Commentary

Behavior of Radioactive Cesium through Paddy Field Works

-Report from Field Tests in Minamisoma City-

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Since 2011, the Cleanup Subcommittee has been conducting puddling tests and paddy rice cultivation tests in Minamisoma City. The overall concept of the field tests was explained first. After that, the radioactivity measurement results for the presence of cesium and potassium in soil, rice plants, and brown rice were examined to understand the migration behavior of radioactive cesium, and the effectiveness of potassium fertilization and zeolite addition in reducing the concentration of cesium was then assessed.

KEYWORDS: Paddy field test, radioactive cesium, decontamination, potassium fertilization, zeolite addition, brown rice, plowing, threshing, polishing

I. Introduction

In the Fukushima Special Project that is being implemented by the Atomic Energy Society of Japan, the Cleanup Subcommittee has been working to pursue environmental remediation and local reconstruction in response to the disaster that occurred at the Fukushima Daiichi Nuclear Power Plant. This work includes radiation monitoring, recommendations related to environmental remediation, the sharing of information on decontamination technologies and temporary storage yards, the performance of field tests to demonstrate paddy restoration technologies, and the holding of talks with local communities [1-3]. Importantly, the committee has been conducting field tests on the decontamination of rice paddies in Minamisoma City, a practice that is little known outside Japan, in order to examine the behavior of radioactive cesium in rice paddies and assess decontamination techniques [4]. **Table 1** presents the decontamination techniques that are applied in paddy rice cultivation. The field tests were deemed necessary for plowing, puddling, and fertilization taking into consideration their levels of difficulty, the strain exerted on farmers, and the expected effects. Puddling tests and other paddy rice cultivation tests were conducted in partnership with the Japan Agricultural Cooperatives (JA) for Soma and Minamisoma City from 2011 to 2014 to study the migration behavior of cesium in rice plants and brown rice as well as the decontamination effect of potassium fertilization. This paper presents the findings from the field tests.

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Table 1 Decontamination techniques in paddy rice cultivation

No.	Method	Description	Remarks
(1)	Plowing	Mechanical or manual plowing to reduce cesium concentration in topsoil	Inexpensive No contaminated materials produced
(2)	Topsoil scraping	Removal of deposited cesium by scraping off topsoil	Depth Secondary contaminated materials
(3)	Puddling	Forced drainage of turbid water during puddling to remove particles contaminated with cesium	Treatment of wastewater, etc.
(4)	Soil washing	Stripping cesium from soil minerals and soil organic matter by using a cleaning solution	Field work Soil recovery
(5)	Phytoremediation	Cultivation of plants that easily absorb cesium and removal after the harvest	Less effective Treatment of secondary contaminated plants
(6)	Fertilization	Fertilization with K (discourage) and NH_3 (encourage) to regulate migration of cesium to crops	Inexpensive

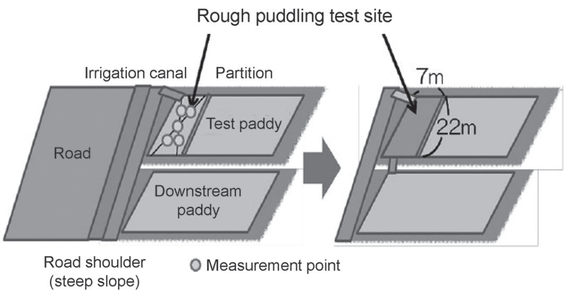

Figure 1 Rough puddling test site

II. Overview of Field Tests

1. Puddling Tests

In 2011, puddling tests were conducted in a rice paddy (10 m × 50 m) located in the Hirohata district of Baba, Minamisoma City, Fukushima Prefecture (**Figure 1**). This district is between 20 and 30 km from the Fukushima Daiichi Nuclear Power Plant. The test paddy draws in water from a nearby reservoir through an irrigation canal and discharges it into a drainage canal. The paddy was dry, and the grass there was knee-high. The tests were conducted three times: once in August, once in September, and once in November. In August, the test paddy was mowed to measure the air dose rate and take soil samples before and after the plowing. The air dose rate was also measured before and after the puddling to examine how much the exposure dose can be reduced during farm work and to perform a rough check of the decontamination rate for the soil. The plowing was followed by flooding, puddling (rough puddling), drainage, and soil sampling. In September, the second rough puddling test was conducted to sample the soil and drainage water. In November, samples were taken from farm water and the like. These samples were sent to laboratories operated by Tohoku University and Toshiba to measure the radioactivity of ^{137}Cs and ^{134}Cs using their germanium semiconductor detectors. The obtained concentration of radioactive materials was examined to assess the effectiveness of plowing in reducing radioactivity and the effectiveness of puddling in decontamination. The tests provided information on secondary contaminated materials, such as contaminated suspended water containing soil, the grain size distribution and major minerals present in the soil, the analysis of the major minerals, and the sedimentation rate of suspension.

2. Paddy Rice Cultivation Tests

From FY2012 onwards, paddy rice cultivation tests were conducted at a test paddy (20 m × 50 m) in the Hirohata district of Baba, Minamisoma City, Fukushima Prefecture. **Figure 2** presents the steps involved in paddy rice cultivation.

Every year from May to October, tasks beginning from planting, fertilization, harvesting, threshing, and polishing were carried out. At each step, the air dose rate was measured and samples were taken of the soil, rice plants, and water. Zeolite was blended into the soil during the plowing and then sprinkled after the puddling. **Figure 3** presents the farming conditions maintained in the test paddy. The test paddy draws in water from a nearby reservoir through an irrigation canal and discharges it into a drainage canal. The paddy was divided into two sections, one with potassium fertilization and the other without. These sections were then further divided into another three sections depending on the amount of zeolite that was sprinkled, which was none, normal, or double, thereby giving a total of six sections (A–F). Samples of the soil, rice plants, and so forth were taken from each section during the fertilization and zeolite sprinkling. The harvested rice was threshed and then divided into brown rice and broken rice. The former was then further divided into polished rice and bran. These samples were sent to laboratories operated by Tohoku University and Toshiba to measure the gamma

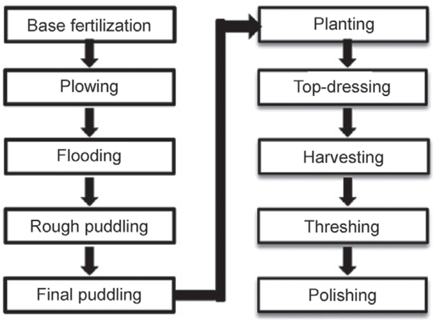

Figure 2 Steps for the paddy rice cultivation test

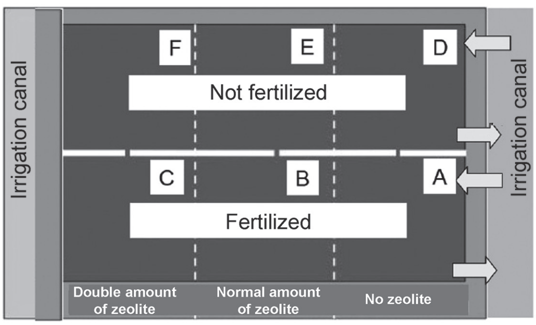

Figure 3 Sections of the paddy used for the rice cultivation test in FY2012

rays emitted from ^{137}Cs and ^{134}Cs with their germanium semiconductor detectors. The obtained radioactivity concentration per dry weight was examined to assess the effectiveness of zeolite addition and potassium fertilization in reducing radioactivity and the effectiveness of puddling in decontamination. The tests provided information on the migration behavior of radioactive cesium and decontamination. Given that top-dressing had no visible impact in FY2012, the emphasis was placed on base fertilizers over the following two years. Further tests were conducted in four sections using different amounts of zeolite, as shown in **Figure 4**.

In addition, following the considerable boar damage that resulted in trampled or eaten rice plants in FY2012, the test paddy was protected by electrical wires in subsequent years, as shown in **Figure 5**. Thereafter, rice could be harvested without any damage. Unfortunately, though, boars invaded the plastic greenhouse used for drying harvested rice in FY2014, leaving behind only a few dozen samples of threshed rice grains.

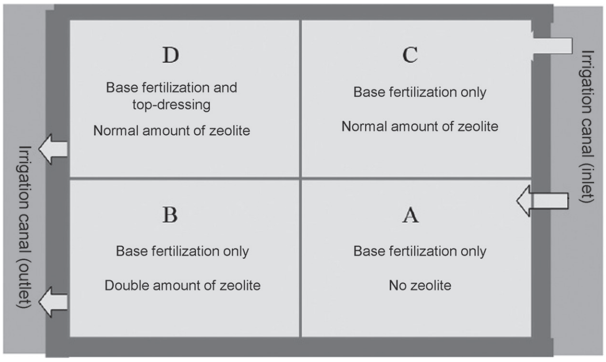

Figure 4 Sections of the paddy used for the rice cultivation tests in FY2013 and FY2014

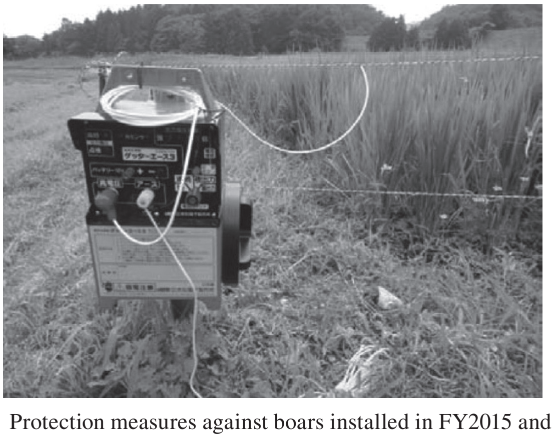

Figure 5 Protection measures against boars installed in FY2015 and FY2016

III. Test Results

1. Behavior of Radioactive Cesium during Puddling Tests

Puddling tests were conducted in the test paddy by performing the following steps: plowing, rough puddling, and final puddling. After the plowing, a simplified ridgeway was

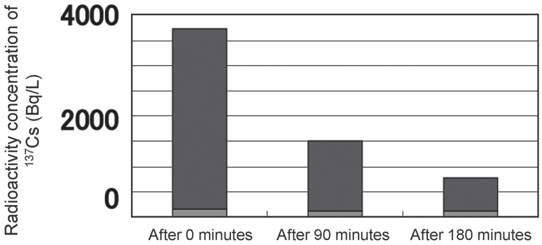

Figure 6 Changes in the radioactivity concentration of ^{137}Cs in drain water over time after the puddling

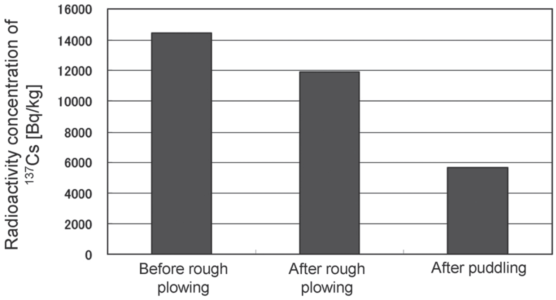

Figure 7 Changes in the radioactivity concentration of ^{137}Cs in the soil before rough plowing, after rough plowing, and after puddling

constructed. Once the paddy had been flooded, rough puddling and final puddling were carried out. Turbid water from the puddling tests was measured after it had been left to stand, with the results demonstrating that the water did not contain cesium. Cesium was contained mostly in the soil particles separated from the water, which indicates that cesium is adsorbed by the clay particles in the soil. These clay particles were suspended by puddling before an attempt was made to remove them from the test paddy by discharging turbid water. **Figure 6** presents the concentration of ^{137}Cs in the discharged water over time after the puddling operation had been performed. The concentration was 3,500 Bq/L immediately before the discharge (i.e., just after the puddling), but this figure dropped to 1,500 Bq/L after 90 minutes and then 750 Bq/L (i.e., less than a quarter) after 180 minutes. Puddling and drainage proved an effective means of performing radioactive cesium decontamination for rice paddies.

Next, changes in the ^{137}Cs concentration in the soil were tracked during the rough plowing, flooding, and puddling steps. The results are shown in **Figure 7**. Rough plowing reduced the concentration of ^{137}Cs in the soil by around 15% from 14,000 Bq/kg to 12,000 Bq/kg, which indicates that the ^{137}Cs adsorbed in the topsoil was diluted through being mixed with the soil underneath. The deeper the plowing was, the greater the reduction in radioactive cesium was. The puddling reduced the concentration even further to below 6,000 Bq/kg. In total, about 60% of the radioactive cesium was eliminated. In conclusion, rough plowing, puddling, and other ordinary techniques that are applied in paddy rice cultivation proved an effective means of reducing the amount of radioactive cesium retained in the soil.

2. Behavior of Cesium during Paddy Rice Cultivation Tests

Paddy rice cultivation tests were first performed at a test paddy in 2012. The average radioactive cesium concentration in the test paddy was 5,400 Bq/kg, which was almost half the level recorded in the puddling test paddy the previous year (over 10,000 Bq/kg). The most likely causes are the decay of ^{134}Cs and the migration of radioactive cesium due to weathering and other weather phenomena. The radioactivity concentration of the cesium and potassium in the soil was measured using samples taken from Sections A to D from the test paddy in FY2013. Similarly, soil samples were taken from two sections of the test paddy in FY2014. The average cesium concentration in the soil was around 3,000 Bq/kg in FY2013 and around 2,500 Bq/kg in FY2014. This concentration had stood at 14,000 and 5,400 Bq/kg in FY2011 and FY2012, respectively. This suggests that the radioactive cesium concentration drops significantly until the third year, after which the reduction slows due to the smaller contribution of ^{134}Cs with a half-life of two years.

In FY2012, the paddy was divided into six segments so that tests could be conducted with and without fertilization and using different amounts of zeolite addition. After the drying and threshing had been performed, the rice plants were divided into straw and roots. Rice husks were collected during the threshing. The measured levels of radioactive cesium radioactivity (^{134}Cs and ^{137}Cs) are presented in **Table 2**. The rice husks and straw contained 100 to 200 Bq/kg of radioactive cesium. Roots washed in water contained about ten times that amount, at between 2,000 and 3,000 Bq/kg. Since the radioactive cesium concentration in the soil of the test paddy was roughly 5,000 Bq/kg, the migration rate to the roots was 60% while that to the straw was up to 2%. In addition, the radioactivity concentration in Sections A, B, and C was slightly lower than that in Sections D, E, and F. Fertilization is believed to have suppressed the cesium absorption by reducing the proportion of cesium in relation to potassium. In a similar manner to that described in another report[5)], a significant reduction was observed for base fertilization, but the impact was reduced in the top-dressing. Moreover, farmers shared a valuable insight when they informed us that excessive potassium addition compromises the taste of the rice. Meanwhile, there were no notable differences associated with the different amounts of zeolite addition used in Sections A, B, and C.

Next, **Figure 8** compares the radioactivity measurement results for radioactive cesium and potassium in the brown rice from each section after threshing in FY2012. This figure demonstrates a low level of radioactivity for cesium of around 15 to 30 Bq/kg compared to about 75 Bq/kg for ^{40}K. The radioactive cesium concentration in Sections A, B, and C, which were fertilized, seems to be slightly lower than that in Sections D, E, and F, which were not fertilized. The proportion of broken rice in the former group was 4.9% compared to 6.3% in the latter group. This difference points to better rice growth owing to fertilization, as well as a

Table 2 Radioactive cesium concentration in rice husks, straw, and roots (Bq/kg)

Section	Fertilization	Zeolite	Rice husks	Rice straw	Roots
A	Fertilized	None	137	189	2844
B	Fertilized	Normal	117	141	2667
C	Fertilized	Double	105	156	1836
D	Not fertilized	None	185	187	2090
E	Not fertilized	Normal	115	180	2013
F	Not fertilized	Double	153	152	1878

reduced specific radioactivity per unit of weight in a heavier rice grain. The reduced absorption of radioactive cesium owing to fertilization should also be taken into account. As a result, the specific radioactivity per kilogram of broken rice was higher than that of brown rice.

Figure 9 presents the concentration of radioactive cesium and potassium in polished rice obtained from the harvested brown rice. In every section, the amount of radioactive cesium was less than 10 Bq/kg. Given that potassium and other nutrients are concentrated in bran (i.e., the outer layers of brown rice), the reduction in the radioactivity concentration of potassium due to the polishing process exceeded that for cesium.

Table 3 shows the concentration of radioactive cesium in the brown rice, broken rice, polished rice, and bran obtained in each section used in the paddy rice cultivation test conducted in FY2013. Broken rice tends to contain more radioactive cesium than brown rice does. The radioactivity is more concentrated in bran than it is in polished rice, which implies that cesium is concentrated in the outer layers of brown rice. The same tendency was confirmed for potassium. No significant differences were noted in a comparison of the figures corresponding to Sections A through D, which indicates that the amount of added zeolite and

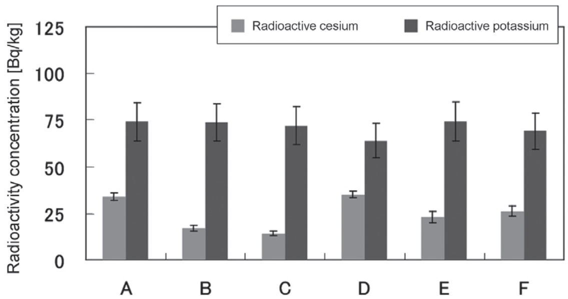

Figure 8 Concentration of radioactive cesium and potassium in brown rice from Sections A to F

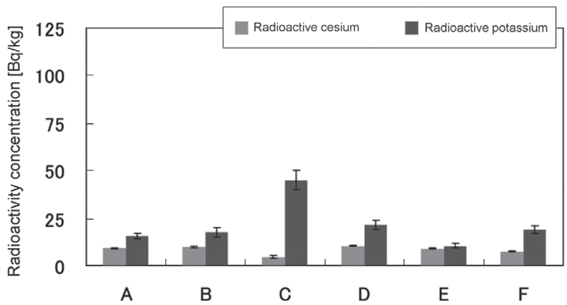

Figure 9 Concentration of radioactive cesium and potassium in polished rice from Sections A to F

Table 3 Radioactive cesium concentration in brown rice, polished rice, etc. (Bq/kg)

Section	Fertilization	Zeolite	Brown rice	Broken rice	Polished rice	Bran
A	Base	None	41	68	27	256
B	Base	Double	27	16	7	174
C	Base	Normal	47	59	13	209
D	Base + top-dressing	Normal	38	99	12	209

top-dressing had a marginal impact. The migration of radioactive cesium from the soil to brown rice was no more than 1%, but greater migration around 4 to 10% was noted for radioactive potassium. Similar results were obtained in the paddy rice cultivation test conducted in FY2014.

IV. Conclusions

This paper reports the results for paddy rice cultivation tests conducted over the course of four years by the Cleanup Subcommittee in Minamisoma City, Fukushima Prefecture. The radioactive cesium concentration in the soil was more than halved over these four years. Base fertilization using potassium proved effective, but not with top-dressing. Zeolite addition had no visible impact. The subcommittee found that only about 1% of cesium migrated from the soil to brown rice, while much more radioactive potassium did. Paddy rice cultivation tests will be continued in the field so that any changes in the migration behavior of radioactive cesium over time can be reported.

We would like to extend our gratitude to JA Soma and farmers for their kind understanding and cooperation in the conducting of these tests.

Members of the Cleanup Subcommittee who participated in the field tests (without honorifics)

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