Identification of ^{90}Sr and ^{40}K Based on Cherenkov Radiation at Lower Background Suppressed Cosmic Rays

Hiroshi Ito, Atsushi Kobayashi, Hideyuki Kawai, Satoshi Kodama, Takayuki Mizuno and Makoto Tabata

***Abstract*—A new detector, real-time ^{90}Sr counter, was developed with sensitivity to ^{90}Sr and less sensitivity to ^{137}Cs, ^{40}K and Cosmic rays, based on Cherenkov radiation. The detector is a threshold type Cherenkov counter using silica aerogel with a refractive index less than 1.042. Since of the threshold energy of 1.31 MeV, the beta ray from ^{90}Y can be identified. This detector would be applied for recovery Fukushima. By the Fukushima Nuclear Accident in 2011, particularly the fisheries were severely damaged due to radioactive contamination in Fukushima, Japan. Recent study is focused to radiation with longer half-life, ^{90}Sr and ^{137}Cs, in the contaminated water. In the study, the veto counter suppressed background event from cosmic rays was upgraded to performance with the detection efficiency of 99.9% or more. As the results, an absolute efficiency of ^{90}Sr, ^{137}Cs, and ^{40}K as the performance of detector was evaluated to 2.01×10^{-3}, 1.87×10^{-6}, and 1.75×10^{-5} Bq^{-1} s^{-1} using the sources, respectively. The efficiency uniformity depending on the source position was measured as peak at the center of the detector and half of the maximum value at the edge, the mean efficiency is estimated as $(1.68 \pm 0.24) \times 10^{-3}$ Bq^{-1}s^{-1}. The relation between the radioactivity and count rate was observed as response linearity, which is fitted a good linear function. Therefore, the count rate was corresponded to radioactivity concentration of contamination in a sample. Detection limit was estimated to be 1.93 (seawater) and 57.3 Bq kg^{-1} (seafood).**

***Index Terms*—Beta-ray Detectors, Cherenkov Radiation, Radiation Environment, Strontium-90**

I. INTRODUCTION

THE Great East Japan earthquake caused the accident of Fukushima Daiichi Nuclear Power Plant in March, 2011, as a result, radionuclides spread around Japan and Pacific Ocean. When radiation dose monitoring centers located near the reactor were broken by the earthquake, it was estimated that the most isotopes spread to Iitate village located direction of north-west from the reactor mainly based on weather simulation by G. Katata et al. [1]. On April 10, 2011, K. Shozugawa et al. collected samples such as soil, plant species, and water in the Iitate village and measured radionuclides such as ^{239}Np, ^{59}Fe, ^{131}I, ^{134}Cs, ^{133}Cs, ^{137}Cs, ^{110m}Ag (^{109}Ag), ^{132}Te, ^{132}I, ^{140}Ba, ^{140}La, ^{91}Sr, ^{91}Y, ^{95}Zr, and ^{95}Nb in the sample using Ge(Li) semiconductor detector [2]. Just after occurring the nuclear accident, the studies were focused to radiation internal exposures such as the thyroid from ^{131}I which has short half-life. Recent studies is focused to internal exposures from radionuclides such as ^{90}Sr and ^{137}Cs which have long half-life.

The Table I lists properties of nuclides in this study: physical half-life (τ_{phys}), a maximum kinetic energy of beta ray (K_{max}), an energy of gamma ray (E_{γ}), percentage of emission, and decay channels. ^{137}Cs has a physical half-life of 30.2 years, decays to ^{137m}Ba, and emits a beta ray of $K_{max} = 0.514\,\mathrm{MeV}$ in 94.4%. The ^{137m}Ba decays to stabled ^{137}Ba and emits a gamma ray of $E_{\gamma} = 0.662$ MeV. And ^{137}Cs decays to ^{137}Ba directly and emits beta ray of $K_{max} = 1.176\,\mathrm{MeV}$. ^{90}Sr has a physical half-life of 28.8 years, decays to ^{90}Y, and emits beta ray of $K_{max} = 0.546$ MeV. ^{90}Y has a physical half-life of 64 hours, decays to stabled ^{90}Zr, and emits beta ray of $K_{max} = 2.28$ MeV. ^{90}Sr and its daughter (^{90}Y) become radioactive equilibrium. ^{137}Cs and ^{90}Sr are artifact radionuclides produced by nuclear fission and water-soluble. In environment, ^{40}K is 0.0117% in potassium. The radiation dose has been estimated as 0.18 mSv/yr by internal exposures of approximation 60 Bq/kg. ^{40}K has a physical half-life of 1.25×10^{9} years, and emits beta rays of $K_{max} = 1.31$ MeV (89.1%) and gamma rays of $E_{\gamma} = 1.461$ MeV (10.7%).

TABLE I
MAXIMUM KINETIC ENERGY OF BETA-RAYS AND ENERGY OF GAMMA-RAYS EMITTED FROM MAIN RADIONUCLIDES WITH THEIR BRANCHING RATIO

Decay mode (τ_{phys})	K_{max}		E_{γ}	
$^{90}\mathrm{Sr} \rightarrow {}^{90}\mathrm{Y}$	0.546 MeV	(100%)		
(28.8 years)				
$^{90}\mathrm{Y} \rightarrow {}^{90}\mathrm{Zr}$	2.280 MeV	(100%)		
(64 hours)				
$^{137}\mathrm{Cs} \rightarrow {}^{137}\mathrm{Ba}$	0.512 MeV	(94.6%)	0.662 MeV	(85.1%)
(30.2 years)	1.174 MeV	(5.4%)	0.032 MeV	(5.8%)
$^{134}\mathrm{Cs} \rightarrow {}^{134}\mathrm{Ba}$	0.658 MeV	(70.2%)	0.604 MeV	(97.6%)
(2.06 years)	0.089 MeV	(27.3%)	0.796 MeV	(85.5%)
			0.802 MeV	(8.7%)
			0.563 MeV	(8.4%)
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca}$	1.311 MeV	(89.3%)		
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ar}$			1.461 MeV	(10.7%)
(1.25×10^{9} years)				

Recently, the fishery has stopped yet by radionuclides spread

---

Manuscript received Nov. 30, 2016; This work was supported by JSPS KAKENHI Grant number 25610049, a public offering research of Chubu of Electric Power Co., Inc. in 2013 by the Nuclear Safety Institute of Technology, a special program of the recovery support for the Great East Japan Earthquake in 2014, the New Technology Development Foundation and Venture Business Laboratory, Chiba University, and the Ogasawara Foundation for the Promotion of Science and Engineering in 2016.

H. Ito, A. Kobayashi, H. Kawai, S. Kodama, T. Mizuno and M. Tabata are with the Graduate of School of Science, Chiba University, Chiba, 268-8522, Japan (e-mail of corresponding author: hiroshi@hepburn.s.chiba-u.ac.jp).

around Pacific Ocean in Fukushima, Japan. Radioactivity of $^{134}\mathrm{Cs}$ and $^{137}\mathrm{Cs}$ (called radio-Cs) in samples of fish and seafood was measured individually using NaI(Tl) scintillation detector by Federation of Fisheries Cooperative Associations of Fukushima Prefecture in 2016, and it was reported the results were enough less than a contamination limit of $100\ \mathrm{Bq/kg}$ in food, which defined by Ministry of Health, Labour and Welfare, Japan. Furthermore, the association built a system monitoring the concentration of contamination in seafood. One of the reasons is $^{90}\mathrm{Sr}$ because it is more dangerous and difficult to measure in fish or seafood.

Cesium is alkali metal as same as sodium and even if it is taken in the body, it is excreted at biological half-life of 70 days. On the other hand, strontium is alkali earth metal as same as calcium and accumulates in the bone. ICRP published the effective dose coefficients of $^{90}\mathrm{Sr}(^{90}\mathrm{Y})$ and $^{137}\mathrm{Cs}$ for adult were estimated as 2.4×10^{-8} and $4.6 \times 10^{-9}\ \mathrm{Sv\ Bq}^{-1}$, respectively. Although a ratio of these coefficient is 5 times for the dose in whole-body, an important point is comparison about the dose coefficient in each tissue. On the red marrow, the dose coefficients of $^{90}\mathrm{Sr}$ and $^{137}\mathrm{Cs}$ are estimated as 1.6×10^{-7} and $4.4 \times 10^{-9}\ \mathrm{Sv\ Bq}^{-1}$, respectively. Thus, the risk of internal exposures of $^{90}\mathrm{Sr}$ is 36 times. The risk has an increasing trend to be low age, and the maximum risk is estimated as 126 times for infants [3]. Therefore, $^{90}\mathrm{Sr}$ is more dangerous than $^{137}\mathrm{Cs}$ for internal exposures.

It is easily to measure radioactivity of radio-Cs by gamma ray spectroscopy. Inspecting radio-Cs concentration was reported for the estuary sediment near the Fukushima Daiichi Nuclear Power Plant, fish, seafood, and other food in Fukushima Prefecture [4], [5], [6]. About concentration of $^{90}\mathrm{Sr}$ was reported $0.46\ \mathrm{Bq/kg}$ in flatfish and a ratio of $^{90}\mathrm{Sr}$/radio-Cs of 0.27 using a method of chemical extraction [6]. Although the method of chemical extraction for the sample ash, it should be measured individual tissue for $^{90}\mathrm{Sr}$. Furthermore, the method cannot apply to inspect concentration of $^{90}\mathrm{Sr}$ in food because its process takes approximately a month [7].

We developed a new detector, real-time $^{90}\mathrm{Sr}$ counter, to measure radioactivity of $^{90}\mathrm{Sr}$ at an hour or to monitoring the radioactivity in real time for a sample without chemical operation. This detector has a sensitive to beta rays from $^{90}\mathrm{Y}$ and less sensitive to radiation from other radiation because it is based on threshold type Cherenkov counter using silica aerogel with a refractive index less than 1.042. The detection limit of $^{90}\mathrm{Sr}$ was deteriorated by background event from cosmic rays, therefore the veto counter using plastic scintillator plates and wavelength shifting fibers was designed and installed over the Cherenkov counter. The detector mechanism and detail components are described in section II. And the result of performance estimation is provided in section III.

II. REAL-TIME $^{90}\mathrm{Sr}$ COUNTER

A new detector, real-time $^{90}\mathrm{Sr}$ counter, was developed based on Cherenkov radiation [8], [9]. The detector has some advantages: (1) easily to handle similar of a Survey meter, (2) rapidly to measure for an hour, (3) to use anywhere without the radiation controlled area, (4) to make a sample without chemical extraction. The detector consists of a trigger counter made of scintillating fibers (Trigger), an aerogel Cherenkov counter with wavelength-shifting fibers (AC) and a veto counter made of plastic scintillator and wavelength-shifting fibers (VETO). The detector is based on a threshold type Cherenkov counter using the silica aerogel with a refractive index less than 1.042. Since of the threshold energy of $1.31\ \mathrm{MeV}$, the beta ray from $^{90}\mathrm{Y}$ can be identified. In this section, a detection mechanism, the parts, the design, and a frontend electronics are described in detail.

A. Detection Mechanism

1) Cherenkov Radiation: Cherenkov radiation is a kind of shock wave. When velocity of a charged particle (v) is higher than light velocity (c/n) in a material with a refractive index of n, photons are emitted, as called Cherenkov radiation. In order to emit Cherenkov photons for only beta rays from $^{90}\mathrm{Y}$ in the other radiation, silica aerogel with the index less than 1.042 was used as the radiator [10], [11]. In this study, silica aerogel with $n = 1.0411 \pm 0.0002$ and optical transmission length of $40.8\ \mathrm{mm}$ in $400\ \mathrm{nm}$ was installed in the detector [12].

A relation between velocity ratio $(\beta = v/c)$ of the electron and the kinetic energy of the beta ray (K) is represented as

$$\beta = \frac{\sqrt{(m_e c^2 + K)^2 - m_e^2 c^4}}{mc^2 + K}, \tag{1}$$

where m_e is the mass of electron. Therefore, the velocity ratio of electron with $K = 2.28\ \mathrm{MeV}$ is calculated as $\beta = 0.983$.

A number of photon (N_{ph}) emitted as an electron with $beta$ passed through a radiator with n is approximately given as

$$N_{ph} \sim 2\pi\alpha L \left(1 - \frac{1}{n^2\beta^2}\right) \int \frac{d\lambda}{\lambda^2}, \tag{2}$$

where α, L, and λ is fine-structure constant, path length of the electron, and wavelength of emitted photon, respectively. As a result, in a case of the beta rays from $^{90}\mathrm{Y}$ using the silica aerogel, a number of emission photons per path length is estimated as approximately $21.4\ \mathrm{cm}^{-1}$, where integral region of optical wavelength is $350 - 600\ \mathrm{nm}$ because of an absorption of short-wavelength-light in SiO_2.

2) Suppressed background noise from Cosmic Muons: Intensity of vertical cosmic muons is known approximately $70\ \mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ in ground level. The velocity of muon over a few GeV/c is almost same of light velocity by relativity effect. If the muons pass through the silica aerogel, Cherenkov photons will be emitted, and background noises become the events. The event which muons passed through the detector can be rejected by operating logical signal of scintillation detector covered the Cherenkov counter.

3) Other background noise suppression: Cherenkov photons are observed by photomultiplier tubes (PMT). Gamma rays from a sample cannot emit Cherenkov photon. However, if gamma rays interacted in a photocathode or an entrance window of PMT, noise signals are produced. In the case of gamma rays interacted in the photocathode, produced electrons become noise signals by amplified between dynodes in PMT. On the other hand, in the case of gamma rays interacted in the entrance window, produced electrons emit Cherenkov photons by the Cherenkov radiation conditions satisfied in the window. Therefore, PMTs are necessary to move away from position of a sample.

B. Parts of the Detector

1) Trigger counter: To satisfy the Cherenkov radiation conditions for beta rays originating from ^{90}Y, the trigger counter (Trigger) should have minimal energy absorption. Trigger consists scintillating fibers (type: SCSF-78MJ) manufactured by Kuraray Co. Ltd. [13] and PMTs (type: R9880U-210) produced by Hamamatsu Photonics K. K. [14]. The fibers were obtained cross section of a 0.2-mm diameter, a double cladding structure, and a trapping efficiency of 5.4% by calculated from total reflection condition. The PMTs have an 8-mm-diameter photocathode of ultra-bialkali, and a maximum quantum efficiency of 40% in 400 nm. A sheet with an effective area of $300\ \mathrm{mm} \times 100\ \mathrm{mm}$ was made of scintillating fibers, where both ends of the fibers were bundled. Polished surface of the end of the fiber were connected to PMTs optically. The detection efficiency of the trigger counter was evaluated as 54.4% using $^{90}\mathrm{Sr}$ source.

2) Aerogel Cherenkov counter: For beta rays with $K_{max} = 1.31\ \mathrm{MeV}$ unsatisfied Cherenkov radiation conditions, it was explained silica aerogel with $n < 1.042$ was required. However, even if the condition is not satisfied, signals output by charged particle hit in a photocathode of PMT. Since a density of silica aerogel is approximately $0.2\ \mathrm{g/cm^3}$, electrons with $K = 1.31\ \mathrm{MeV}$ pass thorough a maximum length of $29\ \mathrm{mm}$ in silica aerogel. The aerogel Cherenkov counter (AC) installed three layers of silica aerogel with thickness of $10.3 \pm 0.2\ \mathrm{mm}$. That is silica aerogel has two functions of Cherenkov radiator and radiation shielding matter for beta rays from ^{40}K.

To Suppress noise events from gamma rays and to extend an effective area, optical light guide using wavelength-shifting fibers (WLSF) was adopted in the AC. After Cherenkov photons were absorbed into the WLSFs, the fibers emit photons shifted longer wavelength. The red-shifted photons which satisfied total reflection conditions propagate toward both ends of the fibers and are observed by PMT (type: R9880U-210) connected to the both ends optically. The fibers are made of two types of WLSFs: B-3(300)MJ and Y-11(300)MJ, manufactured by Kuraray Co. Ltd. because of a continuous spectrum of Cherenkov photons being in inverse propagation to square of the wavelength (see equation (2)). The fibers have a cross section of $0.2\ \mathrm{mm}$ in diameter, an attenuation length of approximately $1\ \mathrm{m}$, a double cladding structure, and a trapping efficiency of 5.4%. B-3(300)MJ and Y-11(300)MJ have a purple-to-blueshift and a blue-to-greenshift, respectively [13].

When beta rays emitted from ^{90}Y passing through silica aerogel while losing energy, a number of emitted Cherenkov photons (N'_{ph}) of approximately 10 is estimated. Extending absorption region of wavelength by using two kinds of WLSFs, collection efficiency (ε_f) was evaluated as 10%, which is considered the trapping- and reemission-efficiency. Therefore, a number of photoelectrons of Cherenkov photons observed via WLSFs ($N_{p.e.}$) is presents as

$$N_{p.e.} \sim N'_{ph} \varepsilon_f \varepsilon_q e^{-d/\Lambda_a - L/\Lambda_f}, \tag{3}$$

where ε_q, Λ_a, d, Λ_a, and L are the quantum efficiency of PMT, a transmission length of silica aerogel, a thickness of the silica aerogel, an attenuation length of WLSFs, and an optical path length propagated along WLSFs, respectively. As a result, $N_{p.e.} \sim 0.32$ was estimated, which the number of photoelectrons is less however important point is less sensitivity to the other radiation. The efficiency estimation would be described in section III.

3) Veto counter: To suppress background event of cosmic rays, veto counter (VETO) based on Scintillation detector was designed to cover Trigger and AC. The VETO consists of two units contained 3 types of blocks: (1) plate surface, (2) long side surfaces, and (3) short side surfaces. The unit consists of these blocks connected WLSFs, one side end of the fibers connected to PMT (type: H11934-200) optically, and other side end of the fibers connected to reflectors of Aluminized Mylar optically. The WLSFs are Y-11(300)MJ with 0.2-mm diameter made by Kuararay Co. Ltd., where the connected sheets are made of four sheets of the fibers. The plastic scintillator was produced by OHYO KOKEN KOGYO CO., LTD. The scintillators performance were evaluated as a number of photons yielded from the scintillator of $1277 \pm 150\ \mathrm{MeV^{-1}}$ and an attenuation length of 312 mm experimentally. Scintillation photons emitted from these blocks is read by PMT (type: H11934-200) via WLSFs. Wherever cosmic muons pass through the veto counter, the number of photoelectrons of 50-60 was observed. Therefore, the performance is estimated as enough efficiency.

C. Detector Design

The trigger counter sets under the AC. The entrance window of the detector is $300\ \mathrm{mm} \times 100\ \mathrm{mm}$ as the effective area of the trigger; nine tiles of the silica aerogel and the WLSF light guide are used in AC. The VETO counter covers the trigger and AC. Therefore, the events of any cosmic rays with incidence at zenith angle of $0 - 90^\circ$ could be suppressed. The sample is made to a paste of less than 1-mm thickness and dried without chemical extraction because the beta rays emitted from ^{90}Y can stop at water depth of about 10 mm and satisfy the Cherenkov radiation condition at the silica aerogel.

D. Frontend Electronics

The detector can be supplied 100 V of alternating current (AC) as household power source. After the supplied the AC voltages are converted to direct current (DC) 12 V by a AC-DC converter, a DC-DC converter supplies directory current voltages to each a HV (DC ± 5 and +12 V) and a DISCR (DC ± 5 V). The HV is 4-channel high voltage supply unit for PMTs (type: RP-1637BS) manufactured by REPIC Co., Ltd., which installed 2 high-voltage chips (BP015205n12) made by iseg Spezialelektronik GmbH company. The HV supplies commonly 1200 V to each PMT. The DISCR is a 4-channel discriminator (type: RP-1637AS) manufactured by REPIC Co., Ltd., which connected to signal cables from PMT sockets (type: E10679-02) made by Hamamatsu K. K. The output signal is NIM unit, and connected to a BRoaD which is a NIM level logic operator unit (type: BRoaD ver. 1) developed by Bee Beans Technologies Co., Ltd.

After the pulse signals from PMTs are discriminated by DISCR, the NIM-level signals with 10-ns width input into the BRoaD. In order to measure the beta rays from ^{90}Y, the logic operator as $Trigger \cap \overline{VETO} \cap AC(M \geq n)$ is required, where $Trigger$ is as an AND logic of two PMTs connected the trigger counter, $VETO$ is as an OR logic of two PMTs connected to the veto counter, and $AC(M \geq n)$ is as a multiplicity logic of $_4C_n$ in four PMTs connected to the AC which means an AND logic for n or more PMTs coincidences in four PMTs and can tune a probability for ^{90}Sr, where $n = 2$ in this time.

III. RESULTS OF PERFORMANCE ESTIMATION

The detector performance was evaluated as an absolute efficiency, a source position uniformity for the efficiency, and a response linearity and estimated as a detection limit for ^{90}Sr using radiation sources.

A. Radioactivity of Sources

The radioactivity of the sources of ^{90}Sr or ^{137}Cs is estimated as

$$A(t) = A_0 exp\left(-\frac{t}{\tau} ln2\right), \tag{4}$$

where $A_0 = 37$ kBq ($\pm 20\%$) defined as the Japan Radiation Association, t is passage of the years since the last calibration, and τ presents each physical half-life. The activity of ten ^{90}Sr sources and a ^{137}Cs source was calculated to be 23.6 ± 0.3 (stat) $\pm\, 4.7$ (sys) and 26.0 ± 5.2 (sys) kBq, respectively. The statistic and systematic errors are determined as deviation of individual activity and uncertainly by the last calibration, respectively. Pure potassium chloride (KCl) was used as a ^{40}K source. KCl has stable mass and an activity concentration of 16.6 Bq/g from ^{40}K. KCl with a purity of 99.5% or more was obtained from Hayashi Pure Chemical Ind. Ltd. [15]. A KCl source with a mass of 30.0 ± 0.1 g (498 ± 2 (sys) Bq) was used for the performance estimation.

B. Absolute Efficiency

Background rates at an hour in 14 times were measured 132.57 ± 12.11, which the errors present standard deviation. An absolute efficiency is defined as

$$\eta_x = (N_x - N_{BG})/A_x T, \tag{5}$$

where $x = {}^{90}$Sr, ^{137}Cs, ^{40}K denotes used radiation sources, $T = 3600$ s is measurement time, and N is the count rate at an hour. The ^{90}Sr source setting on a center of under the entrance window, the count rate was observed 171077 ± 6279 cph corresponded to the efficiency of $[2.01 \pm 0.07(\text{stat}) \pm 0.40(\text{sys})] \times 10^{-3}$ Bq^{-1} s^{-1}, where the statistic error is dominant for the error of N_{Sr} and N_{BG} mainly, and the systematic error is originated from systematic error of A_{Sr}. The other source setting as same as ^{90}Sr, the efficiency of ^{137}Cs and ^{40}K were evaluated as $[1.87 \pm 0.23(\text{stat}) \pm 0.014(\text{sys})] \times 10^{-6}$ and $[1.75 \pm 0.98(\text{stat}) \pm 0.01(\text{sys})] \times 10^{-5}$ Bq^{-1} s^{-1}, respectively. As a result, the efficiency ratios, $\eta_{\text{Sr}}/\eta_{\text{Cs}}$ and $\eta_{\text{Sr}}/\eta_{\text{K}}$, were calculated as 1073.5 and 114.8, respectively, which means the detector can identify substantially the beta rays from ^{90}Y in environmental radiation.

TABLE II
RESULT OF THE BACKGROUND RATE, THE ABSOLUTE EFFICIENCY, AND EFFICIENCY RATIO ON EACH SOURCE

Logic: $Trigger \cap \overline{VETO} \cap AC(M \geq 2)$	
N_{BG}	132.6 ± 12.1 cph
η_{Sr}	$[2.01 \pm 0.07(\text{stat}) \pm 0.40(\text{sys})] \times 10^{-3}$ Bq^{-1}s^{-1}
η_{Cs}	$[1.87 \pm 0.23(\text{stat}) \pm 0.37(\text{sys})] \times 10^{-6}$ Bq^{-1}s^{-1}
η_{K}	$[1.75 \pm 0.98(\text{stat}) \pm 0.01(\text{sys})] \times 10^{-5}$ Bq^{-1}s^{-1}
$\eta_{\text{Sr}}/\eta_{\text{Cs}}$	1073.5
$\eta_{\text{Sr}}/\eta_{\text{K}}$	114.8

C. Efficiency Uniformity by Source Position

The efficiency uniformity was measured setting the ^{90}Sr source at 35 points under the window with the area of 300 mm × 100 mm. As a result, the efficiency of ^{90}Sr tends to peak the value at the center and to reduce to half value at the edge, as a result, mean of the efficiency is calculated as $(1.68 \pm 0.24) \times 10^{-3}$ Bq^{-1}s^{-1}.

D. Response Linearity

The ^{90}Sr sources setting on the center under the window, a relation between the radioactivity and count rate was measured as response linearity for ^{90}Sr. As a result, the relation has good linearity with the fitted inclination of $(1.96 \pm 0.04) \times 10^{-3}$ Bq^{-1}s^{-1} and $\chi^2/NDF = 0.673/11$, therefore the count rate as inspecting result is enable to corresponded to concentration of radioactivity in a sample.

E. Detection Limit of ^{90}Sr

Since the detector should inspect a sample with lower concentration of ^{90}Sr in environment radiation, it is necessary to estimate the limit of detection even if the sample has ^{137}Cs and ^{40}K. In this discussion, it is assumed the radioactivity concentration of ^{137}Cs and ^{40}K in seawater (seafood) sample are $A'_{\text{Cs}} = 100$ Bq kg^{-1} which was determined as the limit concentration by Japanese Government and $A'_{\text{K}} = 12.1$ (150) Bq kg^{-1}, respectively. To inspect surface contamination, the sample volume should be compress drying or heating; the compression factor for seawater (seafood) is $\varepsilon = 0.3$ (0.01) because seawater and seafood have approximately 70% and 99% or more pure water, respectively. The dried-sample weight (with a density of 1 g cm^{-3}) is $m = 30$ g because of the entrance window of 300 cm^2 and making to paste thickness of 1 mm . When the sample is set under the window, the count rate per an hour (N) is calculated by

$$N = (\eta_{\rm Sr} A'_{\rm Sr} + \eta_{\rm Cs} A'_{\rm Cs} + \eta_{\rm K} A'_{\rm K}) m \varepsilon^{-1} T + N_{BG}, \qquad (6)$$

where $A'_{\rm Sr}$ is radioactivity concentration of ^{90}Sr, T is measuring time of 3600 s. The background count rate (N'_{BG}) when the sample has no ^{90}Sr is calculated by

$$N'_{BG} = (\eta_{\rm Cs} A'_{\rm Cs} + \eta_{\rm K} A'_{\rm K}) m \varepsilon^{-1} T + N_{BG}. \qquad (7)$$

The detection limit of radio activity of ^{90}Sr ($A^{min}_{\rm Sr}$) is calculated to be

$$A^{min}_{\rm Sr} = \frac{3\sqrt{N_{BG} + (\eta_{\rm Cs} A'_{\rm Cs} + \eta_{\rm K} A'_{\rm K}) m \varepsilon^{-1} T}}{\eta_{\rm Sr} m \varepsilon^{-1} T}, \qquad (8)$$

from the maximum of $A_{\rm Sr}$ satisfied a condition in Kaise's theorem: $N > N'_{BG} + 3\sqrt{N'_{BG}}$. As the result, the detection limit was estimated to $1.93 \pm 0.29\ (\rm stat) \pm 0.39\ (\rm sys)$ (seawater) and $57.3 \pm 8.6\ (\rm stat) \pm 11.4\ (\rm sys)\ \rm Bq\ kg^{-1}$ (seafood).

IV. CONCLUSION

A new detector, real-time ^{90}Sr counter, was developed based on a threshold type Cherenkov detector, which is higher sensitivity to beta rays from ^{90}Y and less sensitivity to other radiation such as ^{137}Cs, ^{40}K, and Cosmic rays. Therefore, the detector can be measured radioactivity of ^{90}Sr in environmental radiation background. The sample make to paste compressed volume without chemical extraction. In this study, the detector could identify ^{90}Sr and ^{40}K by upgrading the VETO counter for suppression of cosmic-ray muons event. As the results, the absolute efficiency of ^{90}Sr, ^{137}Cs, and ^{40}K as the performance of detector was evaluated to $[2.01 \pm 0.07(\rm stat) \pm 0.40(\rm sys)] \times 10^{-3}$, $[1.87 \pm 0.23(\rm stat) \pm 0.014(\rm sys)] \times 10^{-6}$, and $[1.75 \pm 0.98(\rm stat) \pm 0.01(\rm sys)] \times 10^{-5}\ \rm Bq^{-1}\ s^{-1}$ using the sources, respectively. The efficiency ratio of $\eta_{\rm Sr}/\eta_{\rm K}$ was achieved 100 or more, thus the performance of identification is estimated to enough. The efficiency uniformity depending on source position was measured as peak at the center of the detector and half of the maximum value at edge of the detector, the mean efficiency is estimated as $(1.68 \pm 0.24) \times 10^{-3}\ \rm Bq^{-1} s^{-1}$. The relation between the radioactivity and count rate was observed as response linearity, which is fitted a good linear function. Therefore, the count rate by the detector is corresponded to radioactivity concentration contamination in sample. Detection limit was estimated to be $1.93 \pm 0.29\ (\rm stat) \pm 0.39\ (\rm sys)$ (seawater) and $57.3 \pm 8.6\ (\rm stat) \pm 11.4\ (\rm sys)\ \rm Bq\ kg^{-1}$ (seafood).

REFERENCES

[1] G. Katata, H. Terada, H. Nagai, and M. Chino, " Numerical reconstruction of high dose rate zones due to the Fukushima Dai-ichi Nuclear Power Plant accident", J. Environ. Radio., vol. 111, pp. 2-12, 2012.

[2] K. Shozugawa, N. Nogawa, and M. Matsuo, " Deposition of fission and activation products after the Fukushima Dai-ichi nuclear power plant accident", Environ. Pollution, vol. 163, pp. 243-247, 2012.

[3] ICRP, " Age-dependence Doses to Members of the Public from Intake of Radionuclides: Part 4 Inhalation Dose Coefficients", ICRP publication 71, 1995.

[4] S. Yamasaki, J. Imoto, G. Furuki, A. Ochiai, T. Ohnuki, K. Sueki, K. Nanba, R. C. Ewing, and S. Utsunomiya, " Radioactive Cs in the estuary sediments near Fukushima Daiichi Nuclear Power Plant", Scien. Total Environ., vol. 551-552, pp. 155-162, 2016.

[5] J. Tsuboi, S. Abe, K. Fujimoto, H. Kaeriyama, D. Ambe, K. Matsuda, M. Enomoto, A. Tomiya, T. Morita, T. Ono, S. Yamamoto, and K. Iguchi, " Exposure of a herbivorous fish to ^{134}Cs and ^{137}Cs from the riverbed following the Fukushima disaster", J. Environ. Radio., vol. 141, pp. 32-37, 2015.

[6] H. Nabeshi, T. Tsutsumi, and Y. Uekusa, A. Hachisuka, R. Matsuda, and R. Teshima, " Surveillance of Strontium-90 in Foods after the Fukushima Daiichi Nuclear Power Plant Accident", Food Hygi. Safe. Science, vol. 56, no. 4, pp. 133-143, 2015.

[7] C. Testa, D. Desideri, F. Guerra, M. A. Meli, C. Roselli, and G. Jia, " The importance of separation chemistry for the determination of radionuclides in environmental samples", J. Radio. Nucl. Chem., vol. 229, Issue 1, pp. 23-32, 1998.

[8] H. Ito, S. Han, A. Kobayashi, N. Kaneko, H. Kawai, and Makoto Tabata, " Identification of ^{90}Sr/^{40}K based on Cherenkov detector for recovery from the Fukushima nuclear accident", JPS Conf. Proc., 070002, 2016.

[9] S. Ijima, S. Han, H. Ito, H. Kawai, S. Kodama, and D. Kumogoshi, " Development of Realtime 90Sr Counter Used in Low Rate Radioactive", in: 2014 IEEE NSS/MIC, N09-40, 2014.

[10] S. Iijima, H. Ito, D. Kumogoshi, K. Satoshi, H. Kawai, M. Tabata, K. Mase, and H. Nakayama, " Development of Realtime 90Sr Counter", in: 2013 IEEE NSS/MIC, NPO1-169, 2013.

[11] R. Pestotnik, S. Korpar, P. Krizǎn, and R. Dolenec, " Cherenkov detector of 90Sr based on aerogel as radiator", Nucl. Instrum. Methods A, vol. 595, Issue 1, pp. 278-280, 2008.

[12] M. Tabata, I. Adachi, H. Kawai, T. Sumiyoshi, and H. Yokogawa, " Hydrophobic silica aerogel production at KEK ", Nucl. Instrum. Methods A, vol. 668, pp. 64-70, 2012.

[13] Kuraray Co. Ltd., data sheet, Available: http://kuraraypsf.jp.

[14] Hamamatsu Photonics K.K., data sheet, Available: http://www.hamamatsu.com.

[15] Hayashi Pure Chemical Ind. Ltd., data sheet, Available: http://www.hpc-j.co.jp