Gamma-ray irradiation test of Electric components of rescue mobile robot Quince
–Toward emergency response to nuclear accident at Fukushima Daiichi Nuclear Power Station on March 2011–

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Abstract — On March 11, 2011, a massive earthquake and tsunami hit eastern Japan, particularly the Tohoku area. Since then, the Fukushima Daiichi Nuclear Power Station has been facing a crisis. To respond to this situation, we began a project to redesign our mobile robots for disaster response missions. A key issue to be addressed was to check the radiation hardness of the electric components of our robot. Initially, no information was available in this regard. Therefore, we conducted gamma-ray irradiation tests for the electric components using cobalt-60. In this paper, we introduce the procedure for the irradiation test and report the results of the test.

Keywords: *Rescue robot, gamma-ray irradiation test,*

I. Introduction

On March 11, 2011, a massive earthquake and tsunami hit eastern Japan, particularly the Tohoku area, claiming many lives. Furthermore, the Fukushima Daiichi Nuclear Power Station was also damaged, and meltdown accidents and radioactive material releases occurred. An emergency continues to exist (June 2011).

In this emergency, the first mission for disaster response was to check on the damage to the target environment, e.g., dose measurement at the disaster site. However, the site, including the outside and inside of the nuclear reactor buildings, is very dangerous for humans because of the potential for high levels of irradiation. Therefore, exploration using mobile robotic technology is crucial for such missions.

Our joint research group has been researching and developing tracked robots to assist rescue crews in search and rescue missions in dangerous environments [1]. Therefore, in March 2011, we began a project to redesign these robots for disaster response missions in the Fukushima Daiichi Nuclear Power Station, in a joint effort with TEPCO (Tokyo Electric Power Company) and NEDO (New Energy and Industrial Technology Development Organization).

Unlike other disaster situations, this accident has resulted in high radiation. In 2001, some radiation-proof robots were developed in Japan. However, since then, no nuclear disaster response robots have been researched and developed in Japan because it was believed that Japanese nuclear plants could withstand natural disaster. Therefore, at the beginning of this project, we had no information about the radiation hardness of conventional electric components.

First, we obtained information about the radiation hardness of conventional electric components from the developers of small-sized artificial satellites in Tohoku University and the University of Tokyo. According to their information, conventional CPUs such as the Hitachi H8 or PIC microcontroller capable of withstanding a total dose of 10 krad (=100 Gy). However, they did not check complex CPUs such as Pentium or Atom CPUs.

Second, we obtained information about the radiation on the hardness of conventional electric components from a report of the Manufacturing Science and Technology Center (MSTC) [2] in Japan. According to their information, a conventional note-PC (Dynabook: Mobile Pentium III, 600MHz, Toshiba) encountered problems after a total dose of 23 Gy. However, the manufacturing process for the CPU is 0.18 μm, which is much wider than the current manufacturing process, e.g., Atom's 45 nm.

Third, we tried to calculate the required thickness of a lead plate for effective radiation protection. If we needed to extend the mission time, we would need to cover the critical electric components with lead plates.

Accordingly, we needed to determine the total dose durability of electric components ourselves to proceed with redesigning our redesign of our mobile robots for disaster response missions. Therefore, we asked for Japan Atomic Energy Agency (JAEA) for an opportunity to conduct a gamma-ray irradiation test of the electric components of our rescue robot, Quince. In this paper, we introduce the procedure for determing the thickness of the lead for effective gamma-ray shield, and report the results of the irradiation test.

II. Gamma-ray protection by lead plate

Before our gamma-ray irradiation test, we discussed how thick a lead plate was required to protect weak electric components from gamma-rays. We defined our objective as obtaining of a lead plate that was thick enough to shield gamma-ray radiation in a shield ratio of 10 %. The total penetration probability determination is shown in the following.

1) Settlement of major nuclear species
   In the table 5 in the press releases of NISA (Nuclear and Industrial Safety Agency) [3], nuclear species are listed in this accident. In these species, we picked up Cs134 and Cs137 on the condition that (1) the half-life of a radioisotope was longer than 1 year and (2) radioactive level was over 1.0×10^{16} Bq. The penetration capability of Cs134 (beta ray) is smaller than Cs137 (gamma ray). Therefore, finally, we focused on Cs137 for shielding.
2) Acquisition of each penetration probability of nuclear species for a shield ratio of 10%
   In our case, the penetration probability data of Cesium-137 can be obtained from a text book [4]. A position of the expected data is shown in Table I.
3) Thickness choice for each nuclear species
   According to the table, it required 2.0 cm thick lead for a shield ratio of 10 % against Cesium-137. Therefore, we anticipated tentatively of a 2cm thick lead plate for shield ratio of 10%.

III. Target robot: Tracked vehicle Quince

Quince is a small, light weight 6 degrees-of-freedom tracked vehicle designed for the traversal of stairs, and rubble. It has four sub-tracks to negotiate uneven terrain. An overview of the robot (Redesign for Fukushima disaster response) is shown in Fig.1, and its major electric components are listed in Table II. Basically, these devices were irradiated by gamma-rays to check durability.

The main controller of the robot is an Atom-based embedded CPU board, with an SH7147 microcontroller mounted on each two-channel motor driver board. The Fukushima version of Quince has a wired communication option for tele-operation. Therefore, the POE power feeding device was also tested. Finally, we chose a DSL Modem (NVF-200: HYTEC INTER Co., Ltd.) for wired communication, but we did not include this device in the irradiation test. Basically, the sensors are CCD cameras, and we had planned to mount additional laser range sensors to obtain range data for the robot's navigation. Therefore, we added 2D range scanners (URG-04LN, UTM-30LX, UXM-30LN: HOKUYO AUTOMATIC CO., LTD.) and a 3D scanner (Eco-scan FX8: THE NIPPON SIGNAL CO., LTD.) to the tested devices.

TABLE I

Radiation transmittance for gamma-rays (Cesium-137).

t (cm)	iron trans.	t (cm)	lead trans.	t (cm)	concrete trans.
0.0	1.00	0.0	1.00	0	1.00
0.5	9.34E-1	0.2	8.46E-1	5	8.69E-1
1.0	8.58E-1	0.3	7.77E-1	10	6.36E-1
2.0	6.78E-1	0.4	7.12E-1	15	4.17E-1
5.0	2.48E-1	0.5	6.50E-1	20	2.55E-1
8.0	7.29E-2	1.0	4.05E-1	25	1.49E-1
10.0	3.02E-2	2.0	1.46E-1	30	8.40E-2
12.0	1.21E-2	3.0	5.03E-2	35	4.62E-2
14.0	4.75E-3	4.0	1.69E-2	40	2.48E-2

IV. Irradiation test method

A. General irradiation test method

Our gamma-ray irradiation test was conducted at one of the Cobalt-60 gamma-ray irradiation facilities of the Takasaki Advanced Radiation Research Institute of JAEA. These facilities are available, not only for JAEA, but also for users from universities, private companies, and public institutes.

In the irradiation test, we used three line-shaped Cobalt-60 radiation sources. These sources are typically located in an underground pool for safety. When a test starts, the sources emerge at the center of the shielded experiment area on the lifting mechanism.

The strength, dose rate of the gamma-rays, is adjusted by changing the distance from the radiation sources. The strength is theoretically decreased in inverse proportion to the square distance from the sources. Therefore, in our case, 20 Gy/h gamma-ray points were located 0.66 m from the source, and 40 Gy/h gamma-ray points were located 0.45 m from the source, concentrically.

From the point of view of the past researches shown in the introduction section, a typical conventional device has a total dose durability of 100 Gy. We first planned to test only the CPU board because we anticipated that the CPU board was the most susceptible to gamma-ray irradiation. Therefore, we conducted a five-hour gamma-ray irradiation test for CPU devices at 0.66 m from the source on the first day (April 15, 2011). In this case, the total dose was 100 Gy. Figure 2 shows the test board, which included a CPU board, CCD camera, DC-DC converter, battery video server, and wireless communication device. The procedure for the test is shown in the next subsection.

After the experiment of the first day, as described above, we found that 100 Gy was not sufficient for disabling our electric components. Furthermore, there was the additional requirement of checking the range sensors. Therefore, on the second day (April 20, 2011), we conducted an additional five-hour gamma-ray irradiation test for the CPU devices at 0.66 m from the source (20 Gy/h). Thus, the total dose became 200 Gy. In addition, the five-hour gamma-ray irradiation test was conducted for additional devices such as range sensors at 0.45 m from the source (40 Gy/h). Thus, their total dose also became 200 Gy.

A photograph of the test-configuration on the second day is shown in Fig.3. Radiation sources are supposed to be placed in the cylindrical mesh at the center of the photograph. You can see that the CPU board at the right of the photograph is located at a place (0.66 m from the source) further than that for the sensors (0.45 m from the source). For all of the devices, we

Fig. 1. Tracked vehicle Quince: Fukushima version.

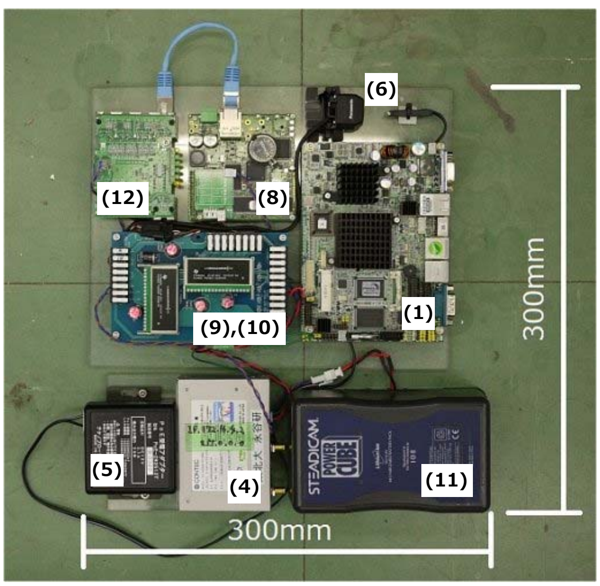

Fig. 2. CPU board with some electric devices and CCD camera.

placed the electric parts perpendicular to the source, so that the configuration of each device became the worst-case condition. Fig.4 shows the layout of the devices and the experimental facility (scale is not correct).

To confirm the total dose of each component, we used an alanine dosimeter, called Aminogray. It can obtain the total dose by measuring the radical amount in alanine crystals using ESR (electron spin resonance). The error is specified to be within 3%. Therefore, in this test, we placed Aminograys close to the target devices.

B. Electrical test items

During the irradiation test, we needed to activate all of the electric components and determine whether or not they worked

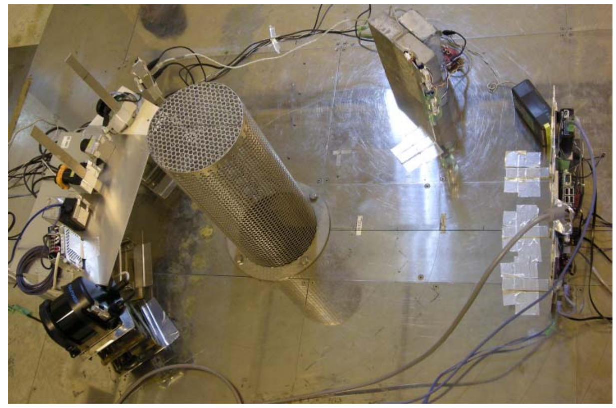

Fig. 3. Device configuration for gamma-ray irradiation test.

correctly. Therefore, we selected the electrical test items shown in the following. Note that numbers of the devices in the following correspond with the numbers in Table II.

1) **Ping test for each device**
   We connected LAN cables from the PC located at the outside of the test area to (1) the CPU board, (8) the video server, and (4) the wireless communication device through (5) the POE (power over Ethernet) device during the irradiation test and watched the ping commands to these devices. If one of the above devices did not reply, it had the possibility of a malfunction condition. In a case where none of the devices replied, the communication part of the POE device, (12) LAN HUB, (9, 10) DC-DC converter, or (11) battery had the possibility of a malfunction condition. In this case, we terminated the entire test and checked which device had the malfunction condition.
2) **Viewing test for CCD camera**
   We connected an analog cable from (6) the CCD camera to (8) the video server, and checked the image from the CCD camera. If the image had a problem, there was the possibility of a malfunction condition. Furthermore, in front of the CCD camera, we put an LED light whose

TABLE II
ELECTRIC COMPONENTS OF QUINCE.

Maker	Model	Function
(1) AXIOMTEK Co. Ltd.	SBC84823	CPU Board (AtomZ510PT)
(2) Technocraft	V-8	Motor driver board (Renesas SH7147)
(3) Lawicel AB	CAN/USB	CAN-USB converter (FT245BM)
(4) Contec Co. Ltd.	FXDS540STDMS	Wireless com. device
(5) Techno Broad Inc.	PoE-ZS251T	POE power feeding
(6) Panasonic Corp.	CY-RC51KD	CCD camera
(7) Axis Inc.	Axis212	Wideview camera
(8) Axis Inc.	Axis282	Video server
(9) TI Inc.	PT6883A	DC-DC Converter
(10) TI Inc.	PT6886A	DC-DC Converter
(11) IDX Co. Ltd.	PowerCube	Battery
(12) PLANEX Com. Inc.	FX-08Mini	LAN Hub
(13) Sanwa Supply	225GBK	USB Hub

Some of the numbers above correspond with the numbers in Fig.2.

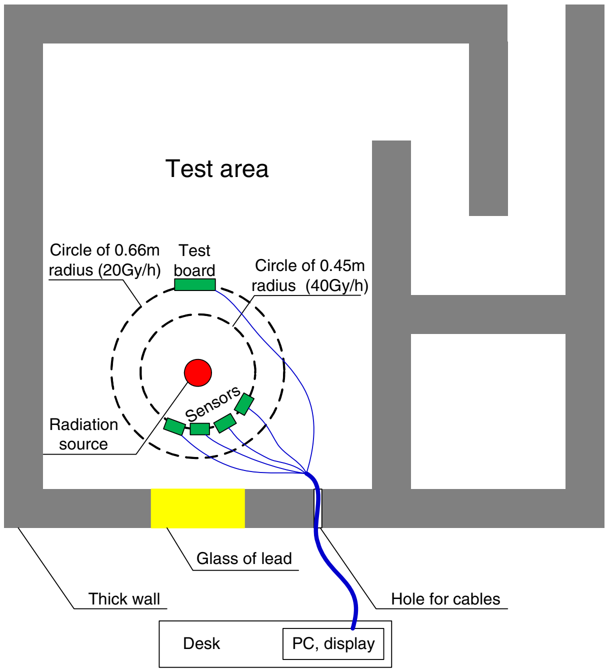

Fig. 4. Layout of devices and experimental facility.

power was supplied by the POE device. If the LED light went off, the power feeding part of the POE device had the possibility of a malfunction condition.

3) **Reboot test for CPU board**
Even if the compact flash card (CF card) mounted on (1) the CPU board was damaged, the CPU board may have continued to work, because the CF card is typically used in the booting sequence of the CPU board in our system. Therefore, we connected a display cable and an extended reset signal cable from the display located at the outside of the test area to the CPU board. Then, once every 30 min, we sent a reset signal to the CPU board and confirmed whether the Operating System booted.

4) **Keyboard test for CPU board**
It was very important to check the USB controller on (1) the CPU board. However, in the above test, it was difficult to check this. Therefore, we connected a USB cable from the CPU board to a USB-keyboard located at the outside of the test area. Once every 10 min, we hit the keyboard and checked the display to determine whether the key input was entered correctly.

5) **Motor driver test**
Typically, the motor driver device is tougher than the CPU, and it was too much work to prepare a motor rotation test in the test area. Therefore, we connected a serial cable from (2) the motor driver board to a PC located at the outside of the test area, and checked the serial console of the motor driver board. In addition, to check (3) the CAN-USB converter, we connected the CAN cable from the motor driver board to (1) the CPU board, and showed the received CAN packet on the CPU's display.

6) **Sensors' test**
On the second day, we added the 2D range scanners (URG-04LN, UTM-30LX, UXM-30LN: HOKUYO AUTOMATIC CO., LTD.) and 3D scanner (Eco-scan FX8: THE NIPPON SIGNAL CO., LTD.) to the tested devices. To check these sensors, we connected each cable to a PC located at the outside of the test area, and checked the sensing results.

V. Irradiation Test Results

A. *Total dose check*

In this test, we used Aminogray to confirm the total dose of each component. On the first day, we used three Aminograys attached at the left, center, and right of the test board, as shown in Fig.2. On the second day, we used a total of 12 Aminograys, which included those for sensors and additional devices. The total dose of each component is shown in Table III.

In this table, you can see that total dose at the center of the CPU board was larger than those at the left and right. Basically, gamma-rays are emitted radially, and the board is flat. Therefore, the center of the CPU board was closer to the radiation source than the side of the board.

In any case, we confirmed that the expected amount of total dose was provided to each device by the measurements using the Aminograys.

Note that, for URG-04LN and the CCD camera, the total doses were logged when they were malfunctioning.

B. *Test results on first day*

An overview of the test is shown in Fig.5. Because the photograph was taken through a thick piece of lead glass for radiation protection, the color became completely yellow. After 5 h, which meant as total dose of 100 Gy, all of the devices were still working fine. Of course, it is risky to conclude that conventional devices have a typical durability of 100 Gy, from the results of just one test. This is because devices have individual differences.

C. *Test results on second day*

On the second day, we added sensors and a motor driver board for additional testing.

TABLE III
Total dose of each device.

Position	Total dose (Gy)	Condition
Test board: left	191.5	It survived.
Test board: center	206.0	It survived.
Test board: right	193.5	It survived.
CAN-USB converter	188.5	It survived.
USB Hub	187.5	It survived.
UTM-30LX	232.0	It survived.
UXM-30LN	229.0	The output was always unstable, but it survived.
Eco-scan: front	225.0	It survived.
Eco-scan: rear	209.5	It survived.
Axis 212	219.5	It survived.
Camera on test board	169.0	It broke after 169.0 Gy.
URG-04LN	124.2	It broke after 124.2 Gy.

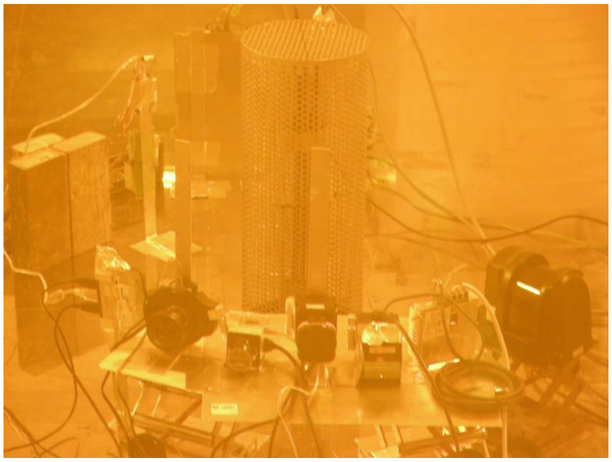

Fig. 5. Overview of gamma-ray irradiation test.

After 2 h and 49 min, the sensor data from one sensor, URG-04LN, stopped. The total dose was about 124 Gy for this sensor. We checked the sensor later and found that it was completely malfunctioning.

After 3 h, the picture obtained by the CCD camera (CY-RC51KD) began changing gradually to bluish coloring, and it never displayed after replacing the battery (after 3 h 51 min). The video server still worked correctly, so we determined that the CCD camera itself was broken. The total dose was about 169 Gy for the camera.

On the other hand, the UXM-30LN sent range data with a large spike of noise just after gamma-irradiation started. When the radiation source disappeared, the sensor started working correctly. Although we were unable to determine the reason, we confirmed that sensing results may be affected by gamma-rays even if the sensing device works.

Contrary to our expectation, the other devices worked fine after a total dose of 200 Gy.

VI. Conclusions

In this paper, we reported the results of a gamma-ray irradiation test of the electric components mounted on the tracked vehicle Quince. On the first day of the test, we set a total dose of 100 Gy, and all of the devices were fine. On the second day, we set a total dose of 200 Gy. In this test, URG-LN04 malfunctioned after receiving total dose of 124 Gy, and the CCD camera malfunctioned after total dose of 169 Gy. The other devices continued working after receiving a total dose of 200 Gy.

In the initial stage of the disaster response at the Fukushima Daiichi Nuclear Power Station, the maximum dose in the target environment was around 100 mSv/h. This means that almost all of the electric devices in the Quince will work for 2,000 h. Of course, these devices have individual differences. Therefore, a safety margin should be considered. However, a typical location in the target environment has much less than 100 mSv/h, and 2,000 h is too long for exploration missions.

Note that the above devices are conventional, not products of radiation-proof. Furthermore, we could not conduct a sufficient quantity test for a statistical proof. Therefore, the above results can be one reference, but not guarantee a validity in all conditions.

Furthermore, based on the discussion of the penetration efficiency of gamma-rays in section II, effective protection from gamma-ray requires a thick and heavy sheet of lead. Therefore, we determined that we would use conventional electric devices without any lead protection.

After its redesign for exploration missions, on June 20, 2011, one of the Quinces was offered to Tokyo Electric Power Co.: it will be deployed in an actual disaster situation. We believe that it can contribute to the mitigation of this emergency situation.

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