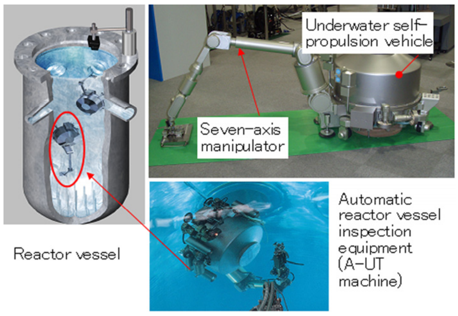
MHI's Maintenance Technologies Supporting High Plant Availability of PWR Nuclear Power Plants



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Nuclear power generation is expected to continue to contribute to stable energy supply and global warming countermeasures and hence plays an important role as a key low-carbon energy source. Twenty-four pressurized water reactors (PWRs) are in operation in Japan, and those constructed in the early phase is reaching the 40-year mark since the start of operation. We believe that the elimination of unplanned or extended outages, enhanced availability and the achievement of stable and safe operation of nuclear power plants regardless of the aging of components would contribute to building a low-carbon society. This report describes the latest maintenance technologies that have been developed to meet these requirements, including the enhanced reliability of plant components by means of the application of preventive maintenance and inspection technologies as well as the streamlining and advancement of work processes through reduction in the load of and radiation exposure to workers.

1. Introduction

To take full advantage of nuclear power plants that do not emit carbon dioxide in the power generation process, it is important to perform appropriate aging countermeasures to achieve long-term stable operation. Mitsubishi Heavy Industries, Ltd. (MHI) has been engaged in energy issues through maintenance work at domestic PWR plants. In order to achieve safe and stable operation with high availability, a variety of maintenance and inspection technologies, such as those for replacement of heavy components as well as cladding and overlaying for material improvement, have been developed and applied to eliminate any unplanned or extended outages.

This report describes the measures against stress corrosion cracking and the advancement of inspection technology to make more contribution to the maintenance work. It also describes the efforts of improving the workers' skill, reduction in the load of and radiation exposure to the workers, and the development and application of various tools that contribute to improving the work reliability that are intended to streamline and advance the various maintenance work performed during periodic inspections.

2. Effectiveness of peening methods for mitigating stress corrosion cracking

Defects that become obvious with time include stress corrosion cracking (SCC), which is estimated to occur due to the combined effects of the environment, material and stress. As measures against SCC, two types of peening methods that can improve surface residual stress into compressive stress were developed, verified and applied to the reactor vessel (RV) and steam generator (SG). These methods are the water jet peening process[1] (WJP) and the ultrasonic shot-peening process[2] (USP) shown in **Figure 1**. Considering the situations where SCC has frequently occurred at PWR plants in Japan and overseas, it is important to confirm whether there is any adverse impact on defects and improving effect on residual stress following the application of a peening process to a region where micro defects exist, in order to discuss the maintenance of components and piping subjected to peening.

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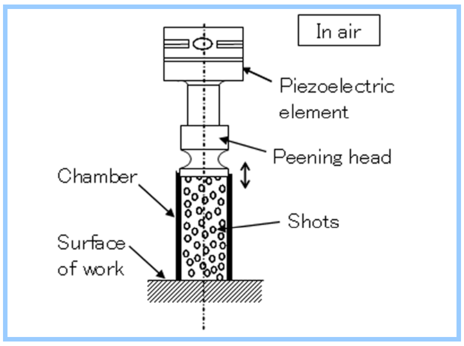


Figure 1(a) Ultrasonic shot-peening process
The method applies shot peening by giving the shots a to-and-fro motion between the object and the peening head in a chamber by the ultrasonic vibration of a piezoelectric element.

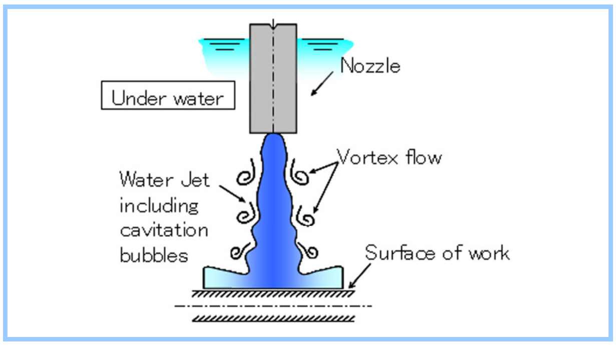


Figure 1(b) Water jet peening process
An injection of high-speed water jet through a nozzle into water generates cavitation bubbles on the boundary surface between the stationary water around the nozzle and the high-speed jet due to high velocity. The water jet peening process is a method of applying peening on the object surface using the impact pressure generated when these cavitation bubbles collapse.

To verify these concerns, the impact of peening on defects and the stress improving effect near defects were evaluated after introducing SCC-type micro defects (hereinafter, "latent defects") into a plate specimen.[3] As a result, it was determined that WJP and USP are effective maintenance techniques even when there are latent defects that are unlikely to be detected before applying WJP/USP, as described below.

(1) Improvement of residual stress in regions where latent defects exist

To experimentally confirm that the residual stress adjacent to latent defects is improved by the application of WJP or USP regardless of the existence of latent defects, a test specimen (NCF600/SUS316 specimen with 150 mm long × 30 mm wide × 10 mm thick) was prepared. Latent defects, as shown in **Figure 2**, were introduced in the specimen by applying a stress by means of four-point bending in polythionic acid solution. WJP or USP was performed after introduction of defects in the specimen, and then residual stress was measured by the X-ray diffraction method. The test results for the SUS316 specimen are shown in **Figure 3** as a representative case. Regardless of the existence of defects, about the same level of residual stress was observed and compressive residual stress was observed within the depth of 1 mm from the surface.

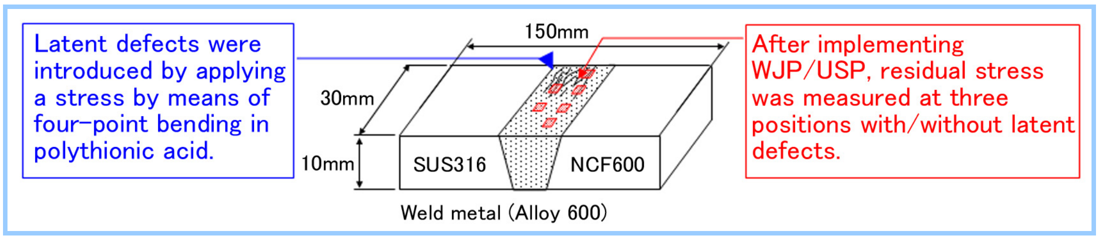


Figure 2 Plate specimen for measuring residual stress
The test was carried out by introducing SCC-type micro defects (latent defects) in a half part of each specimen. The specimen in the figure shows the one using Alloy 600 weld metal.

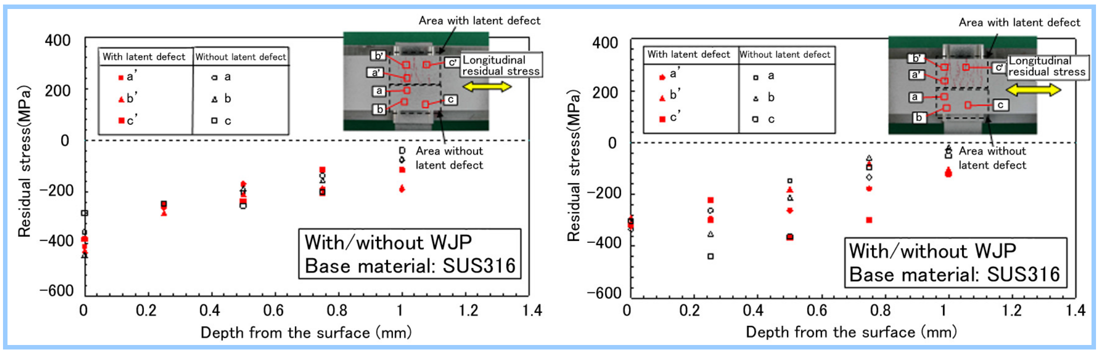


Figure 3 Measurement results of residual stress after peening (in the case of SUS316)
In-depth residual stress distributions with or without the latent defects measured by the X-ray diffraction method are shown. It was confirmed that the residual stresses are compressive regardless of the presence of latent defects.

(2) Suppression of SCC progress in regions where latent defects exist

To experimentally confirm that latent defects subjected to WJP/USP do not develop into SCC (peening is effective) during service, a test specimen (NCF600/SUS316 specimen with 150 mm long × 40 mm wide × 10 mm thick), shown in **Figure 4**, was prepared in the same way as described above. The specimen was cut off along the central line of the 40-mm width, and WJP or USP was applied to only one of the cut pieces. Then, SCC testing was carried out with the specimens immersed in polythionic acid under application of a stress equivalent to that encountered during operation by means of four-point bending to determine by destructive examination after testing whether SCC develops. A magnified observation was carried out on two cross sections for each test condition to measure the depth of all defects observed, and the result was graphed on a Weibull plot.

The test results obtained for SUS316 specimens are shown in **Figure 5** as a representative example. After peening was implemented, there was no significant difference in defect depth between the specimens with and without SCC testing, suggesting there was no development of SCC. In addition, a comparison between with and without WJP/USP showed a greater SCC progress in the specimens without WJP/USP, revealing that the SCC testing was performed under appropriate conditions.

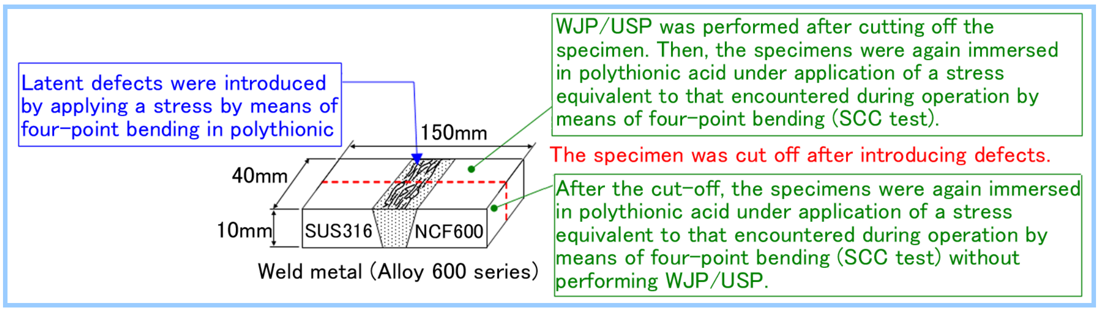


Figure 4 Plate specimen for determining the effectiveness of inhibiting SCC progress
The specimen was divided into two pieces after introduction of latent defects. The SCC test was performed for both pieces after applying WJP/USP to only one of them.

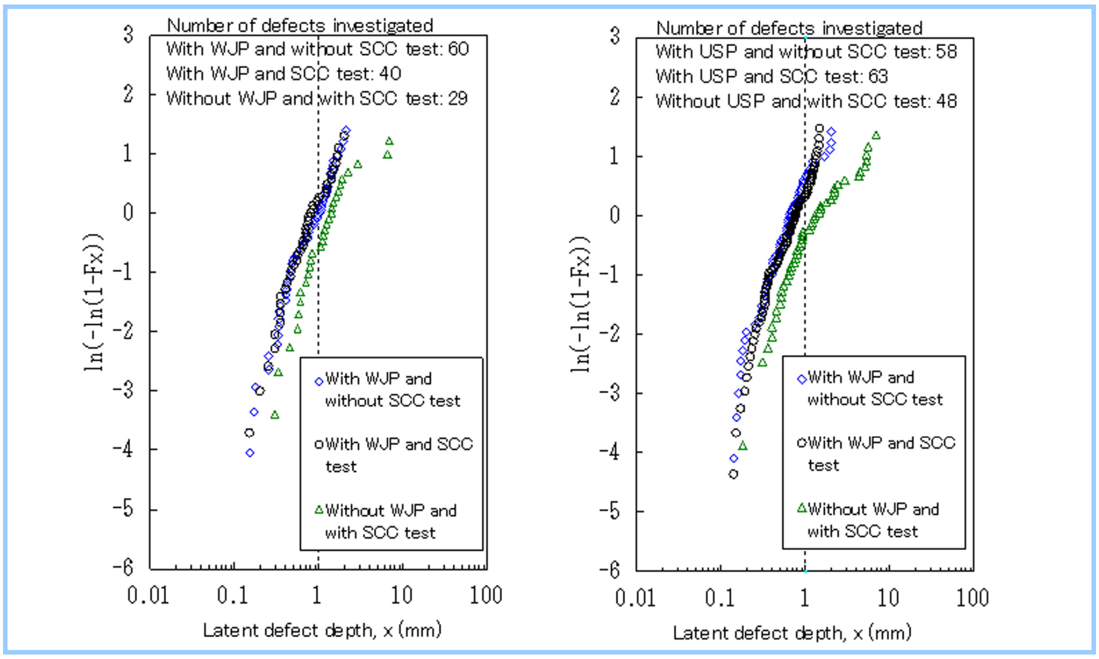


Figure 5 Weibull plot of latent defect depth (in the case of SUS316)
The depth of all defects identified by cross-sectional observation was measured. In the equation of the vertical axis, Fx is the cumulative frequency of a defect whose depth is less than the value in the horizontal axis. Although the two results were not obtained for the same latent defect, they indicate that the peening processes (WJP and USP) are effective in suppressing SCC progress.

3. Advancement of inspection technology

3.1 Advancement of ultrasonic testing technology

Although ultrasonic testing (UT) has been applied to the inspection of piping and pressure vessels, since it has a problem in inspecting an area with complicated geometry, such as a nozzle, and a portion through which ultrasonic waves penetrate poorly, such as a weld region, and there is an increasing need for the quantification of defects, development of phased array UT technology is being pursued[4].

An overview of the development is shown in **Figure 6**. A matrix phased array UT having higher flaw detection speed and superior sizing accuracy is being developed. A probe of the phased array UT consists of more than one piezoelectric element, while a regular UT probe consists of only one piezoelectric element. The control of transmitting/receiving timing of these piezoelectric elements allows for transmission at an arbitrary angle and focusing on an arbitrary position of a synthesized wave. While a general phased array transducer, which is called a linear array, consists of transducers that are arrayed one-dimensionally, the matrix array consists of transducers that are arrayed two-dimensionally and is capable of three-dimensional ultrasonic beam scanning, which allows improved defect detection and depth sizing accuracy.

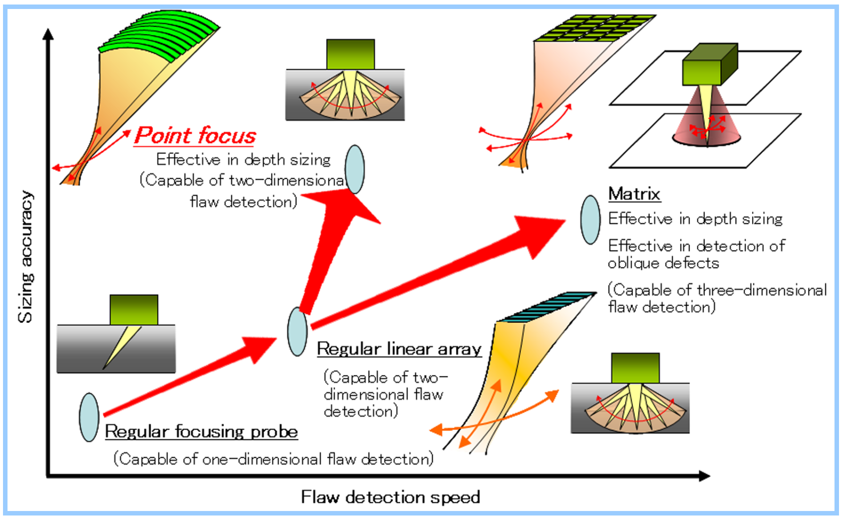


Figure 6 Overview of technology development of the phased array UT
A transducer consisting of more than one piezoelectric element is called phased array UT.

Figure 7 shows the test results for the detection of oblique defects using the matrix array. The results show that the matrix array is capable of clearly detecting all defects with tilt angles between 0 and 20 degrees, while a regular linear array can hardly detect a defect with a tilt angle of 20 degrees. At present, development of a new-type matrix array probe is in progress to improve accuracy in the sizing of Alloy 600 weld of RV and SG nozzle, which is technically difficult. **Figure 8** shows an example of the new-type matrix array probes designed for use of RV nozzle, which has been determined to have superior sizing accuracy to the conventional method.[5]

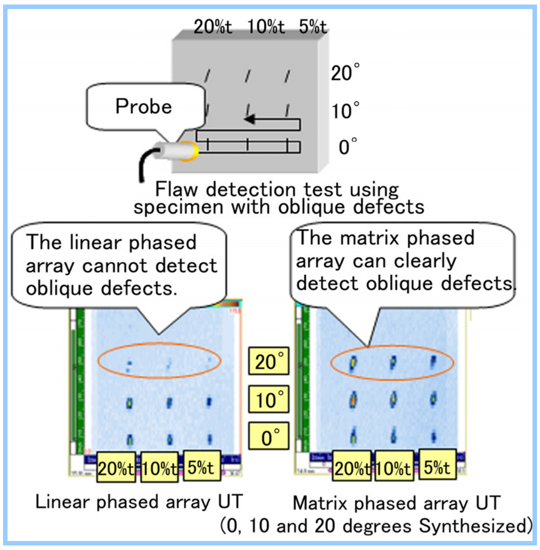


Figure 7 Detection result of oblique defects with the phased array UT
The matrix phased array UT allows for the detection of defects including oblique ones.

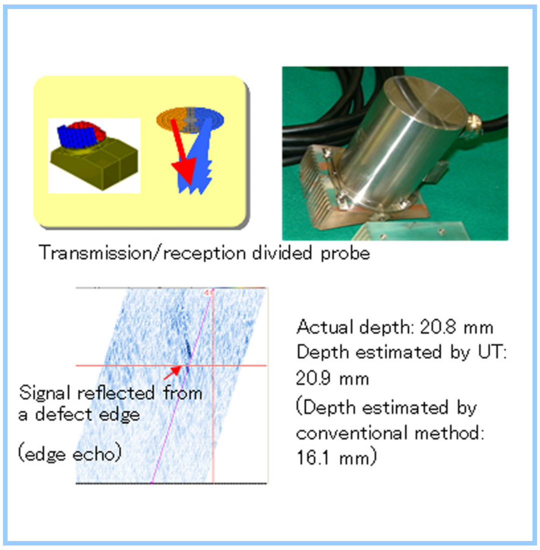


Figure 8 New-type matrix array probe
The matrix array probe designed for application to an area of Alloy 600 weld metals through which ultrasonic waves penetrate poorly has superior performance to the conventional method.

3.2 Efforts to improve inspectors' skills

Although, as described above, development and commercialization of inspection technologies are promoted to meet a wide variety of inspection needs, it is essential to improve inspectors' skills for the actual use of these technologies. MHI is building better skill training programs designed to maintain and improve inspectors' skills, and is making efforts to enhance the workers' abilities to obtain relevant qualifications. Examples of acquired qualifications include: JIS Z 2305 "Nondestructive inspection personnel qualification" (number of personnel qualified: 427), NDIS 0603 "Qualification and certification of personnel for performance demonstration of ultrasonic testing systems" (number of personnel qualified: 8), and "Qualification based on US EPRI's certification" (number of personnel qualified: 16 for ECT/QDA*[1], 35 for UT/PDI*[2]).

*1 Qualified Data Analyst: Qualification of personnel who analyze ECT data for steam generator tubing that is certified according to Appendix G of EPRI's SG Guideline.

*2 Performance Demonstration Initiative: Qualification for UT of pressure vessels and piping specified by the ASME Sec. XI.

4. Sophistication of maintenance

During outage, various components are overhauled and various maintenances are conducted to improve reliability. These efforts have been made for each component. Using modern digital technologies, efforts are being made for streamlining, such as reducing workers' exposure and shortening work time periods, and improving reliability.

4.1 Deployment of tablet PC for work management

During overhauling, in principle, paper-based work procedures and records are implemented, and generally, data are written down by hand in the field and then summarized after returning to the office. On the other hand, since portable personal computers (PCs) are in general use these days, we have tried to use a lightweight hand-held PC (hereinafter, "tablet PC") for the overhauling of components conducted in the field.

This has made a significant contribution to the improvement of work reliability and reduction in the workers' load, such as display of cautions and important matters for each work item on a tablet PC, automatic judgment of measurement results, visualization of measurement progress (to prevent any oversight of work and human error using a colored display), and understanding of trends through comparison between the measured data and the preceding data stored in the tablet PC. For future use, we expect that incorporation of circumstance photographs and size measurement results obtained in the field inspection into the tablet PC using a digital camera and digital pen will help shorten the work period in a high radiation environment and make a database of various adjustment results for instrumentation and equipment (collective record management), as shown in **Figure 9**, and that these deployments will enable us to achieve streamlining (work period and workers' exposure) and to improve work reliability.

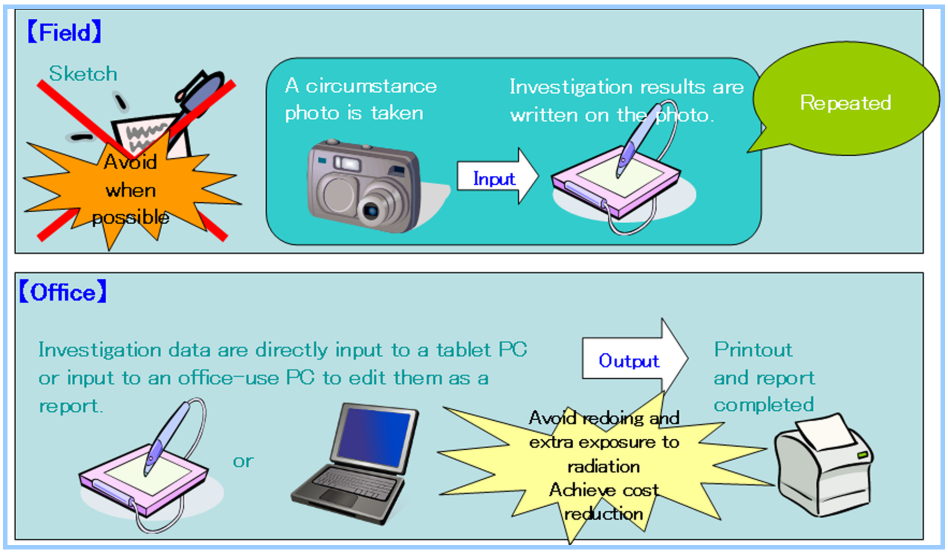


Figure 9 An example of the use of tablet PC as a tool to support field inspection
The input of data to the tablet PC using a digital camera and digital pen during work allows for the streamlining of work procedures.

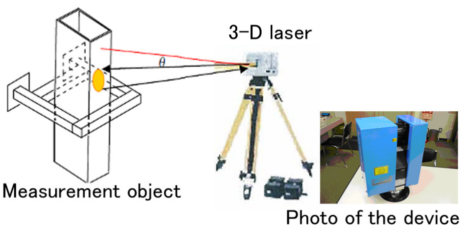
4.2 Utilization of three-dimensional laser measurement technology for modification design

Previously, field inspections were generally performed by workers who made measurement by taping, drew a sketch by hand, and made a fair drawing (two-dimensional CAD, etc.) in his or her office. This led to an increased load on workers in a high radiation environment, etc., and reduced exposure and a higher level of survey effectiveness are desired. Aiming at improvement in the on-site survey process, a three-dimensional laser measurement device generally used in the industry was introduced into the processes of field survey, work feasibility check and design of modification to streamline the entire modification process.

The laser measurement method is to obtain three-dimensional coordinate information through measurement in the direction of laser transmission by calculating distance based on the time and phase difference measured when a laser beam is transmitted between the sensor and the target of measurement (e.g., piping, duct, support structure). An overview of the three-dimensional laser measurement device used in this study is shown in **Figure 10**.

An example of the point data (measured data of three-dimensional coordinates) obtained in a on-site survey is shown in **Figure 11**. This information was converted to a three-dimensional model (three-dimensional CAD information in the present case), which is shown in **Figure 12**. This conversion allows for confirmation of the whole appearance of the site and as-built dimensions, and thereby enables us to easily check the circumstances of component installation and operation, availability of space after modification, and presence of interfering objects, as well as to perform modification design. The images shown in Figures 11 and 12 were prepared for modification intended for enhancement of seismic resistance. Using these, modification was conducted with high accuracy.[6]

Since the effectiveness of this method has been verified, it is considered possible to reduce workers' exposure and improve prior investigation through the utilization of collected data (for three-dimensional CAD) for planning modification under conditions where constant access is not easy to achieve, such as during plant operation and in a high radiation environment.



Item	Specification
Measurement method	Phase contrast method
Measurement time	Approx. 10 minutes (approx. 500,000 P/s)
Measurable distance	Approx. 1 - 75 m
Measurable range (angle)	Horizontal direction: 360 deg. Vertical direction: 310 deg.
Dimensions and weight	Approx. 200 × 300 × 300 mm, 15 kg

Figure 10 Overview of three-dimensional laser measurement device
Three-dimensional coordinate information is obtained by calculating distance based on the time and phase difference measured when a laser beam is transmitted between the source and the target.

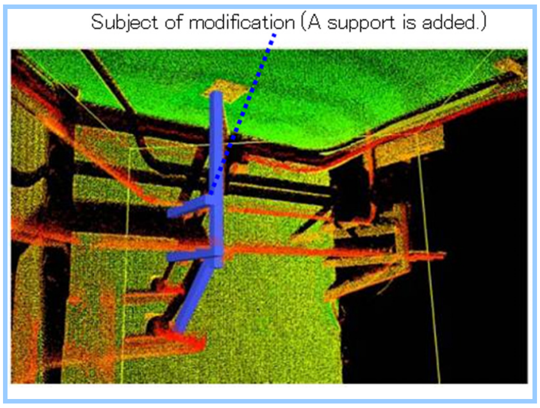


Figure 11 An example of laser measurement data
The laser measurement data (point data) contains three-dimensional coordinate information contained. The subject of modification (three-dimensional CAD information) is added for reference.

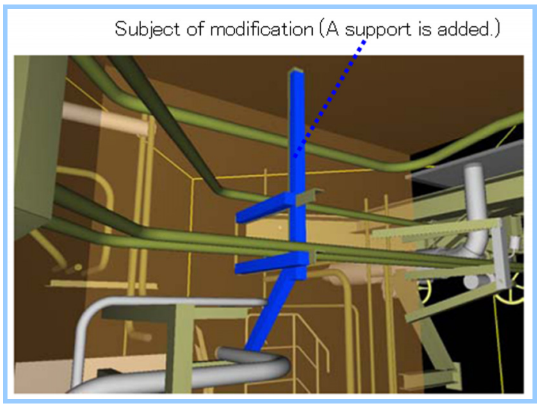


Figure 12 Confirmation of the feasibility of modification using three-dimensional CAD data
The feasibility of modification was confirmed by using a three-dimensional model (three-dimensional CAD data) converted based on point data.

5. Conclusion

This paper describes the sophisticated maintenance technologies on which MHI is working. We will continue our efforts to develop maintenance technologies aiming at higher availability of nuclear power plants and to pursue sophistication and streamlining of maintenance work.

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