Monitoring Rainwater and Seaweed

Reveals the Presence of ^{131}I in Southwestern and Central British Columbia Following the Fukushima Nuclear Accident in Japan

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Résumé

Une analyse détaillée des concentrations d'iode 131 dans l'eau pluviale et dans trois espèces de varech (*Fucus distichus* Linnaeus ou fucus fourchu, *Macrocystis pyrifera* et *Pyropia fallax*) récoltées dans le sud-ouest de la Colombie-Britannique et à Bella Bella (C.-B.) a été réalisée par spectrométrie gamma à la suite de l'émission de substances nucléaires à la centrale nucléaire de Fukushima provoquée par un puissant tremblement de terre suivi d'un gigantesque tsunami le 11 mars 2011. Il a ainsi été déterminé que l'activité maximale de l'iode 131 était de 5,8(7) Bq/L dans l'eau pluviale récoltée sur le campus de l'Université Simon Fraser à Burnaby (C.-B.), 9 jours après l'accident. En même temps, il a été observé que l'activité maximale dans le *Fucus distichus* Linnaeus sous forme sèche était de 130(7) Bq/kg dans les échantillons récoltés à North Vancouver 11 jours après l'accident, et de 67(6) Bq/kg, toujours sous forme sèche, dans les échantillons récoltés 17 jours après l'accident au Bamfield Marine Sciences Centre localisé sur l'île de Vancouver. L'activité de l'iode 131 dans les échantillons de varech récoltés dans le sud-ouest de la Colombie-Britannique après l'accident de Fukushima était d'une magnitude moindre que celle observée dans les échantillons pris à la suite de l'accident de Tchernobyl. Par ailleurs, l'activité de l'iode 131 dans le *Fucus distichus* Linnaeus pouvait toujours être détectée 60 jours après l'accident et pouvait être décelée dans chacune des espèces de varech récoltées. Le Germanium Detector for Elemental Analysis and Radioactivity Studies (GEARS) a été modelé en fonction du progiciel GEANT4 et créé en tant qu'instrument analytique par le Nuclear Science Group du département de chimie de l'Université Simon Fraser afin d'effectuer ces mesures.

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Introduction

Following the Tohoku earthquake and subsequent tsunami on March 11, 2011, the damaged Fukushima Daiichi nuclear power plant released radioisotopes from fission fragments and nuclear fuel into the environment. Some fission fragments were released as aerosols or gases and dispersed over a large geographic region through the atmosphere. The gaseous fission fragment ^{131}I represents ~2.89% of the fission yield of enriched uranium (England and Rider, 1994) and is of particular concern to human health due to accumulation in the thyroid. Iodine-131 is not naturally present in the environment, but with an 8.0252 day half-life (National Nuclear Data Center, 2012), it survives long enough to be transported in the atmosphere across the Pacific Ocean. Therefore, during the current studies any ^{131}I detected in rainwater or seaweed was attributed to releases from Fukushima.

Fallout of ^{131}I following the Fukushima accident was widespread. Airborne ^{131}I was observed in Europe (Ioannidou et al., 2012; Manolopoulou et al., 2011; Perrot et al., 2012; Pham et al., 2012), the Canary Islands off the northwestern coast of Africa (L´opez-P´erez et al., 2013), South Korea (Kim et al., 2012) and in the northwestern United States (Diaz Leon et al., 2011). Iodine-131 concentrations in rainwater of ≤3.5 Bq/L were reported in Bordeaux, France (Perrot et al., 2012), Milano, Italy (Ioannidou et al., 2012), and Jeju, South Korea (Kim et al., 2012). Measurements of ^{131}I in Washington State indicated that releases from Fukushima first arrived between March 16 and March 18. Subsequently, ^{131}I was first detected on the European continent between March 21 and March 28 and in South Korea on March 28.

As part of the global effort to monitor fission fragment releases following Fukushima,^{131}I was measured in rainwater collected in British Columbia at the Simon Fraser University (SFU) campus on Burnaby Mountain and in seaweed samples collected in North Vancouver, the Bamfield Marine Sciences Centre (BMSC) on Vancouver Island, located ~ 250 km west of Vancouver, and Bella Bella, located on the Pacific coast ~ 650 km north of Vancouver. The perennial brown seaweed species *Fucus distichus* Linnaeus (henceforth *Fucus*) was chosen as the primary biological monitor for ^{131}I releases from Fukushima. *Fucus* was chosen because it concentrates iodine present in the environment, is widespread in intertidal zones in the Pacific Northwest where it can accumulate iodine from rainfall, and was used as a biological monitor in BC following the Chernobyl disaster (Druehl et al., 1988). In addition, *Macrocystis pyrifera* and *Pyropia fallax* samples collected in Bella Bella served as secondary biological monitoring systems. The monitoring campaign provided an opportunity to compare ^{131}I contamination in BC following Fukushima and Chernobyl, and to develop the equipment and techniques necessary to perform highly accurate analytical radiochemistry at SFU.

Iodine-131 content in rainwater and seaweed was monitored following the analysis of gamma-ray decay spectra, acquired using a shielded high purity germanium (HPGe) detector. HPGe detectors possess excellent energy resolution, which facilitates the detection of weak sources of radiation that would otherwise be lost in the background if detectors with poorer energy resolution, such as inorganic scintillators, are used (Knoll, 2002). HPGe detectors are therefore the preferred tool to measure complex spectra such as those found in environmental samples, which contain many gamma-ray lines that must be resolved for proper analysis.

Materials and Methods

The Germanium Detector for Elemental Analysis and Radiation Studies

The Germanium Detector for Elemental Analysis and Radioactivity Studies (GEARS) is an Ortec GEM Profile Series HPGe coaxial gamma-ray detector that was operational at the time of the Fukushima accident. GEARS is coupled to an ORTEC DSpec jr. 2.0 multichannel analyzer (MCA) with bias voltage provided by a built-in power supply. Gamma-ray decay spectra are collected by a computer running the Ortec Maestro32 software.

A low-activity lead shield with dimensions 51 x 51 x 64 cm ($l \times w \times h$) constructed from 10 cm-thick lead was used to house the GEARS detector and reduce low-level background due to naturally occurring radioactive materials (NORM) (Malain et al., 2012). The lead shield is coupled with a Cu/Cd graded-Z shield to decrease the flux of low energy gamma rays and X-rays from NORM and the lead shield (Knoll, 2002).

GEARS was energy-calibrated with a set of standard radioactive point sources, and absolute efficiency was measured using a calibrated ^{60}Co source. A linearized χ^2 fit was performed on a relative efficiency curve measured using a ^{152} Eu source with a power law relating relative efficiency $\varepsilon\rho\varepsilon\lambda$ and energy E given by Equation 1.

$$\log \varepsilon_{rel.} = k \log E + b \qquad (1)$$

The 1σ (68.27%) confidence interval was calculated for the best fit line and defines the error on the relative efficiency. An absolute efficiency curve from 250 keV to 1400 keV was

constructed by scaling the ^{152} Eu relative efficiency to the absolute efficiency measured from the ^{60}Co source; this is shown in Figure 1.

GEANT4 Simulations

GEANT4 is a software package developed by the European Organization for Nuclear Re-search (CERN) to simulate the interaction of radiation with matter (Agostinelli et al., 2003; Allison et al., 2006). GEANT4 allows the user to create an experimental hall of custom dimension and incorporate objects of various geometries and materials into the hall. The GEARS detector, housing, graded-Z shield, lead shield, and other components were modelled using this framework as shown in Figure 2. Extended radioactive sources have been implemented in GEANT4 to simulate the available sample configurations. Implemented configurations include 24 mL, 60 mL, and 120 mL glass vials.

Gamma ray self-absorption in extended source samples can be simulated in GEANT4, provided the elemental composition and density of the samples are known. Extended sources composed of water were implemented in GEANT4. The density of processed seaweed was measured from various samples; the exact elemental composition was not known and assumed to be 100% carbon. Simulations implementing gamma ray self absorption was used to correct for extended source efficiency.

Extended Source Efficiency Correction

The efficiency calibration described above in the Germanium Detector for Elemental Analysis and Radiation Studies section was completed using standard point sources, whereas rainwater and seaweed samples were measured in 24 mL, 60 mL, and 120 mL glass vials. Altering the source geometry and composition has a large effect on the efficiency of gamma ray detection; this effect must be quantified for proper data analysis. The corrected efficiency for extended sources can be calculated using Equation 2, where the correction factor C_s,which accounts for the change in detection efficiency, is source dependent.

$$\varepsilon_{extended} = \varepsilon_{point} \times C_s \qquad (2)$$

A sample of purified UO_2Cl_2 crystals, a water soluble uranium salt containing depleted and physically separated ^{238}U obtained from the SFU Department of Chemistry was used to construct a point-like source. The point-like source was measured at two geometries: placed on the detector can and at 10.5 cm above the detector. Extended sources with identical geometry to those used in the measurements described in the Rainwater and Seaweed sections below were constructed by dissolving the UO_2Cl_2 point source sample to prepare a series of dilutions. UO_2Cl_2 from the point source was transferred to a 24 mL glass vial, dissolved completely in distilled water, and measured on GEARS. Subsequent serial dilution measurements were performed using 60 mL and 120 mL vials; during each transfer, the smaller vial was thoroughly rinsed into the larger volume with distilled water.

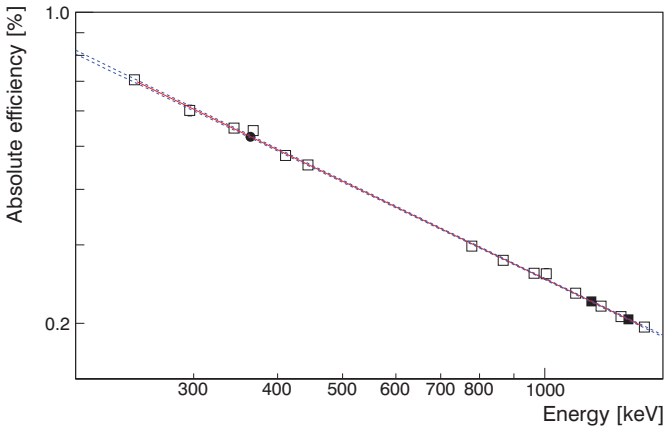

Figure 1: Absolute efficiency of GEARS as a function of energy, measured using point sources. The detector was calibrated by scaling data obtained with a 152Eu source placed 10.5 cm above the detector can to a calibrated 60Co source in the same configuration. The $\chi 2$ best fit to Eq. 1 is shown in red, the 1σ confidence intervals are shown as blue dashed lines. Data shown are 152Eu [hollow squares], the absolute efficiency measured for 60Co [filled squares], and calculated absolute efficiency for the ^{131}I peak of interest [filled circle].

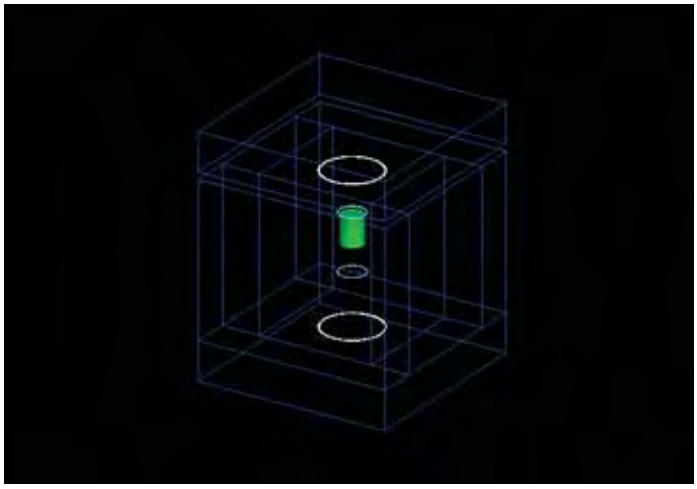

Figure 2: The GEARS geometry implemented in the GEANT4 software package. The box superstructure [dark blue] is lead shielding, the large wire-frame cylinder [white] is the Cu/Cd graded-Z shield, the small wire-frame cylinder [light blue] is the aluminum can that houses the detector, and the solid cylinder [green] is the HPGe crystal of the GEARS detector.

This process was carried out in order to create a series of standard calibration sources with constant activity.

The ^{238}U decay chain up to ^{234}U is in secular equilibrium due to the use of depleted UO_2Cl_2 starting material; thus, the number of excited state ^{234}U atoms populated following the β-decay of ^{234}Pa, which decay to the ground state by gamma-ray

emission, is constant with respect to the measurement duration. To analyze the efficiency of each extended source, the 258.227, 945.94, 1001.03, 1193.73, and 1737.75 keV (National Nuclear Data Center, 2012) gamma rays of ^{234}U were measured after each dilution. Following each measurement, the activity ratio with respect to the point source was calculated over this range of energies. Two independent measurements were completed.

The results of the two measurements and GEANT4 simulations for the 24 mL, 60 mL and 120 mL vials are shown in Figures. 3, 4, and 5. The two measurements in the 24 mL vial were consistent. GEANT4 simulations of this extended source were completed and found to be consistent with the experimental values. The measurements in the 120 mL vial were also consistent with one another. However, the experimental results were ~ 50% below the activity ratio, calculated using GEANT4 simulations.

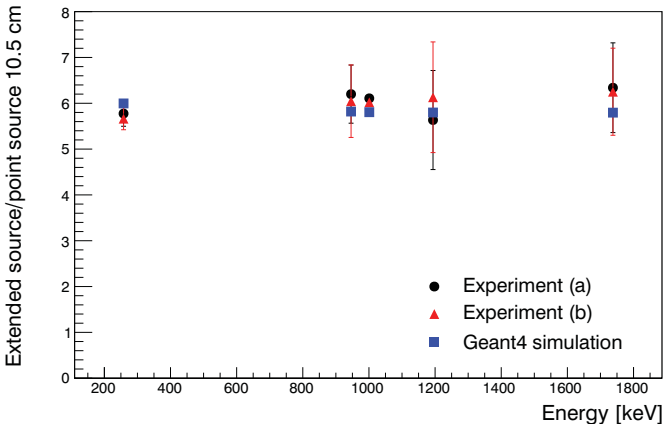

Figure 3: Extended source/point source efficiency ratio at prominent gamma-ray energies of 234U. The results from two independent experiments (a) and (b) are shown with GEANT4 simulations for the serial-dilution measurements described in Extended Source Efficiency Correction. Results shown are for the 24 mL vial, the initial step of the serial-dilution process. GEANT4 simulations and experimental results are consistent.

This disagreement could arise from an inhomogeneous distribution of UO_2Cl_2 in the vial due to the formation of so-called radiocolloids or adsorption on the glass walls, phenomena that have been previously observed in dilute solutions of radioactive salts (Tölgyessy et al., 1971). A control experiment to test the adsorption of UO_2Cl_2 on the walls of the glass vials was completed and non-reversible adsorption on glass was observed following the rinsing procedure used to construct the extended sources for calibration.

Every vial used during the rainwater monitoring campaign was filled to capacity and therefore only a single correction factor for each vial size was necessary. However, seaweed samples were measured in all three vials filled to varying degrees. GEANT4 simulations were conducted to assess how detection efficiency

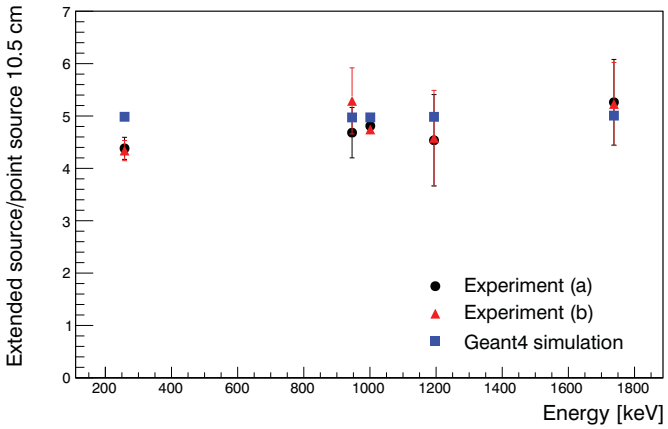

Figure 4: Extended source/point source efficiency ratio at prominent gamma-ray energies of 234U. The results from two independent experiments (a) and (b) are shown with GEANT4 simulations for the serial-dilution measurements described in Extended Source Efficiency Correction. Results shown are for the 60 mL vial, the second step of the serial-dilution process. GEANT4 simulations and experimental results are consistent for energies ≥ 945.94 keV.

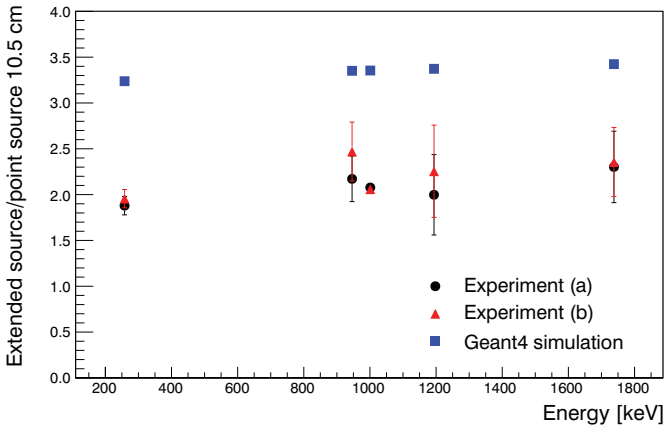

Figure 5: Extended source/point source efficiency ratio at prominent gamma-ray energies of 234U. The results from two independent experiments (a) and (b) are shown with GEANT4 simulations for the serial-dilution measurements described in Extended Source Efficiency Correction. Results shown are for the 120 mL vial, the final step of the serial-dilution process. Experimental results are consistent but show a ~50% discrepancy from GEANT4 simulations attributed to adsorption of UO2 Cl2 on the walls of the vial.

varied with vial fill level in order to properly correct the seaweed data. GEANT4 simulations with a 364.489 keV gamma-ray source were performed with vials 1/4 full, 1/2 full, 3/4 full, and filled to capacity. A least squares fit with a second order polynomial was performed on these data. Efficiency corrections for partially filled vials were made using the correction factor obtained from the fit and Equation 2. These data and the accompanying fits are shown in Figure 6.

Sampling Procedure

Rainwater Sampling

Rainwater samples were collected at the SFU campus approximately once per day. Following collection, the rainwater was filtered using 110 mm diameter Whatman filter paper to remove particulates and transferred to 24 mL and 120 mL glass vials. The vials were placed on the GEARS detector and measured. The 364.489 keV line indicative of ^{131}I decay was selected for quantitative analysis. Rainwater collection began on March 16, 2011, and continued through April 14, 2011.

Seaweed Sampling

Fucus samples were gathered primarily from BMSC on Vancouver Island and from the Burrard Inlet in North Vancouver. The sample collection site from North Vancouver was located near a storm drain, potentially exposing the seaweed to ^{131}I contained in sewage effluent and runoff. Once obtained, samples were rinsed with tap water to remove sand, rocks, aquatic animals, and epiphytes from the surface of the seaweed and air dried until most of the rinsing water had evaporated (~ 4 hours). The air-dried seaweed was placed in a commercially available food dehydrator and dried overnight at a temperature of ~ 70°C. Samples were ground into a powder using a mortar and pestle and transferred to 24 mL, 60 mL, or 120 mL glass vials and weighed. Seaweed collection began in North Vancouver on March 15, 2011, and at BMSC on March 22, 2011.

Results

Monitoring ^{131}I Following Fukushima

The presence of ^{131}I was confirmed following the identification of the characteristic 364.489 keV and 284.305 keV gamma rays in environmental samples as well as a lifetime measurement of the 364.489 keV gamma-ray line in a single seaweed sample shown in Figure 7. To perform the lifetime fit, activity ratios in a single sample were measured as a function of time. The sample used to generate these data was collected on March 28, 2011, in North Vancouver and initially measured on March 31, 2011. The same sample was remeasured on April 9, 2011, and May 4, 2011. The data was fit with the exponential function given in Equation 3.

$$\frac{A(t)}{A(t_0)} = e^{-(t-t_0)/\tau} \qquad (3)$$

Where $A(t)$ is the activity at time t, $A(t_0)$ is the activity measured on t_0 = March 31, 2011, t is the time since t_0 in days, and τ is the best fit lifetime in days. A remeasurement of the sample was performed on November 9, 2012 and no ^{131}I was observed. The decrease to zero ^{131}I activity justifies the exclusion of a constant in the exponential fit. The best fit lifetime was τ = 11.2(1.1) days, in agreement with the literature value of 11.5779(7) days (National Nuclear Data Center, 2012).

Activity concentrations of ^{131}I were measured by observation of the 364.489 keV gamma-ray line. The activity concentration in rainwater and seaweed samples at the collection time was corrected for measurement delay, ^{131}I half-life, the efficiency of the detector, and the known branching ratio (0.815) of the 364.489 keV gamma ray (Khazov et al., 2006).

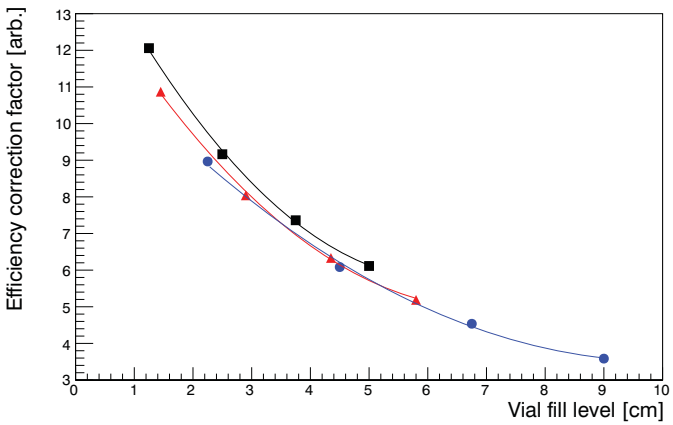

Figure 6: Extended source efficiency correction curve for the 24 mL [black], 60 mL [red], and 120 mL [blue] vials; extended source efficiency is defined in Extended Source Efficiency Correction and calculated using Eq. 2. Data points are GEANT4 simulated extended/point source ratios corresponding to the vial being 1/4 full, 1/2 full, 3/4 full and filled to capacity; error bars are smaller than the data points. The curves shown are second order polynomial fits to the ratio of the extended source efficiency to point source efficiency at 10.5 cm with a vial fill level of x cm.

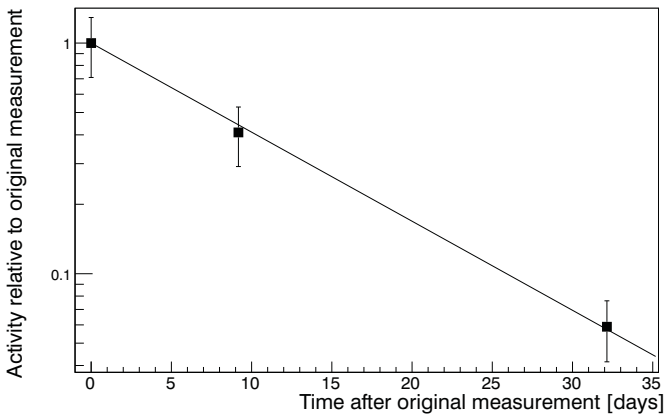

Figure 7: Activity in North Vancouver seaweed of the 364.489 keV gamma-ray line relative to the original measurement as a function of time. The data were fit using Eq. 3. The best-fit lifetime is = 11.2(1.1) days, in agreement with the literature value of 11.5779(7) days.

Source: National Nuclear Data Center, 2012.

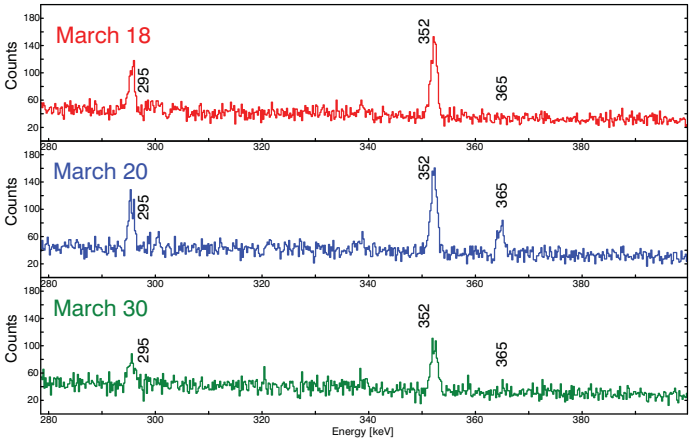

Figure 8: Three gamma-ray spectra measured by GEARS during the rainwater monitoring campaign. The 364.489 keV peak is characteristic of ^{131}I and indicates its presence in the samples collected at SFU. The 295.224 keV and 351.9 keV peaks are natural background radiation from the 238U decay chain. Damage to the Fukushima Daiichi plant occurred on March 11, 2011. No ^{131}I was observed in the sample collected on March 18, while the spectrum from the sample collected on March 20 contained the highest measured ^{131}I activity. Collection stopped shortly after March 30, 2011, when ^{131}I levels dropped below the detection limit.

Rainwater

Iodine-131 was first observed in rainwater on March 19, 2011, eight days after the tsunami damaged the reactors at the Fukushima Daiichi plant on March 11. Maximum activity was observed on March 20, nine days after the tsunami. The activity of ^{131}I in rainwater was below the detection limit of GEARS by early April 2011 and was no longer monitored once the 364.489 keV gamma ray was consistently not observed. Several gamma-ray spectra illustrating the change in activity measured during the rainwater monitoring campaign are shown in Figure 8, and a time profile of ^{131}I concentration on Burnaby Mountain rainwater is shown in Figure 9.

Seaweed

The maximum measured ^{131}I activity concentration occurred on March 22 for local seaweed and on March 28 for seaweed from BMSC, 11 and 17 days after the earthquake, respectively. Iodine-131 concentration in seaweed demonstrates a significant positive correlation with precipitation, and ^{131}I levels in *Fucus* have been shown to reflect observed levels in rain (Druehl et al., 1988). Seawater samples in Korea collected at the surface and at depths up to 2000 m did not contain measurable amounts of ^{131}I (Kim et al., 2012), which indicates that rainwater is the primary source of ^{131}I uptake in *Fucus*. By mid-May, one month after ^{131}I was last observed in rainwater, the ^{131}I content in the seaweed samples had decreased to below 5 Bq/kg dry weight, therefore the seaweed monitoring campaign was halted. Gamma-ray spectra

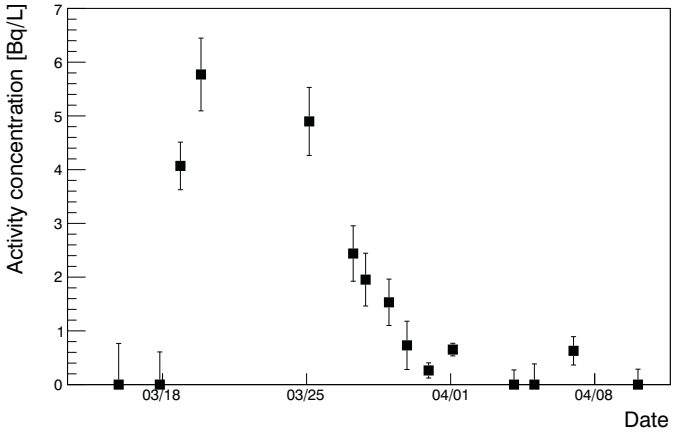

Figure 9: Time profile of ^{131}I activity concentration in rainwater collected at the SFU campus on Burnaby Mountain following the Fukushima accident. Maximum activity due to the presence of ^{131}I was observed on March 20, nine days after the tsunami. By April, no more ^{131}I was present in collected rainwater, indicating no continuous releases from the Fukushima reactors. Gaps in the collection correspond to days when there was no rainfall

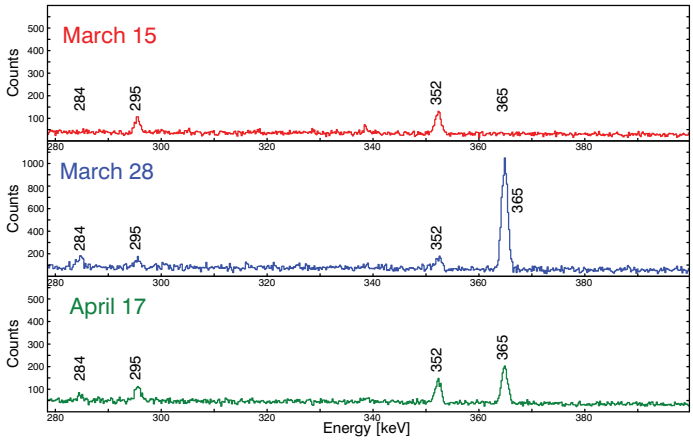

Figure 10: Three gamma-ray spectra from North Vancouver Fucus measured by GEARS during the seaweed monitoring campaign. The 364.489 keV and 284.305 keV peaks are characteristic of ^{131}I and indicate its presence in the seaweed collected in North Vancouver. The 295.224 keV and 351.9 keV peaks are natural background radiation from the 238U decay chain. No ^{131}I was observed in the sample collected on March 15, while the spectrum from the sample collected on March 28 exhibits two gamma-ray peaks characteristic of ^{131}I loading. There is a marked decrease in ^{131}I activity by mid April, and Fucus samples from North Vancouver were not collected past May 10 due to negligible ^{131}I content.

showing the change in ^{131}I content measured in North Vancouver seaweed are shown in Figure 10. Time profiles of ^{131}I activity concentration in North Vancouver and BMSC seaweed samples are shown in Figure 11.

Two samples of *Macrocystis pyrifera* (giant kelp), two samples of *Fucus*, and one sample of *Pyropia fallax*, formerly known as *Porphyra fallax* (Sutherland et al., 2011) collected in Bella Bella were received and processed following the procedure outlined above, the data are shown in Table 1.

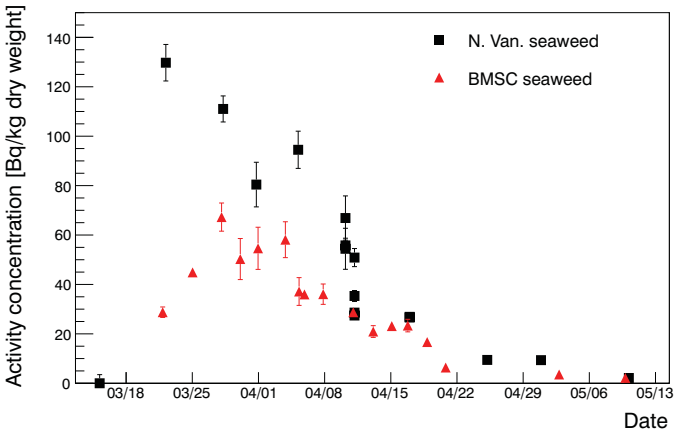

Figure 11: Time profile of ^{131}I activity concentration in Fucus collected in North Vancouver and Fucus collected at BMSC. Maximum measured activity was observed on March 22 for seaweed collected in North Vancouver and March 28 for seaweed collected at BMSC, 11 and 17 days after the tsunami, respectively. By mid-May, there was very little observed ^{131}I activity in seaweed, and the monitoring campaign was halted.

Discussion

The discrepancy between GEANT4 simulations and the extended source calibration was accounted for when constructing the time profiles shown in Figures 9 and 11. For the rainwater samples, only the 24 mL and 120 mL vials were used during the monitoring campaign. The GEANT4 simulations and extended source measurement using the 24 mL vial were consistent, therefore GEANT4 simulations were accepted as accurate for the 24 mL vial efficiency corrections. The 120 mL vials were only used for rainwater measurements following March 31, 2011, when the ^{131}I content was approaching negligible levels. Because the activity concentration measured in these cases was very low, a large error on the measurement due to adsorption on the glass does not significantly impact the interpretation of the results. Since the *Fucus* samples were not in solution and the ^{131}I is concentrated in cells, adsorption effects on the glass walls of the vials was not considered.

Iodine-131 was first observed in rainwater at SFU on March 19 and maximum activity concentration was measured on March 20. This result is consistent with results reported from Washington State where airborne ^{131}I activity concentration was first observed on March 18, with a maximum occurring on March 20 (Diaz Leon et al., 2011). Airborne ^{131}I activity concentration in Washington State was higher than concentration observed in Europe, the Canary Islands, and South Korea. Concurrent rainwater measurements at SFU demonstrate larger ^{131}I activity concentration com-

Table 1: Activity concentration in Bq/kg dry weight of a variety of seaweed species collected from Bella Bella, BC on April 1, 2011, following the Fukushima accident. Errors values at the 1σ level are shown in parentheses. Efficiency correction factors were calculated from the appropriate best-fit curves shown in Fig. 6. The measurement livetime was ≥99% of the measurement duration. The variation between collected samples suggests different accumulation rates of ^{131}I as a function of seaweed size, age, or habitat. All samples were collected by A. Salomon.

Species	Measurement livetime [s]	Sample mass [g]	Counts in ^{131}I photopeak	Efficiency correction factor	Activity concentration [Bq/kg]
Macrocystis pyrifera (a)	25422	3.5065	145(22)	9.26(2)	59(9)
Macrocystis pyrifera (b)	48048	2.9702	340(34)	9.85(2)	90(9)
Fucus (a)	14564	9.8619	223(25)	8.90(2)	63(7)
Fucus (b)	71949	7.0597	564(44)	10.70(3)	40(3)
Pyropia fallax	21025	2.4901	26(3)	8.07(2)	15(8)

Table 2: Maximum measured ^{131}I activity concentration in Bq/kg dry weigh for Fucus collected following the Chernobyl accident (Druehl et al., 1988) compared to the current work following the Fukushima accident. Errors values at the 1 level are shown in parentheses.

Sample location	Chernobyl [Bq/kg]	Current work [Bq/kg]
Vancouver area	4750(380)	130(7)
BMSC	4930(680)	67(6)

pared to values reported in Europe and South Korea (Ioannidou et al., 2012; Kim et al., 2012; Perrot et al., 2012).

The results of the current work were also compared to measurements performed following the Chernobyl disaster (Druehl et al., 1988). Similar experimental conditions (using a shielded HPGe detector, measuring *Fucus*) allow for a direct comparison of ^{131}I loading in *Fucus* samples collected from the Vancouver area and BMSC; the results are shown in Table 2. The ^{131}I activity concentration observed in seaweed was an order of magnitude less than the concentration observed following the Chernobyl disaster. Dose estimates for Canadian residents following Chernobyl were estimated to be ~ 1 μSv (Snell and Gordon, 1991). The observed ^{131}I activity in the current study implies an upper limit for the radiation dose attributable to Fukushima of ~ 0.1 μSv, an order of magnitude less than the concentration reported following Chernobyl. For comparison, the annual effective dose from naturally occurring radiation in Vancouver is 1.3 mSv (Canadian Nuclear Safety Commission, 2013).

Conclusions

The measured ^{131}I activity in seaweed in the current work is an order of magnitude less than the concentration observed in BC following Chernobyl. The maximum observed ^{131}I concentration in rainwater of 5.8(7) Bq/L is two orders of magnitude lower than the government action levels set on drinking water by Health Canada following a nuclear emergency (Health Canada, 2000). The estimated dose in Vancouver attributed to Fukushima is four orders of magnitude less than the annual dose from background radiation. Therefore, the short- and long-term impact of Fukushima on human health and the environment in Canada is expected to be insignificant.

Iodine-131 was observed in rainwater samples for ~ 1 month following the Fukushima accident, while ^{131}I activity in *Fucus* samples collected in southwest BC was observed for ~ 2 months.

The observations made in the current work confirm that *Fucus* can be used as an efficient system to measure the distribution of small amounts of ^{131}I in the environment, as previously proposed (Druehl et al., 1988). This result is particularly relevant when governments and coastal communities need to choose an indicator source and monitoring timeframe when ^{131}I contamination in the environment is a concern.

Additionally, the current work establishes GEARS as a high-precision tool for radiochemical analysis. A well-shielded, absolutely calibrated HPGe detector is a powerful instrument for detecting small amounts of radiation as demonstrated by the low levels of activity measured with high precision in rainwater and seaweed. There is significant interest in monitoring and quantifying radioisotopes present in the environment, and the Nuclear Science group at SFU is actively pursuing this research opportunity.

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