the procedure was mastered through training in advance.

(1) O-ring attachment work for new UCS

Since the O-ring attachment work for the new UCS must be manually done by workers, it was conducted in the state of a temporary shield plug being inserted in the guide sleeve. The cleaning of the O-ring groove and the attachment of the O-ring must be conducted using gloves via the vinyl bag in a confined place. Using the jigs and the procedure developed based on the work training results in the full-scale mock-up test, the O-ring for the new UCS could be successfully attached to the O-ring groove. The state of the O-ring installation work for the new UCS is shown in Figure 5.

(2) New UCS insertion work

In the new UCS insertion work using the wire jack equipment, the total load was generally stable at about 16.6 tons as shown in **Figure 11**. Interference between the new UCS and the guide sleeve was detected at the position of about 4500 mm, but according to the interference avoidance procedure established through the full-scale mock-up test, the interference could be avoided by moving the insertion position by about 5 mm in the horizontal direction using the guide equipment. Thus, it was confirmed that the avoidance procedure was appropriate. With the levelness control and load control during the insertion work and the function of the guide equipment, no interference that prevented the insertion of the new UCS was produced after that[2].

Furthermore, the new UCS was required to be installed within ±1.02 mm from the planned position based on the old UCS installation position and the new UCS manufacturing dimensions. In the placement/installation of the new UCS on the bottom, as shown in Figure 11, after it was confirmed that the tip of the guide bolts were projected out through the new UCS flange bolt holes, each guide ring adjusted to the given dimensions was inserted into the gap between the bolt hole and the guide bolt. The installation accuracy was measured after the new UCS was placed/installed on the bottom, and the results showed that the error was within the maximum of 0.35 mm ± 0.1 mm from the planned position[2].

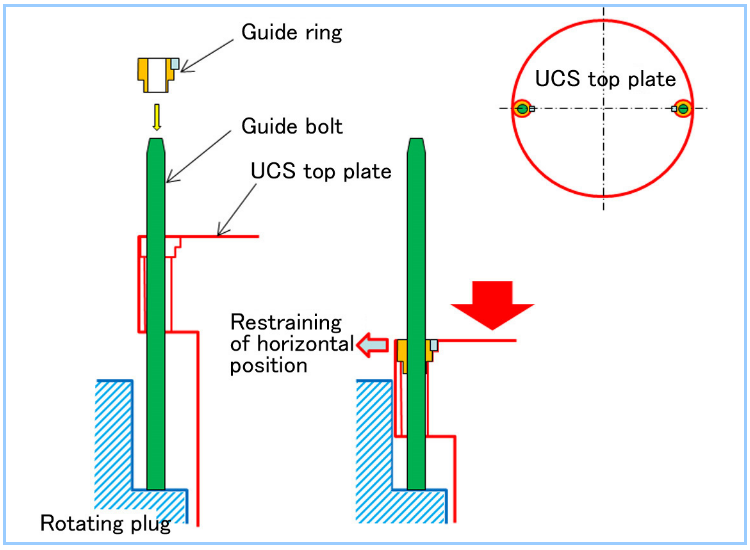

Figure 11 Method of positioning in installation of the new UCS
Using the guide bolt and the guide ring, the new UCS was installed at the given position.

5. Conclusion

The maintenance and repair works for reactor core internal equipment in sodium-cooled fast reactor must be conducted in a high-radiation dose, high-temperature environment and inert-gas sealed environment. Therefore, development of maintenance and repair work techniques which are different from those for light water reactor power plant is required. For this replacement work of the upper core structure of “Joyo,” the special equipment and construction method under the new concept were developed, the full-scale mock-up device of the actual equipment was manufactured, and the technical verification, feasibility check and training of operators were carefully repeated before the actual replacement works, and finally, the replacement of the upper core structure was successfully completed as initially planned. The techniques, experiences and findings obtained through this replacement will greatly contribute to the progress of maintenance and repair techniques for the fast reactor in the future.

Lastly, we would like to express our gratitude to JAEA and the concerned parties for their guidance and cooperation in the study of the methods, the manufacturing of the equipment and the field work for the upper core structure replacement operation, and would like to ask for further understanding and support for the development of fast reactors in the future.

[Explanation of terms]

- Upper Core Structure: One of the fast reactor core internal structures. It has the functions of guiding and holding the control rod driving mechanism and measuring the temperature of the coolant at the core fuel assembly outlet.
- Gas boundary: The space in which the target gas is enclosed or the material which forms the space.
- Full-scale mock-up: A facility composed of full-scale mock-ups of all objects for target actions.

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