Development of New Technology for Fukushima Daiichi Nuclear Power Station Reconstruction

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OVERVIEW: Since the accident at Fukushima Daiichi Nuclear Power Station of the Tokyo Electric Power Co., Inc., remediation work at Fukushima has needed to deal with high radiation environments and has demanded new techniques. This requires the development of remote-controlled robots along with radiation measurement, water treatment, and other technologies, as well as ways of utilizing these technologies in tandem. It is also necessary to conduct a site survey (including radiation measurement, visual assessment, and the identification of access routes), formulate a cleanup plan for decontamination and the removal of rubble, and to use remote-controlled equipment for performing essential tasks. Similar enhancements are also needed for treating the contaminated water produced by reactor cooling (removing the radioactive material).

INTRODUCTION

IN addition to work on instruments for measuring radioactivity and remote-controlled robots for conducting surveys and taking measurements in a highly radioactive environment, work is currently in progress on the use of robots to remove rubble at the Fukushima Daiichi Nuclear Power Station of the Tokyo Electric Power Co., Inc. Various systems and robots are also seen as necessary, to support the planning of decontamination based on measurement data, and to perform decontamination work to clean up the site.

In response to these disaster site requirements, Hitachi has developed radiation detection techniques; a remote-controlled decontamination system; a remote monitoring robot system that uses wireless communications; and the small double-arm, heavy-duty robot. Hitachi is also working on developments that will enable work at the disaster site to proceed from site surveys to rubble removal and cleanup. Meanwhile, other developments that will contribute to the cleanup involve the treatment of contaminated water produced by reactor cooling.

This article describes technologies that have been developed and applied to date for radiation measurement, decontamination, remote-controlled robots, and the treatment of contaminated water.

DEVELOPMENT OF RADIATION DETECTION TECHNIQUES

The accident at the Fukushima Daiichi Nuclear Power Station has left walls, floors, ceilings, and other parts of the reactor buildings in particular contaminated with radioactive materials. For decommissioning work to proceed smoothly, these contaminated sites need to be cleaned up. Decontamination consists of five main steps: (1) Radiation measurement to assess contamination, (2) Decontamination plan, (3) Decontamination, (4) Verification, and (5) Transportation and storage of radioactive waste. To provide the radiation detectors required for decontamination to proceed efficiently and effectively, Hitachi has developed a gamma camera that provides a broad visualization of contamination, and a plastic scintillation fiber (PSF) that provides an ambient dose distribution along the fiber. It has also developed, a radiation field mapping software that helps in a decontamination plan by using the large amounts of radiation data obtained by the detectors.

Development of Radiation Detection Techniques

Gamma Camera[1]

Fig. 1 shows the vehicle-mounted gamma camera. To allow measurements to be made in the highly radioactive environments inside the reactor buildings, Hitachi has made the gamma camera better than previous cameras at minimizing radiation background effects (through better shielding of the camera body and the addition of a shutter mechanism), and has added a remote control function for taking measurements remotely and a tilt function to better assess contamination inside the building.

Gamma camera images were taken at about five locations in each of reactor buildings 1 to 3. The

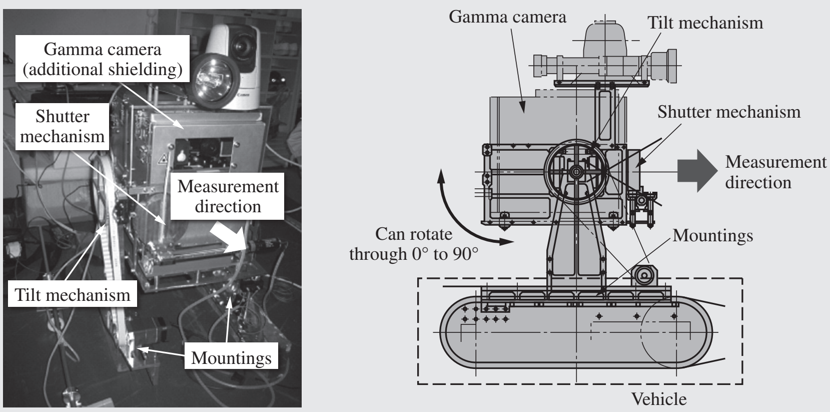


Fig. 1—Vehicle-mounted Gamma Camera.
The system consists of the gamma camera itself together with a tilt mechanism, shutter mechanism, and mounting. The tilt mechanism allows measurements to be performed up to a vertical angle of 90°, and the shutter mechanism improves accuracy.

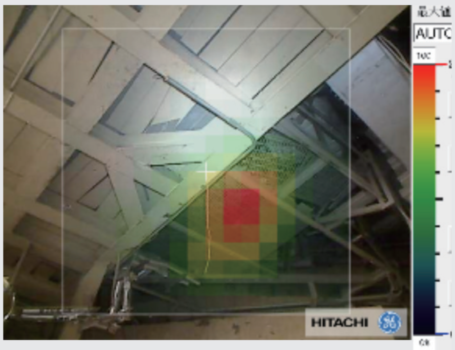
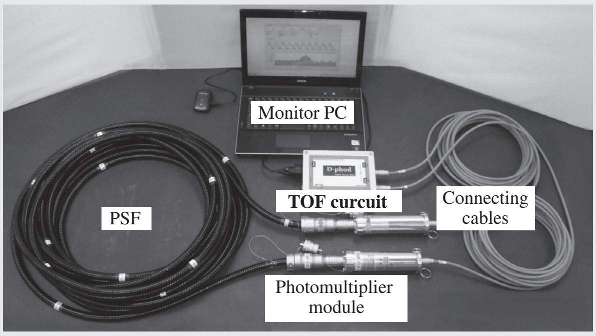


Fig. 2—Image Taken Using Gamma Camera.
This image of the exterior of the containment vessel in reactor building 3 was taken from the heavy equipment access door. It shows the location of hot spots (ports in the containment vessel).



PC: personal computer PSF: plastic scintillation fiber TOF: time of fight

Fig. 3—PSF System.
The PSF system consists of the PSF, photomultiplier module, TOF circuit, personal computer (PC) for displaying results, and connecting cables. It can be used outdoors and in the absence of an external power supply.

ambient dose equivalent rates at the image locations were in the range 10 mSv/h to 100 mSv/h. As shown in the Fig. 2 example, hot spots could be detected from all of these locations.

PSF system(2)

Fig. 3 shows the PSF system for measuring ambient dose equivalent rates using a time of flight (TOF) technique. A characteristic of the system is that the radiation distribution along the fiber can be obtained in roughly the same time and with the same accuracy as a scintillation survey meter. The system consists of the PSF, photomultiplier module, TOF circuit, personal computer (PC) for displaying results, and connecting cables. It is designed to be more sensitive, smaller, lighter, and more robust than previous models, and it can be used in the absence of an external power supply.

The system was used to measure dose equivalent rates at a total of 31 locations in the building surroundings, car park, and grounds in an area of roughly 80 × 60 m. The displayed radiation map provides a clear indication of the contaminated areas (see Fig. 4).

Fig. 4—Measurement of Dose Equivalent Rate Using PSF system.
The data measured by the PSF system is displayed on a digital map to provide an accurate indication of the contaminated areas and to facilitate efficient and effective decontamination.

Hitachi has made improvements to allow its use where radiation levels are high, and also has plans to adapt it to the measurement of dose equivalent rates on the surfaces of walls, floors, and ceilings in the reactor buildings.

Software for Preparing Decontamination Plans(3)

Hitachi has developed a computer system for producing maps of dose equivalent rate distribution. To do this, it is able to rapidly calculate the dose equivalent rate at any point in space by using data on the attenuation of radiation by air or concrete predetermined using three-dimensional Monte Carlo N-Particle Transport Code 5 (MCNP5); measured dose equivalent rates for wall, floors, ceilings, and other surfaces; and data on hot spots identified by the gamma camera. Its most important feature is the ability to estimate the reduction effect in ambient dose equivalent rate that will be achieved by measures such as decontamination or shielding.

Fig. 5(a) shows a dose equivalent rate map produced by the above system for the reactor 3 building at Fukushima Daiichi Nuclear Power Station. Fig. 5(b) shows the dose equivalent rate distribution after decontamination of walls and floors and the installation of shielding at specific locations. This provides an easy way to assess the extent of contamination and predict how well decontamination will work, allowing a decontamination plan to be formulated that will achieve the target dose equivalent rate.

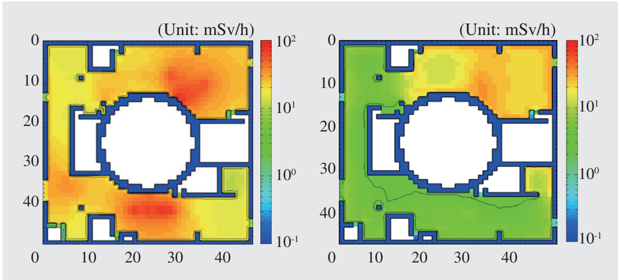


Fig. 5—(a) Indoor Dose Equivalent Rate Distribution Produced by Software for Preparing Decontamination Plans, (b) Prediction of Decontamination Effectiveness.
Using actual radiation level measurements as its input, the software can calculate the ambient dose equivalent rate for any specified location and produce a map of radiation level distribution.

DEVELOPMENT OF DECONTAMINATION TECHNIQUES

In response to the need to reduce exposure of the workforce while decontaminating the site of a nuclear accident, Hitachi has developed a remote-controlled decontamination system.

Overview of Remote-controlled Decontamination System(4)

The remotely operated system uses high-pressure water to clean up various different forms of contamination from the interior of reactor buildings.

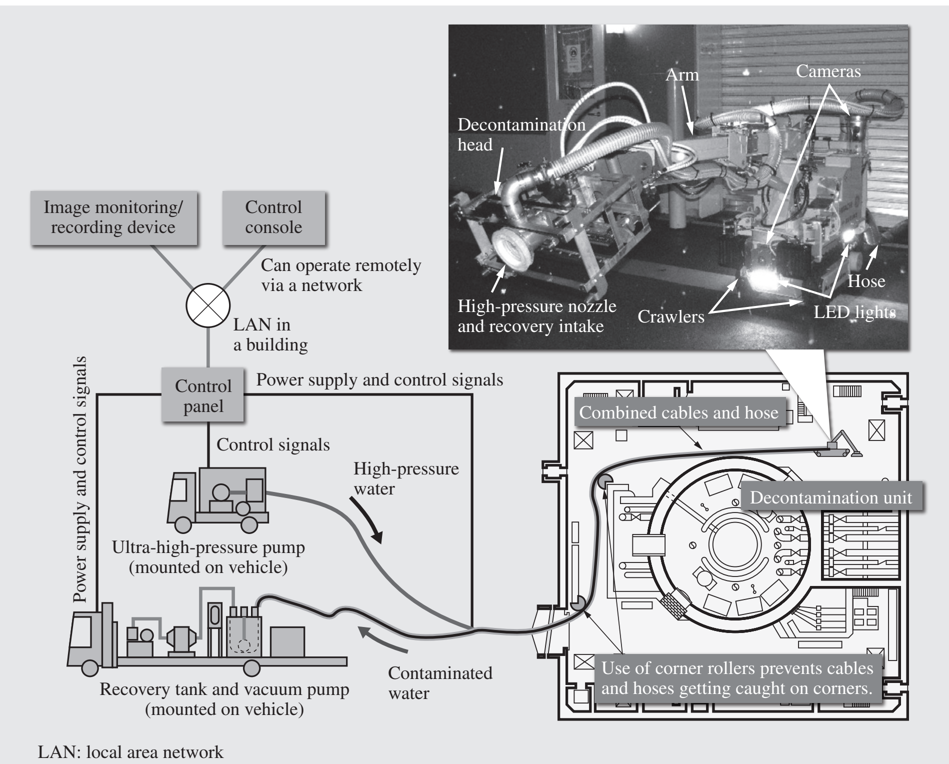


Fig. 6—Remote-controlled Decontamination System and its System Configuration.
The pumps and other decontamination equipment can be operated from a remote control room. This system decontaminates floors and walls by simultaneously spraying them with water supplied at high pressure and recovering the sprayed water.

Fig. 6 shows a photograph and block diagram of the system.

Developed by Hitachi, a remote-controlled robot system removes and collects radioactive material that has adhered to floor or wall surfaces. It can clean up the interior of a building and also prevent the dispersal of contaminated cleaning water. To make it suitable for a wide range of decontamination work inside reactor buildings, Hitachi designed the decontamination unit to be small and incorporated an arm mechanism that presses the head used to spray and recover the high-pressure water up against the floor or wall surface.

System Features

(1) Water pressure control to suit different uses

The ability of the decontamination system to vary the water pressure in the range 25 MPa to 200 MPa allows it to be selectively configured for surface cleaning, paint stripping, or chipping of surfaces. Accordingly, it can be used in a variety of situations, extending from the cleaning of surfaces that can be decontaminated by removing surface deposits through to cleaning concrete into which contaminants have penetrated.

(2) Full recovery of all cleaning water

The system has a decontamination head that simultaneously sprays and recovers the high-pressure water. The head produces the high-pressure water spray internally. Hitachi has optimized the brushes around the edges of the head to recover all of the cleaning water (high-pressure spray) and contaminated water.

This ensures that decontamination is performed reliably without spreading contaminants in the process.

DEVELOPMENT OF TECHNOLOGY FOR REMOTE-CONTROLLED ROBOT

Work at the Fukushima Daiichi Nuclear Power Station proceeds by incorporating information collected at the site into subsequent work plans. Furthermore, because of the high levels of radioactivity at the site, this also requires the use of remote-controlled robots to collect this information and to carry out other tasks inside the buildings.

Monitoring Robot System[5] for Conducting Surveys

To provide remote-controlled robots for this purpose, Hitachi is working on the development and deployment of a monitoring robot system that uses wireless communications for remote-controlled operation.

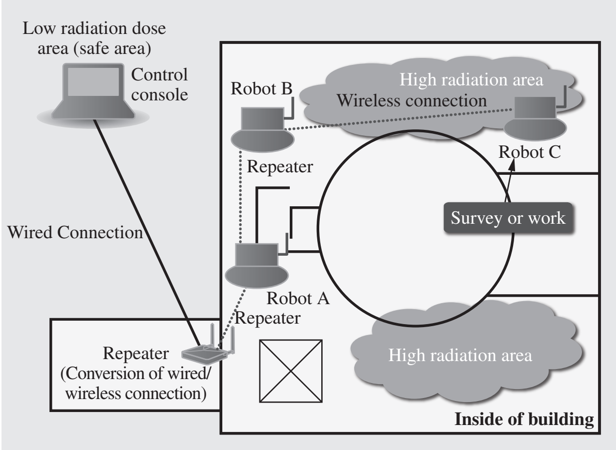


Fig. 7—Configuration of Remote-controlled Robot System.
Because the three remotely controlled robots can relay wireless communications between each other, a system can be configured to conduct surveys deep inside buildings, even when no communications infrastructure is available.

System Configuration

Fig. 7 shows a block diagram of the remote-controlled monitoring robot system. The system can operate three robots from a single console, with each robot able to relay signals to the others. Use of this wireless relay technique allows the robots to survey highly radioactive areas that are too dangerous for people to enter, and to do so even if the disaster site lacks communications infrastructure or has poor reception inside buildings.

Robot System Features

(1) Each console can operate multiple robots

Fig. 8 shows the system's control console. The user can switch the control screen between the different

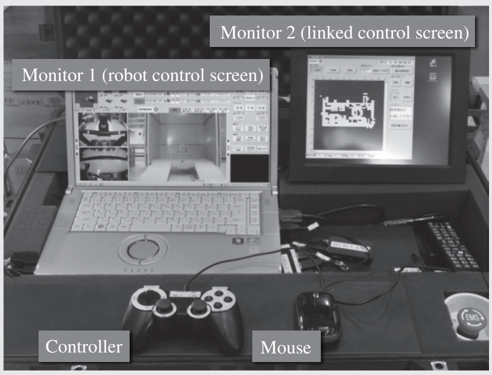


Fig. 8—Control Console.
The system configuration allows three robots to be operated from a single console. The map screen (linked control screen) displays the robot position and information about nearby obstacles.

robots to display the monitoring camera and front and rear bird's eye camera images from the selected robot. Using the monitor, the user controlling the robot can also select which of the multiple camera images available to observe as they do so. To monitor conditions at the robots' locations, sensor information (radiation level, temperature, and humidity) from three robots is displayed continuously.

(2) Map function

The mobile robots used by the system are fitted with laser rangefinders to collect measurements on their surroundings as they move, and to determine their location. This self-location data is then combined with a map of the area to avoid collisions with obstacles or other robots.

The map displayed on the console's operation screen is overlaid with a mesh. To help identify robot position and obstacles, and to make operation easier for the operator, whether or not the robot is able to pass can be specified for each square of the mesh.

Double-arm, Heavy-duty Robot[6]

To provide remote-controlled robots for use at disaster sites, Hitachi is working on the development and deployment of a heavy-duty robot with two arms that has been designed for use in nuclear accidents.

Overview of Robot

To provide flexibility for working indoors, a heavy-duty robot developed by Hitachi has a compact body (980 mm wide) and two arms. The two arms can reach up to 2.5 m high. The arms can lift 150 kg each and 300 kg in tandem.

Furthermore, the tools at the ends of the arms can be swapped to suit different tasks. Fig. 9 shows a heavy duty robot in operation using its two arms.

This robot uses radio control and was designed for tasks such as removing rubble from the reactor buildings.

It also has good operating characteristics, with extensive functions provided to assist remote control by the operator.

Robot System Features

(1) Swappable tools

To enable the robot to perform a wide range of tasks, the ends of the two arms can be fitted with gripping or cutting tools, rotating tools, or an extension arm that incorporates a camera.

To provide the flexibility to deal with conditions at the site, these tools can be swapped remotely.

The provision of two arms, the ends of which can each be fitted with different tools, allows the robot to perform delicate indoor rubble removal and dismantling work. When removing rubble, for example, one arm can be used to hold material while the other performs cutting.

(2) Use for making site measurements

In addition to cameras, the robot is also fitted with a radiation dosimeter, sensors for temperature and humidity, sensors for oxygen and hydrogen concentration, and an infrared camera. The sensor information is constantly updated on the remote control console to provide monitoring of the conditions inside the building at the robot locations.

(3) Support functions for remote control

This robot is operated via radio control from a remote control console. The console can display five monitor images at a time selected from the six camera feeds provided by the robot. Each of these six cameras is fitted with light-emitting diode (LED) lighting to facilitate rubble removal and other tasks in the dark interior of the reactor buildings at the disaster site. Fig. 10 shows the remote control console.

DEVELOPMENT OF TECHNOLOGY FOR TREATING CONTAMINATED WATER

Water treatment systems are being used at the Fukushima Daiichi Nuclear Power Station to remove radioactive cesium (Cs) from the high-level radioactive waste water that has collected inside the turbine buildings and other locations, and to help prevent corrosion of the reactor by removing salts that originally came from seawater (see Fig. 11). Hitachi

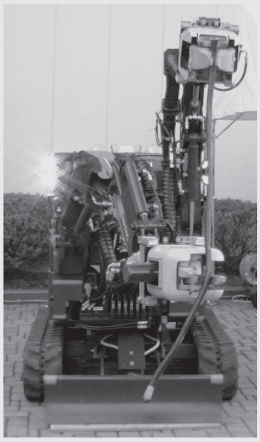


Fig. 9—Small Double-arm, Heavy-duty Robot.
Different attachments can be fitted to the end of each arm. This allows the robot to perform delicate tasks that take advantage of its two arms, using one arm to hold material while the other cuts it, for example.

Fig. 10—Remote Control Console.
This robot is operated by the four joysticks at the center. The console can display five camera images selected from the six camera feeds from the robot.

was given the job of installing reverse osmosis (RO) membrane systems and evaporative concentrators at the site, and has also been helping ensure that the RO membrane systems operate reliably.

However, because the current systems remove only Cs, Hitachi has also set out to develop a technique for removing strontium (Sr) in particular. Due to the use of seawater to cool the reactors in the immediate aftermath of the disaster, and the flooding of buildings with groundwater that contained seawater, the concentration in the contaminated water at Fukushima of non-radioactive Sr originating from this seawater is an order of magnitude greater than the concentration of radioactive Sr (seawater contains about 8 ppm of Sr). This means that the adsorbent used to remove Sr needs a high level of adsorption to also collect all of this seawater-derived Sr.

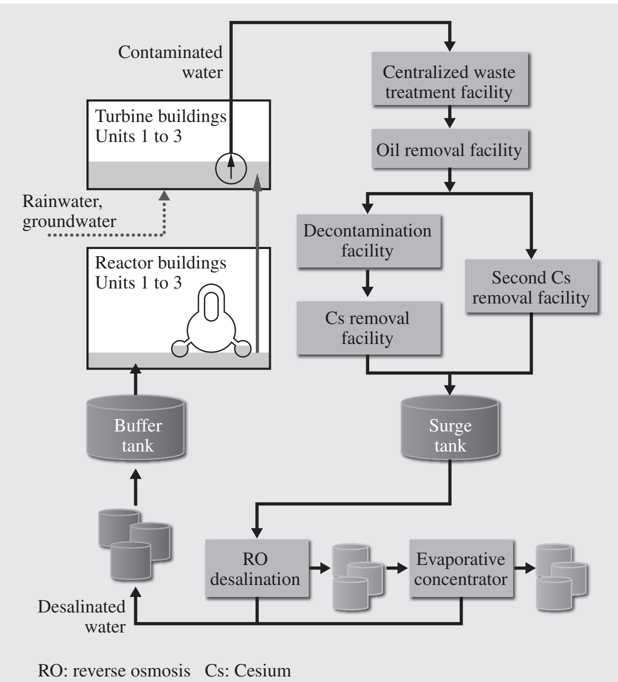


Fig. 11—Treatment of Water Contaminated with High Levels of Radioactivity.
Water contaminated with high levels of radioactivity that has collected inside the reactor, turbine, and other buildings due to flooding by the tsunami or reactor cooling water is treated and then reused as reactor cooling water for removing the decay heat from the fuel still inside the reactor (operation commenced on June 27, 2011).

Development of Adsorbent for Both Cs and Sr

Hitachi-GE Nuclear Energy, Ltd. and the Hitachi Research Laboratory have developed an adsorbent for both Cs and Sr that adsorbs Sr in sufficient quantities to make it suitable for use on the contaminated water at Fukushima(7).

Cs is an alkali metal and Sr an alkaline earth metal. The two have different ionic valences and radii in aqueous solution. For these reasons, the conventional practice for removing these elements has been to use separate Cs-specific and Sr-specific adsorbents. The advantage of using this single adsorbent is that it simplifies the equipment design.

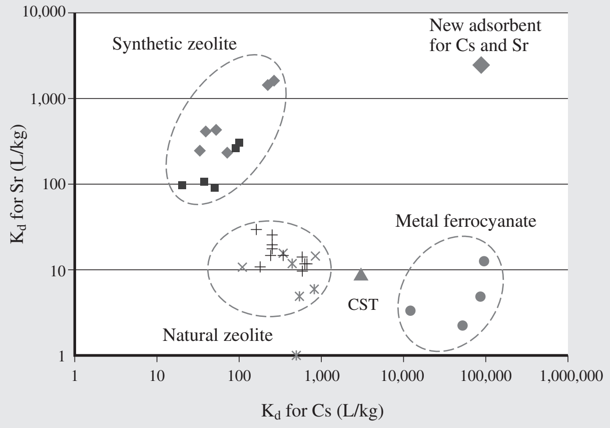
The following describes how the distribution coefficient (K_d) provides a way of comparing the amount of material adsorbed by the new adsorbent compared to Cs-specific and Sr-specific adsorbents.

The adsorbent was dipped into artificial seawater to which Cs-137 and Sr-85 had been added, and K_d was obtained according to the following formula.

$$K_d=C_0=C_t/C_t \times V/m$$

Where, C_0 is the concentration of Cs-137 prior to inserting the adsorbent, C_t is the concentration of Cs-137 after one week, V is the volume of the solution, and m is the mass of adsorbent. Accordingly, the higher the value of K_d, the greater the amount of material adsorbed.

The results for the new adsorbent were then plotted on a graph along with those for the Cs-specific and Sr-specific adsorbents (see Fig. 12). The values for the latter materials were taken from data reported by a group associated with the Atomic Energy Society of Japan(8). The horizontal and vertical axes represent the K_d values for Cs and Sr, respectively. Note that the K_d values for particular adsorbents are different depending on factors such as their composition and shape. The graph shows that the new adsorbent is suitable for adsorbing both Cs and Sr, with a high K_d for both elements.



Sr: strontium K_d: distribution coefficient
CST: crystalline silico titanate

Fig. 12—Performance of Newly Developed Adsorbent for Cs and Sr.
The graph plots the distribution coefficients (K_d) measured for the case when nuclides were added to artificial seawater. The horizontal and vertical axes represent the K_d values for adsorption of Cs and Sr respectively. A high value of K_d indicates a high level of adsorption. K_d values for other adsorbents are shown for reference.

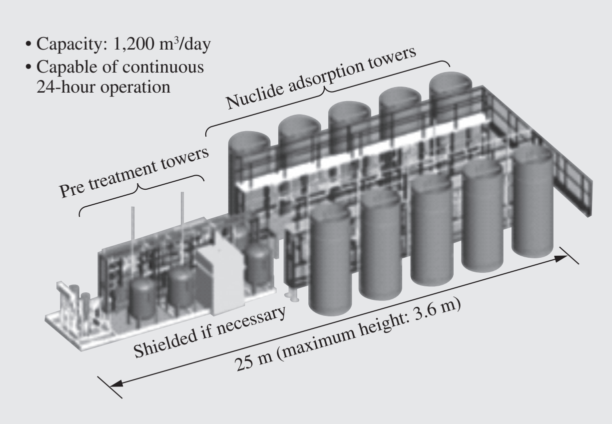


Fig. 13—Sub-drain Water Treatment System.
The system includes a number of adsorption towers to allow various different adsorbents to be used for the different nuclides contained in contaminated water. Through the adoption of the new adsorbent for Cs and Sr together with pre treatment (filters for removing soil, colloids, and other similar material), Hitachi succeeded in building a compact nuclide removal system with fewer adsorption towers (operation to commence in September 2014).

Development of System for Treating Contaminated Water

This section describes a sub-drain water treatment system that uses the Cs/Sr adsorbent to treat contaminated water.

The water from sub-drains located around the buildings has been found to contain antimony (Sb) as well as Cs and Sr. In addition to the new adsorbent described in this article, the system also uses a number of other adsorbents to deal with any other radioactive nuclides that may be present in the sub-drain water (see Fig. 13). Another feature is that, along with the adsorbents, the system also includes pre treatment equipment with conventional filters and a filter that can remove colloids. This equipment can ensure that the concentration of nuclides in the sub-drain water is below the permitted level for discharged water. Hitachi is contributing to the treatment of contaminated water at Fukushima Daiichi Nuclear Power Station by ensuring the reliable operation of this sub-drain water treatment system along with existing equipment.

CONCLUSIONS

This article has described technologies that are essential to decontamination work, including the gamma camera, PSF, Software for Preparing Decontamination Plans, and the remote-controlled decontamination system, which are used for radiation measurement, to support decontamination planning, and as remote-controlled decontamination equipment. It is anticipated that these technologies will make a major contribution to improvements in the efficiency and precision of tasks that extend from accurately determining the level of contamination before starting decontamination through to identifying which areas need decontamination, performing the work by remote control, and assessing the results once decontamination is complete. Hitachi has been working on preparations for cleanup work, extending from surveying building interiors to rubble removal, by developing remotely operated technologies for use at the Fukushima Daiichi Nuclear Power Station, namely a monitoring robot system and a double-arm, heavy-duty robot.

In terms of technology for treating contaminated water, Hitachi has also been developing an adsorbent for both Cs and Sr, and a treatment system for contaminated water.

In addition to deploying these technologies it has developed at the Fukushima Daiichi Nuclear Power Station, Hitachi also intends to continue working towards its remediation.

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