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Overview of Advanced Liquid Process System: Circulation of Tritiated Water in Oceanic Environment

Haewon Park[1] and Yener Ulus[#]

[1]North Lodon Collegiate School Jeju, Republic of Korea
[#]Advisor

ABSTRACT

The recent Japanese disposal of Advanced Liquid Processing System (ALPS)-treated water is controversial as ALPS does not filter tritium. The objectives of this paper are (a) to examine how anthropogenic tritium triggers biological health impacts and (b) to review the circulation of tritiated water into the oceanic territory of the Republic of Korea. Possibility of the bioaccumulation of tritium in the oceanic environment and its overall health impact was reviewed. To be of significant status, they require complex conditions. Simulations of the possible path that disposed pollutants could take from Fukushima were also reviewed. The simulations were then compared with the measured level of radionuclides around the Republic of Korea's oceanic territory by year. The data is divided into three parts (east, west, and south) and analyzed to check if the trends show any patterns in the level of tritium in the Republic of Korea. The levels checked in three areas showed partial uniformity, which may be evidence that radionuclides entered the oceanic territory of the Republic of Korea. However, the level of radionuclide was extremely low compared to the regulations set by the World Health Organization and the Republic of Korea. Thus, the disposal of tritium will be less likely to affect the natural environment. Nevertheless, it is recommended to monitor disposed tritium by a third party and conduct intense research on the circulation of tritium to support the prevention of sudden failure of the emission system.

Introduction

The use of nuclear energy is estimated to increase throughout the century (Adamantiades et al., 2009). Its eco-friendly operation and efficiency are the reasons why it is widely used. Over the past 50 years, nuclear power stations (NPS) have saved 70 gigatons of carbon dioxide (International Energy Agency, 2023).

However, the operation of NPS generates a significant problem: nuclear waste. Spent nuclear fuel from a nuclear reactor is nuclear waste, causing radiation effects (Ewing et al., 1995). Nuclear wastes are causing irritating troubles in terms of treatment. Difficult dilution processes, stochastic harms, and high costs of storage cause problems in many aspects, for which there have been controversial solutions. The recent controversy over the Japanese government's decision to release refined radioactive waste directly addresses this problem. In the status quo, the Japanese government plans to release the refined radioactive waste that was used to cool the reactors in the Fukushima Daiichi nuclear power station. With many ecosystems and cultures integrated into the ocean, the decision is momentous. Tritium (^{3}H), the main radionuclide that will be emitted by this decision, is a radionuclide that is considered to be less adverse than ^{137}Cs or ^{129}I (Silini et al., 1973) but still is a radionuclide. After the decision, East Asian countries were alarmed. In Republic of Korea (RoK), several parties publicly announced a refusal to emit refined radioactive waste. Even though the International Atomic Energy Agency (IAEA) accepted the Japanese government's choice, some civilians do not agree. Especially because even though radioactive water went through the refinery process at Fukushima Daiichi Nuclear Power Station (FDNPS), tritium was not filtered, which made people more frightened and outraged.

As a potential problem for all Pacific countries, many are aware of the current situation. However, where much untruthful information is active, the current situation brings confusion to the community. Therefore, to fully inform people about tritium and the current situation, in this paper I will discuss 1) basic information about tritium, and 2) throughout evaluating simulation of cesium-137 during the Fukushima Daiichi accident (FDA) and estimating tritium flow around the Pacific Ocean due to the release of refined waste, I will investigate the circulation of tritium around the marine environment with a possible conclusion of how much to an extent tritium release will affect the RoK.

Background

Disposal Process of Tritium

Recently, Japan's release of refined radioactive wastes included mainly tritium (IAEA, 2023). Tritium in NPS normally exists in liquid (HTO) form (Hyuga et al., 2018). Caesium, strontium, and 62 other types of radionuclides are removed by KURION, SARRY systems, and the Advanced Liquid Processing System (ALPS) (IAEA, 2023). Even though the majority of radionuclides are removed, tritium is not refined by ALPS because it cannot be removed chemically or physically (The Subcommittee on Handling of the ALPS-treated Water (SHATW), 2020). After ALPS treatment, it goes through a dilution process again in order to lower the tritium concentration (IAEA, 2023). Tokyo Electric Power Company Holdings (TEPCO) will release 22 trillion becquerels per year over the next 20–30 years (TEPCO, n.d.). Its target for detection limits is less than 1,500 Bq/L of tritium (TEPCO, n.d.), 1⁄4 of Japanese legal limitations and 3/20 of World Health Organization limits (10,000 Bq/L), but fifteen times higher than the European Union's regulation (100 Bq/L) (Canadian Nuclear Safety Commission (CNSC), n.d.).

Effect on Health

Tritium's physical half-life is 12.3 years, and as it decays, tritium emits beta rays with a maximum of 18.6 KeV (Straume & Carsten, 1993; Gragtmans et al., 1984) and leaves helium as a decay product (Wood et al., 1993).

These beta rays that tritium emits are weak, as they cannot penetrate 0.56 µm on average of air (Matsumoto et al., 2021). Thus, only tritium's internal exposure has radiological risks (Bondareva et al., 2022; Okada & Momoshima,- 1993). When tritium is consumed, it is equally distributed around the body (Hill et al., 1993; Matsumoto et al., 2021). Tritium may be excreted through the body's excretory system, though some might be incorporated into the organs and stay longer. This causes contamination of the body's organs. The impact of internal exposure is determined by the radiation dose, the amount of energy that is absorbed by organs, and mainly by the biological half-life (Matsumoto et al., 2021; Environmental Radioactivity and Radiation in Japan, n.d.). Figure 1 displays the biological half-lives of tritiated water and OBT and the overall process of circulation inside the human body. Due to its short half-life, tritium is considered to be less adverse than other radionuclides. Still, it is noted that a large dose of tritium can have a biological impact on mammal bodies.

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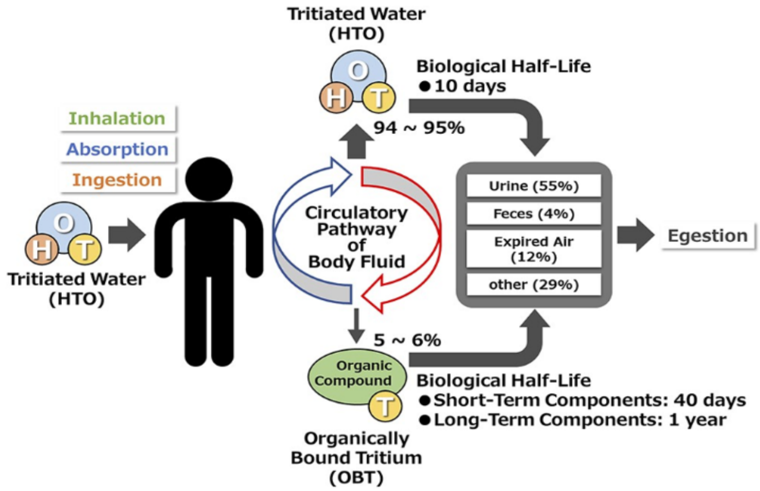

Figure 1. Tritiated water's metabolism in the human body (Matsumoto et al., 2021).

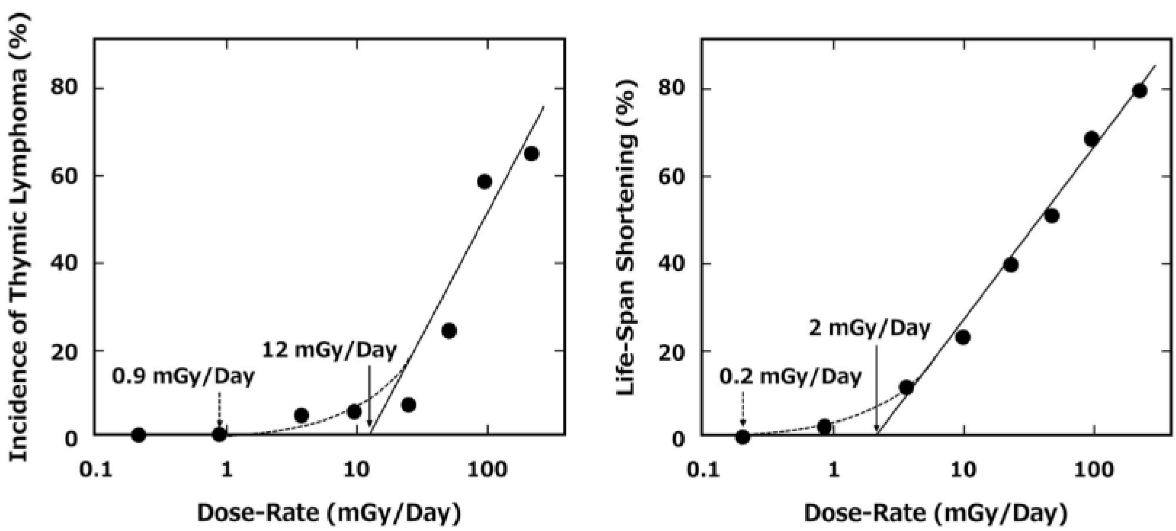

Figure 2. Dose rate against incidence of thymic lymphoma and life-span shortening (Matsumoto et al., 2021).

From figure 2, when mice were continuously exposed to beta rays with tritiated water at low dose rates of 3.6, 0.9, and 0.2 mGy/day, "a relationship in a semi-log plot was found between the frequency and the dose rate above a threshold dose rate of 12 mGy/day" (Yamamoto et al., 1998, p. 535). In figure 2, the incidence of thymic lymphoma (%) and life-span shortening (%) increases as the dose rate (mGy/day) increases, and at the 2–12 mGy/day point, minimum biological detection becomes possible (Yamamoto et al., 1998). This leads to two conclusions: 1) even low continuous doses of tritiated water can cause health problems such as cancer or thymic lymphoma; and 2) there is a threshold dose rate, a dose of a chemical that causes the minimum animal's detectable biological effect (Yamamoto et al., 1998). However, it should be considered that this experiment was done on mice, and the results may not apply to the human species, though they act as a reference for the possibility of a biological effect of tritiated water.

Bioaccumulation of Tritium

Bioaccumulation of tritium is crucial in determining the effect of tritium in the human body because, when bioaccumulation is possible, a higher trophic level would be disturbed as OBT can be transferred up the trophic level, leading to further biomagnification. There is contradictory research on the bioaccumulation of tritium. Some research stresses the biomagnification of tritium as one method of OBT entering the human body (Diabate & Strack, 1993). On the other hand, IAEA reported that tritium in the current case, ALPS-treated water, will rarely bioaccumulate in nature, and even though tritium enters the body, it will be excreted in a short amount of time (IAEA, 2023). Flatfish, crabs, and brown seaweeds, species all widely inhabited around the sea area near FDNPS, were examined (IAEA, 2023).

Table 1. Radiological Impact Assessment on Animals and Plants in the Sea (IAEA, 2023).

Species	International Safety Standards (mGy/day)	Assessment Results (mGy/day)
Flatfish	1-10 x 10^{-6}	0.710^{-6}
Carp	10-100 x 10^{-6}	0.710^{-6}
Brown Seaweed	1-10 x 10^{-6}	0.810^{-6}

From table 1, we can see that these three species of animals and plants around the FDNPS sea area had a lower exposure level than the Derived Consideration Reference Level (DCRL) of international safety standards made by the International Commission on Radiological Protection (IAEA, 2023). A level below DCRL means that no noticeable bioaccumulation of tritium occurred in these species in oceanic environments near FDNPS. Nevertheless, the fact that only 3 species were investigated during the examination is a flaw because there are many factors, such as habitat depth, date of birth of these species, and type of species, that were not taken into account. To consider more factors, there should be more investigation into the impact of the FDA by investigating more species. Furthermore, geochemical factors should also be considered. After the Fukushima Daiichi accident, tritium was flowing through ocean surface currents that may not have stayed thoroughly near FDNPS, which made it difficult for tritium to enter only marine species near FDNPS. On the other hand, evidence of bioaccumulation in the oceanic environment was found. In Cardiff Bay and the Irish Sea in 2006–2007, places that had exposure to tritium had a high concentration of OBT among marine species (flatfish, crustaceans, and molluscs) (Eyrolle et al., 2018). This shows that even in an oceanic environment, bioaccumulation of tritium is possible.

Other than oceanic surroundings, evidence proves the bioaccumulation of tritium in fish is feasible. Two species of minnows native to the southwest United States of America and their offspring lived in tritiated water for 5 months (Patzer et al., 1973). Three conditions were examined. Fish living in tritiated water, fish living in a tritiated environment, and the persistence of tritium in fish tissue were considered where the influence of tritiated food was notable (Patzer et al., 1973). Furthermore, fish living in tritiated water had 30% higher tritium-specific activity equilibrium than mammals tissue (Patzer et al., 1973), which shows that there might be more harm in aquatic environments. However, the experiment took place in a water tank where fish and water were stable, which is different from the oceanic environment. Therefore, the results from this experiment may not apply to oceanic environments where many more geochemical and geophysical factors are present. However, importantly, there is a possibility of bioaccumulation in the organs of fish and mammals when exposed to tritiated water, which can potentially lead to the accumulation of tritium in humans through biomagnification. However, these possibilities of bioaccumulation can be canceled out by dilution with the oceanic environment (IAEA, 2023), and the fact that tritium has a short half-life makes estimation of the bioaccumulation of tritium difficult, which needs more specific research to accurately conclude the contradictions on the bioaccumulation of tritium in the oceanic environment.

Study Area

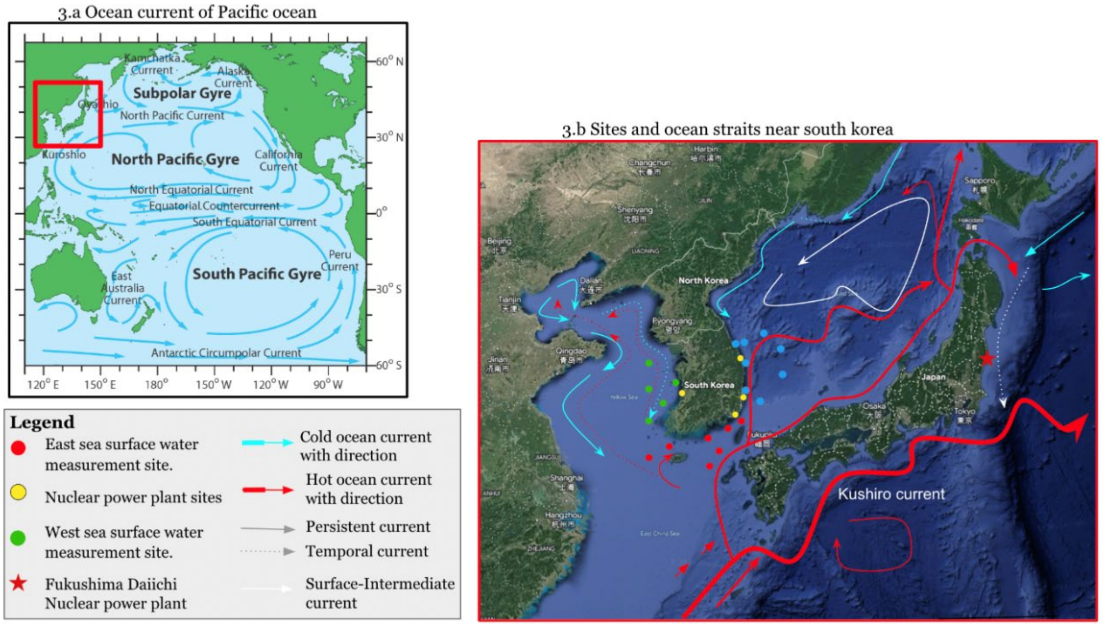

Figure 3. General information of the sites. 3.a) Ocean current of Pacific Ocean 3.b) Map of the Korean peninsula with sites of NPS, sites of measurement, and ocean straits. Modified from Marine Environmental Radioactivity Survey, Korea Hydrographic and Oceanographic Agency, and Google Earth.

Figure 3a) shows the ocean straits around the Pacific Ocean. Figure 3b) shows the map of RoK and the places where tritiated water was measured. It meets its border with North Korea and is closely located with Japan. The Korean Oceanic Territory is rich in marine habitat (Khim et al., 2021), with many straits incorporated. In figure 3b), FDNPS is located in the eastern and southern parts of the Tohoku region. It faces the Pacific Ocean to the east. Tohoku earthquakes occurred on March 11, 2011, with an estimated Mw (moment magnitude) of 9.0 (Koshimura & Shuto, 2015). This earthquake caused a tsunami that led to the FDA on March 11 (Koshimura & Shuto, 2015). The nuclear accident was classified as 7, the highest level of danger made by the IAEA (Britannica, 2023). It caused many leakages of radionuclides, including ^{137}Cs and ^{129}I.

Method

Data Collection

The level of radionuclide data were provided by Korea Institute of Nuclear Safety (KINS). The selecting criteria are: (a) level of ^{137}Cs and ^{3}H should be available; (b) samples should be collected from the surface ocean (<100 meters); (c) data before FDA should be available with consistent measurement at the same site for over 10 years; (d) all samples should be collected around RoK oceanic territory, covering large oceanic territory with clear methodology.

For simulation of the circulation of radionuclides, this paper used the simulation of Behrens et al. for ^{137}Cs simulation and Liu et al. for ^{3}H simulation. The selecting criteria are: (a) change and circulation of ^{137}Cs and 3H levels should be available; (b) all simulations should focus on Pacific Ocean surface water (<100m) and include the Republic of Korea. I directly used simulations from the literature for both cases.

Measurement of the level of ^{3}H and ^{137}Cs

According to KINS, the data on radionuclides contained inside the ocean surface water was collected twice a year, beginning in 2006 and six times during 2022. The measurement started with 23 places and gradually became 34 spots in 2022. Out of 80kg of seawater sample collected, 2L of sea water in the plastic bottle was used for the ^{3}H examination (KINS, 2021). The level of tritium measurement was operated and supervised by KINS. A seawater sample went through a nickel-nickel electrolytic concentrating device to measure high levels of tritium. A seawater sample was poured into a distillation beaker with a small amount of potassium permanganate ($KMnO_4$) and distilled. Silver nitrate ($AgNO_3$) was poured into the distillate to verify the chloride ion (Cl^-). Distillate was distilled until it did not contain a chloride ion (Cl^-). 800 ML of distilled solution was poured into an electrolysis cell with 8 grams of powdered sodium peroxide (Na_2O_2) to dissolve and electrolyze the concentrate completely.

The sample is then distilled again, and 10 ml of distillate is placed into a 20-ml Teflon vessel and put in the Ultimate Gold LLT Scintillation Cocktail (10 ml), stirred, and stored at 0–15°C with no sunlight for 1 day.

Data Analysis

Radionuclide data were assessed with the amount of radionuclides included in the surface water (< 100 meters). All uncertainty values were ignored, and the data were modified to an exact value. ^{137}Cs data were converted into a box plot graph using Excel. The box plot graph is an interdisciplinary graph of the median, mode, mean, and range of the ^{137}Cs data measured by year. The independent variable selected is the year, and the dependent variable is the level of ^{137}Cs. The data was divided into three different areas (south, west, and east), and each area was plotted on a separate graph. The graph of ^{137}Cs was compared with simulations of ^{137}Cs spread after the FDA. Simulations were compared with theoretical currents to ensure they are valid. Analyzed ^{137}Cs data will be a reference for ^{3}H and simulation of the current status quo. Data recorded with an inequality sign was modified to the greatest value. The ^{3}H (Bq/L) data were also converted into a box plot graph using Excel with the same independent variable. The dependent variable is the level of ^{3}H. ^{3}H trend is a determinant factor in assessing how tritiated water will affect RoK. The graph of 3H was compared with the simulation of the release of ^{3}H from FDNPS.

Where ocean current is an important factor in drifts of water pollutants such as ^{3}H and ^{137}Cs (Klemas, 2012), understanding the ocean current can be a vital factor in examining the possibility and time that tritium will enter the Republic of Korea oceanic territory. Where major surface currents are already established through the use of satellite-tracked surface drifters (Cenedese & Gordon, 2023), though many factors, such as waves and tides, are not considered (Cenedese & Gordon, 2023), using general surface current enriches simulation and provides a good reference to be used.

Results

Theoretically, in figure 3a) there are surface ocean currents connecting FDNPS and RoK oceanic territory. Water will travel across the Pacific Ocean and arrive in the western coastal areas of the United States. It will then travel to California. When it delivers ocean water to the equator, it will then follow the north equatorial current and arrive at the Kuroshio current. Fukuoka divides the Kuroshio current into two, and possible ocean water flows to the eastern coast of the Korean peninsula. In this case, if ocean water takes longer to flow back to the Korean peninsula, the amount of radionuclides arriving to RoK will be less. Even if tritiated water flows through the Kuroshio current and enters Korean oceanic territory, it will be less severe than in other places as the current entering RoK is weaker than the Kuroshio current. Where the Oyashio current has a temporal surface intermediate current, it might bend ocean water north of the Pacific gyre, which bends in the middle of the straits with a quickly entering north equatorial current, and flow back around the RoK peninsula. For these case, more specific ocean current speed and time is recommended to be correctly measured if there is a possibility that this contaminated ocean water can enter the Korean peninsula. Nevertheless, in the second case, the general ocean current is much weaker, which suggests that it will be less happening. However, in both cases, there is no strong current flowing between Japan and the RoK, which means theoretically, RoK might be less affected by the release.

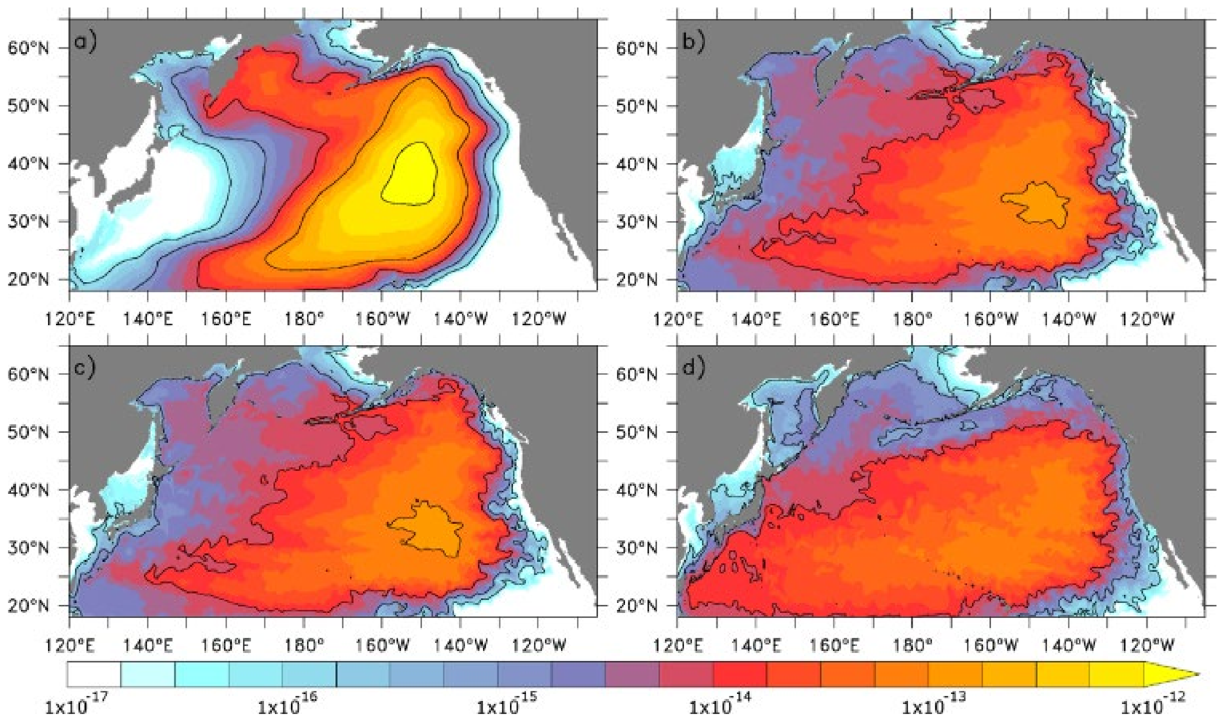

Figure 4. Effect of model resolution and discharge period on relative tracer concentration for the upper 1000 m after 5 years for 4a) 14 day release period, 4b) 14 day release period, 4c) 54 day release period, 4d) 54 day release period; four are different simulation (Behrens et al.,2012).

Despite the possibility of transportation of pollutants from the FDA to the Republic of Korea, the simulation of ^{137}Cs after the FDA would be a better-modified version of the general surface ocean circulation. Figure 4 shows the results of the simulation of caesium spread in the Pacific Ocean. For all cases (4b), (4c), and (4d), there was a rise in the level of ^{137}Cs near the Republic of Korea. Where four simulations had different estimated levels of radionuclide leaked from the accident, 4a) did not have an increase. Even in 4b), 4c), and 4d), the level of ^{137}Cs around the Republic of Korea was much lower than in other areas. Rather, North America and the Middle Pacific zone had a higher level of ^{137}Cs than the Republic of Korea. Despite ^{137}Cs's high half-life, ^{137}Cs that was released from the FDA did not have a substantial impact on Korea but rather more on North America. This agrees with the general surface ocean current. Moreover, in figure 5, all three areas across the RoK oceanic territory had a lower level of cesium than the Korean standard which supports the claim.

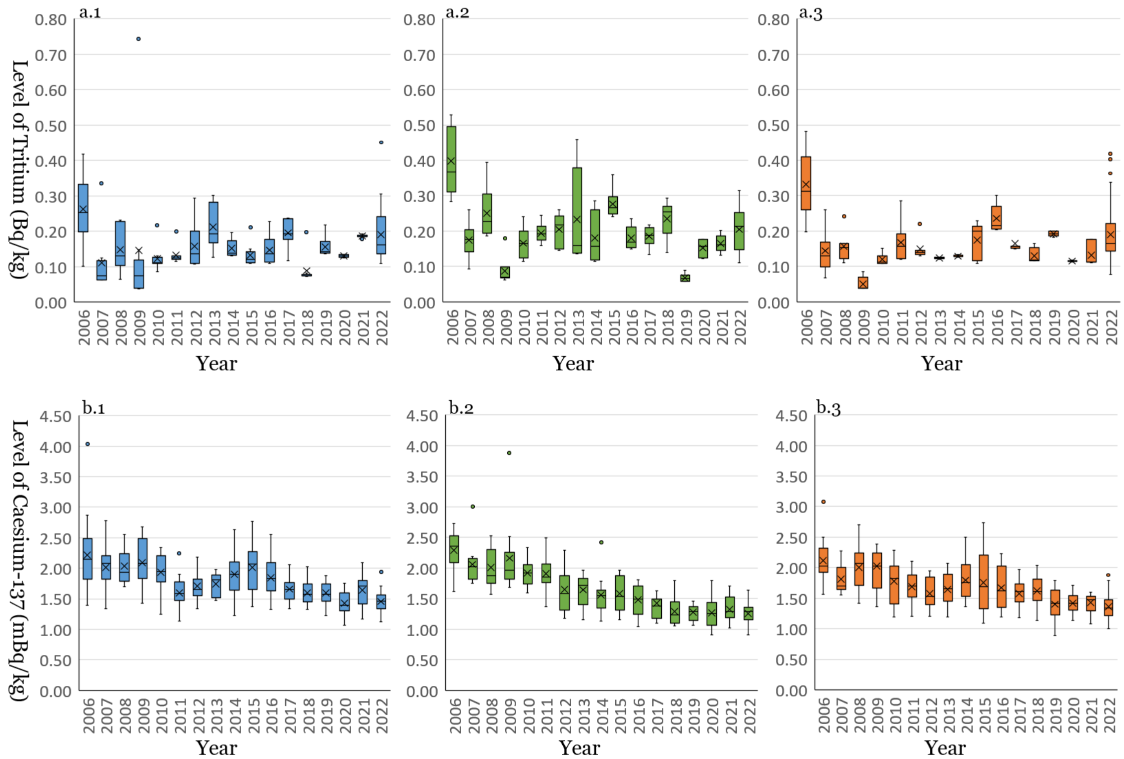

Figure 5. Trend of level of radionuclides around the RoK oceanic territory by area. a.1) Tritium level on the east coast, a.2) Tritium level on west coast, a.3) Tritium level on south coast, b.1) level of caesium-137 on east coast, b.2) level of caesium-137 on west coast, b.3) level of caesium-137 on south coast, Modified from KINS.

It was similar to the tritium level as well. In figure 5a), we can figure out that the eastern part of Korea had the highest level of tritium becquerel per kilogram in 2006, and the level of tritium was gradually decreasing until 2011. Thus, we can conclude that the pre-FDA era was on a curve as tritium was decreasing. However, during 2012 and 2013, the level of tritium measured increased. The operation of NPS on the eastern coast started before 2012, so the impact of NPS is not considered. Even the 2012 Busan Gori NPS incident had a rate of 2, which means there was no emission of radioactive material into the environment. Therefore, no particular incident or accident related to the increase in rate existed. Thus, we can assume that the FDA and emitted tritium may have arrived near the eastern coast of Korea. However, the fact that the level of tritium measured soon stagnated and fluctuated discredits this assertion that the 2012–2013 level was caused by the FDA. The fluctuation during 2015–2022 can potentially prove that the 2012–2013 level was also a fluctuation in the tritium level. Furthermore, tritiated water only has a half-life of 40 days, and when tritiated water goes over 2 or 3 years, the level will eventually decrease. Despite the fact that the east part of Korea is potentially the least affected by the currents from FDNPS, the level rise during 2012 and 2013 was more on fluctuation.

On the other hand, the western part of Korea has a similar trend compared to the eastern area. Western Ocean also had the highest value in 2006 and declined in average level of tritium until 2010, and a sudden increase was spotted in 2011, a year when FDA happened. If seawater passed a shorter route to the Korean Peninsula, the measurement in 2011 is relatable. However, the fact that the measurement is on the western side in which only smaller currents are flowing and at the same time, the east part did not have an increase lowers the probability that the increase in 2011 is caused by FDA. However, in 2015 and 2016, both areas had higher levels of tritium, which could possibly explain why tritiated water from the FDA entered Korea's oceanic territory. Furthermore, during 2017 and to 2021, the average tritium level decreased, which shows that tritiated water circulated again or diluted.

This ^{137}Cs simulation and ^{3}H data strengthen the argument that since pollutants from the FDA will travel toward North America, their impact will be lower. However, the ^{137}Cs simulation certainly differs from the status quo. It is crucial that tritiated water has a smaller half-life than ^{137}Cs, and because the ocean current and straits are very uncertain, the simulation is not perfectly accurate. Furthermore, the amount of leakage is remarkably polar. FDA is only a one-time leakage where the current decision on tritiated water disposal will be a potentially 30-year-long project (IAEA, 2023; TEPCO, n.d.), which makes the probability of bioaccumulation an issue as the biological half-life is much higher than tritiated water's half-life, which is likely to have much more impact. To address a more relevant simulation, a simulation of the release of HTO from FDNPS

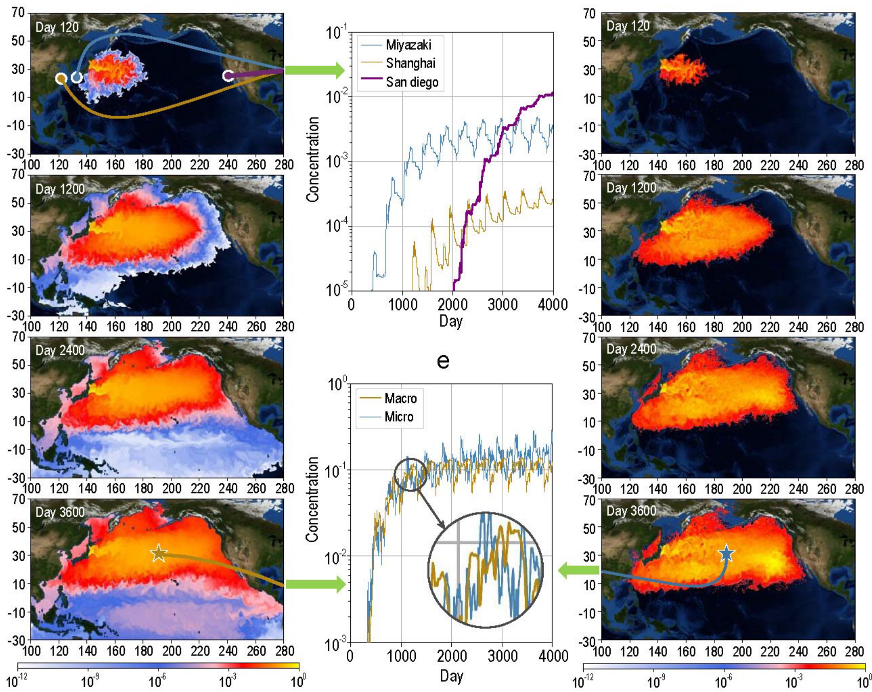

Figure 6. Simulation of ALPS-treated water release (Liu et al., 2021).

Nevertheless, the simulation for tritium leakage in the recent controversy shows that the release of tritium will be substantially impactful around the whole globe. In figure 5, when the total emitted tritium is estimated, the overall simulation shows that throughout the circulation through straits, tritium is widely spread. Interestingly, as the disposal continues, the average level of tritium around the Pacific Ocean will increase and will be remained (Liu et al., 2021). The average level will reach its maximum within approximately 3600 days, and Korea will be affected after approximately 1200 days (Liu et al., 2021). However, due to weak ocean currents entering Korean oceanic territory, the concentration of tritiated water entering is lower than in other parts of the world, such as North America or San Diego. However, it is important that the average level of tritium remains elevated across the Pacific Ocean. Thus, more bioaccumulation and health impacts will increase, potentially affecting RoK.

Discussion

From the scientific experiment, it was identified that bioaccumulation of tritium is possible, even in the oceanic environment as well. Furthermore, if bioaccumulation becomes excessive and exceeds a threshold dose, the biological impact is validated. The experiments were lacking in the sense that they were not directly a cause of harm for a human organ system but rather for other mammal species. The fact that tritium's dose rates are impossible to accurately measure (Doucette, 2002) is a factor that determines the level of biological impact. This may result in different points of threshold dose for humans. However, the fact that it can bioaccumulate applies to mammal species where human species are included. Evidence further shows that bioaccumulation is available in oceanic environments. It can be concluded that the current status quo, where ALPS is treated and emitted into the ocean, will also be viable for bioaccumulation. However, the investigation of the IAEA on tritium on oceanic territory near FDNPS suggests no bioaccumulation occurred for the marine species. Though the research is limited in a way that it only involved three species.

The circulation of tritium might also affect RoK's oceanic territory, but more than approximately five years later, as can be seen from the graphs. All three parts had a similar trend: a decline in pre-FDA and an increase in post-FDA. However, it is not perfectly trustworthy since the marine environment has many factors integrated, which means there is a possibility that these values are just coincidental values that have nothing to do with the FDA. Still, it is suspicious that the FDA's tritium leakage had entered Korean oceanic territory through a shorter oceanic current and showed possibility. But, most importantly, the fact that the level measured after the FDA is lower than the global standards, which relieves the treatment of tritium; even though it can accumulate in the body if ingested excessively, the fact that the level itself is extremely low can show that tritium disposal might not be very much affecting human health.

The tritium that will be produced from ALPS water disposal is expected to be lower than Japanese government standards, which is different for other nations, but still the amount is less than natural radiation (TEPCO, n.d.). Still, when tritium enters the body for a substantial amount of time and amount, the research proves it can cause harm. The half-life of OBT is much longer than that of tritiated water, which means that bioaccumulation will be much more considered. The short half-life of tritiated water means that relatively, people or the environment near FDNPS will be affected.

On the other hand, it is crucial that the level of tritium around the sea remains high. This may result in higher biomagnification in ocean species.

Future Needs

For the safeguarding of the marine environment, third-party monitoring of disposal is necessary. As ALPS water disposal is a long-term plan that will likely be continued in the future, monitoring the disposed level of tritium and other unfiltered radionuclides is essential, and the long-term effect of disposal is needed. As this situation is crucial for the marine environment and other neighboring nations, in order to prevent a rigged measurement, third-party monitoring is recommended with other nations or international organizations cooperating to maintain a safeguarding. The fact that the stored water had other harmful radionuclides even after the first filteration suggests careful monitoring is necessary in order to prevent worst cases (SHATW, 2020). If operated with no problems and as planned, less harm will be caused.

Furthermore, compensation plans for potential victims is necessary (Lu et al., 2021). As continuous disposal of tritium may lead to the potential accumulation of stoichiometric effects on human health, especially for people integrated into ocean business, firm and clear compensation for victims should be planned. There are many cultures integrated into the ocean, such as Ama culture in Japan and Haenyeo culture in Jeju. This may include monetary compensation or support in hospitality or medical care. The United Nations Convention on the Law of the Sea clearly requires that all harm caused by any party should be managed and compensated (Lu et al., 2021). As Japan selected oceanic disposal from the other viable 4 options (SHATW, 2021), its compensation, if anything goes wrong, should be ready.

Conclusion

The recent decision of the Japanese government's disposal of ALPS-treated water can have an impact on ocean culture, especially in close proximity. People's perception that tritium is less severe than other radionuclides exists. Though it may not be as dangerous as cesium-137 or iodine-90, its potential danger is addressed in this paper. However, more direct impact of tritium on marine ecosystems is not known. Especially how much bio-accumulation of tritiated water can occur in marine creatures and potentially its impact on the food web needs immediate investigation. In doing so, tritium's physicochemical forms should be identified so that more circulation of tritium can be observed (Eyrolle et al., 2018). It is thus, irrational to perceive that consuming disposed of tritium will significantly impact life. Still, careful measurement and monitoring are necessary with aids of technology such as satellite alineray and autonomous vehicles to track pollutants.

Limitation

The methodology lacks a specific measurement, especially ocean currents. The simulation is only a prediction and modeling through mathematical and physical theory. Where the ocean environment remains different every year, and many unmeasurable factors exist such as current turbulence, it is impossible to accurately simulate the circulation of tritiated-water. However, approximate time and path can be seen in the methodology, which can approximately tell where tritium circulates and how many times it takes to enter RoK oceanic territory. Furthermore, the data for level of radionuclides were also modified by ignoring uncertainties and inequality signs, which means that it may not be the exact value.

Throughout the case study of the FDA, we could see the path of ^{137}Cs and how much to an extent it affected Korea. However, the ALPS-treated water is different in many ways. One way is that tritium will be disposed of over a much longer period of time (SHATW, 2020; Behrens et al.,2012). Thus, circulation and biological impact might be affected. FDA cannot completely match the current status quo; thus, monitoring the circulation of tritium for disposal of ALPS-treated water is requisite, but rather a reference to the real-world consequences of leakage.

Secondly, more measurement of the level of tritium is needed. Currently, the investigation takes place four times a year or six times a year. But to see clear trends in level fluctuation, release of measurement of tritium will be helpful. Furthermore, more research on tritiated water could potentially lead to a much more specific understanding of biological thresholds and impacts.

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