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The Impact of Nuclear Contaminated Water Discharge into the Ocean on Marine Ecosystems

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Abstract. Against the backdrop of the rapid development of nuclear power plants worldwide and the frequent occurrence of nuclear accidents, the Marine discharge of nuclear-contaminated water has become a global environmental issue that transcends national boundaries. Nuclear-contaminated water contains radioactive nuclides such as tritium, carbon-14, strontium-90 and cesium-137 that are difficult to be completely removed. Its discharge into the sea causes multi-level hazards to the growth, reproduction, community structure and physiological functions of Marine plankton and benthic organisms. This paper systematically reviews the types and contents of nuclear-contaminated water discharged. By combining domestic and international research results, it analyzes the inhibitory effects, appearance distortions, community succession and food chain transfer mechanisms of radioactive nuclides on plankton and benthic organisms, and reveals the ecological risks of long-term discharge of nuclear-contaminated water. Studies have shown that radioactive nuclides in nuclear-contaminated water can pose a continuous threat to the stability of Marine ecosystems through pathways such as water diffusion, biological absorption, and food chain amplification.

Keywords: Nuclear contaminated water, marine ecosystem, biological absorption, food chain amplification

1. Introduction

Against the backdrop of the rapid development of nuclear power plants worldwide and the frequent occurrence of nuclear accidents, the disposal of nuclear-contaminated water has become a global environmental issue that transcends national boundaries. Nuclear-contaminated water mainly comes from the cooling of nuclear reactors, emergency response to nuclear accidents, and the operation of nuclear facilities. It has a complex composition and persistent radioactivity. Once discharged into the ocean, it will spread over a wide range through water flow, posing a long-term threat to the Marine environment and ecosystem [1]. At the early stage of the incident of nuclear-contaminated water being discharged into the sea, all sectors of society generally paid high attention. However, as time went by, public attention gradually declined, and the continuous ecological risks brought about by the discharge of nuclear-contaminated water were gradually ignored. And this kind of hidden and long-term environmental hazard is precisely the key factor affecting Marine ecological security.

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Refocusing on the ecological impact of nuclear-contaminated water being discharged into the sea and restoring its true destructive effect on the Marine environment is an important issue that cannot be avoided in the current field of Marine ecological protection [2].

The Marine discharge of nuclear-contaminated water is a phased and continuous process, and there are significant differences in the volume of wastewater, discharge scope and regulatory intensity at different discharge stages. In the initial stage of discharge, due to the restrictions of disposal conditions and environmental regulations, the nuclear-contaminated water was piloted for discharge in a small area and with a small flow rate. The volume of each discharge was approximately several thousand tons, and the discharge area was mainly concentrated in the shallow coastal waters. At this stage, the main focus was on data monitoring and environmental impact testing. With the increase in disposal demands, emissions have entered a mid-term large-scale stage, with the volume of single emissions rising to tens of thousands of tons. The emission range has gradually expanded from the nearshore to the nearshore. Affected by ocean currents and hydrological conditions, the pollution range can cover tens to hundreds of square kilometers of sea area. During the long-term discharge stage, nuclear-contaminated water will be continuously discharged at fixed intervals, with a total discharge volume reaching the million-ton level. The pollution range will further expand to the open waters near the sea, and the impact on the surrounding Marine ecosystem will show long-term and cumulative characteristics [1].

In terms of discharge supervision, both the International Marine Environment Convention and the Marine radiation environmental standards of various countries have clear constraints on the discharge of nuclear-contaminated water, requiring environmental impact assessment before discharge, real-time concentration monitoring during discharge, and ecological tracking investigation after discharge. However, in the actual discharge process, problems such as insufficient transparency of some monitoring data, inconsistent implementation of regulatory standards, and an imperfect cross-border pollution collaborative control mechanism make it difficult to effectively manage the environmental risks of nuclear-contaminated water discharge and also pose hidden dangers to the ecological security of the surrounding sea areas [3].

This article aims to systematically assess the toxic effects and ecological risks of discharging nuclear-contaminated water into the sea on key biological groups in Marine ecosystems (plankton and benthic organisms). The main research contents include: clarifying the concentration levels and over-limit characteristics of the main radioactive nuclides in nuclear-contaminated water; Analyze the damage mechanism of radionuclides to the growth and reproduction, feeding behavior and community structure of plankton and benthic organisms; Clarify the enrichment and transfer laws of radionuclides along the food chain. This research is conducive to deepening the understanding of the Marine ecological degradation process under the long-term discharge of nuclear-contaminated water, and provides a scientific basis for improving the monitoring standards of Marine radiation environment and building a cross-border ecological risk early warning system.

2. Types and contents of emissions

Nuclear-contaminated water contains a variety of radioactive nuclides that are difficult to be completely removed. Among them, tritium, carbon-14, strontium-90 and cesium-137 are the types of nuclides with relatively high content and the most prominent ecological risks. Relevant monitoring data show that the activity concentration of tritium in the discharged nuclear-contaminated water can reach the order of 10^4 $Bq \cdot L^{-1}$. Although the concentrations of nuclides such as carbon-14, strontium-90, and cesium-137 have decreased after treatment, they still remain at monitorable levels. Among

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them, the detected concentration of strontium-90 is approximately at the order of 10 $Bq \cdot L^{-1}$. The detection concentration of cesium-137 is stable between 10^0 and 10^1 $Bq \cdot L^{-1}$ [3].

By comparing the content of the above-mentioned nuclides with the international standards for radiation safety limits in Marine environments, it can be seen that the actual emission concentrations of some nuclides have approached or exceeded the safety threshold range. According to the standards set by the International Atomic Energy Agency and the United Nations Commission on the Protection of the Ocean Environment, the safety limit for strontium-90 in seawater is 10 becquerels per liter, and the safety limit for cesium-137 is 100 becquerels per liter [2]. However, the measured concentration of strontium-90 in nuclear-contaminated water has repeatedly exceeded the safety limit, while the concentration of cesium-137 has not significantly exceeded the limit. However, its long-term cumulative discharge will still cause the total amount of nuclides in water bodies to continue to rise. Tritium, as a hard-to-remove nuclide, although its single discharge concentration meets some standards, has a half-life of over ten years and can persist in water bodies for a long time. The half-life of carbon-14 is as long as several thousand years, making it extremely easy for it to enter the body and participate in material metabolism, thereby posing a persistent ecological risk [3]. The excessive discharge and long-term accumulation of these nuclides will cause all-round potential harm to the Marine ecosystem through water diffusion, biological absorption, food chain transfer and other pathways.

3. The impact of nuclear wastewater discharge on Marine plankton

3.1. Effects on growth and reproduction

Plankton is the most sensitive group of organisms in Marine ecosystems to pollution stress. The radioactive radiation produced by the discharge of nuclear-contaminated water directly inhibits the growth and reproduction processes of plankton [4]. For phytoplankton, radioactive nuclides can damage their chloroplast structure, reduce the efficiency of photosynthesis, decrease the rate of organic matter synthesis, and lead to a decline in the growth rate of phytoplankton and an extension of the cell division cycle. Lowman conducted field measurements of plankton in the waters near the Marshall Islands and found that in the waters affected by radioactive fallout, phytoplankton accumulated a higher concentration of radioactive nuclides, their cell division activities were significantly inhibited, and the biomass decreased significantly compared with that in the unpolluted waters [5, 6]. Monitoring data shows that in the sea areas affected by nuclear-contaminated water, the biomass of phytoplankton is more than 30% lower than that in clean sea areas, and the content of chlorophyll a has significantly declined, directly affecting the primary productivity level of the ocean.

For zooplankton, nuclear radiation can directly damage their digestive tract epithelial cells and filter-feeding appendages (such as the first tentacle bristles of copepods), leading to the obstruction of feeding behavior. The specific manifestations are: atrophy and shedding of microvilli in the digestive tract, vacuolation of midintestinal adenocytes, and reduction of mechanical digestion and enzymatic hydrolysis efficiency of food. The swing frequency of the filter feeding appendages decreases by approximately 35% to 50%, directly reducing the amount of food particles captured. Due to the decline in feeding efficiency, the assimilation rate of zooplankton decreases, energy absorption reduces, individual growth rate slows down, and their body size is significantly smaller. In addition, radionuclides can also inhibit the activity of acetylcholinesterase, interfere with neural signal transduction, cause movement disorders of swimming appendages, and further weaken the predatory ability [5]. Studies have confirmed that under low-concentration exposure to cesium-137,

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the feeding rate of copepod zooplankton can be reduced by approximately 42% compared to the control group [7, 8].

In terms of reproduction, radionuclide exposure can significantly reduce the reproductive capacity of plankton, leading to a decline in reproductive rates and a decrease in the survival rate of larvae. Radionuclides (especially tritium) can be incorporated into the DNA molecules of germ cells, inducing single-strand or double-strand breaks, leading to the arrest of germ cell development and abnormal cleavage of fertilized eggs. Research data shows that in an exposure environment with a tritium concentration of 10^4 $Bq \cdot L^{-1}$, the egg-laying volume of zooplankton can decrease by more than 40%, and the hatching rate of fertilized eggs is less than 60% [5]. Meanwhile, nuclear radiation causes even more severe damage to plankton larvae. The defense systems of these larvae are not yet fully developed, and their antioxidant enzyme systems are not yet mature, making it impossible for them to effectively eliminate radiation-induced free radicals. Their tolerance to radioactive substances is extremely low, and the survival rate of plankton larvae in contaminated sea areas is less than half of that in clean sea areas, directly affecting the continuation and renewal of plankton populations [4].

3.2. Changes in appearance and community

The discharge of nuclear-contaminated water will directly alter the community composition and structural characteristics of plankton, leading to phenomena such as the replacement of dominant species and the reduction of biodiversity. In clean sea areas, the plankton community structure is uniform and the species richness is high. Phytoplankton such as diatoms and dinoflagella form a stable community pattern with zooplankton such as copepods. After being affected by nuclear pollution, plankton species with stronger tolerance (such as certain diatoms with thick-walled cysts) gradually gained the upper hand, and the number of sensitive species sharply decreased or even disappeared, showing a trend of homogenization in community structure [5]. Relevant studies have shown that the Shannon-Wiener diversity index and Pielou homogeneity index of plankton in polluted sea areas are significantly lower than those in clean sea areas, and the community stability has decreased significantly [2].

Plankton is the fundamental link in the Marine food chain. An imbalance in its community structure will directly undermine the underlying support of the Marine food chain. A reduction in the biomass of phytoplankton can lead to insufficient food supply for zooplankton, which in turn affects the survival of upper organisms such as small fish and shrimp, causing problems such as food chain breaks and blocked energy flow [5]. At the same time, the alteration of the plankton community structure will also reduce the material circulation efficiency of the Marine ecosystem, affect ecological functions such as water purification and carbon sink regulation, and plant hidden dangers for the degradation of the entire Marine ecosystem.

3.3. Physiological damage of typical nuclides to plankton

Typical nuclides such as tritium and cesium-137 can cause irreversible damage to plankton at both the cellular and physiological levels. Tritium readily combines with water molecules and enters the bodies of plankton, replacing hydrogen to participate in cellular metabolism. Through the low-energy electrons produced by beta decay, it destroys the base pairs and phosphodil bonds of DNA, causing gene mutations, apoptosis and other problems. At the same time, it also inhibits the activities of superoxide dismutase (SOD) and catalase (CAT) in the body. Interfere with core physiological processes such as respiration and photosynthesis [4]. Cesium-137 has a strong

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bioaccumulation property and can rapidly accumulate in plankton. As a chemical analogue of potassium ions, cesium-137 competitively inhibits the activity of Na^+/K^+ -ATPase, disrupts the integrity of cell membranes, leads to an imbalance in cell osmotic pressure and nutrient loss, and at the same time damages the mitochondrial crest structure, reducing the ATP energy supply of the body. It causes physiological dysfunction of plankton [5].

The enrichment pattern of nuclides in plankton shows a clear concentration dependence. The higher the concentration of nuclides in water, the greater the enrichment amount in plankton, and the bioenrichment coefficient can reach tens to hundreds of times [4]. Lowman quantitatively confirmed for the first time in his study in the Marshall Islands that plankton have a much higher ability to accumulate radioactive nuclides than the surrounding seawater, and the concentration of some nuclides in plankton can reach hundreds of times that in seawater [6]. Subsequent studies have further demonstrated that the polysaccharide and protein components in the cell walls of phytoplankton have a high adsorption affinity for cesium ions, which is an important reason for the high enrichment of radionuclides at the bottom of the food chain [9]. Plankton, as the starting point of the Marine food chain, the radioactive nuclides accumulated in their bodies will be passed on to upper-level organisms through feeding relationships, gradually expanding the food chain of radioactive substances and ultimately posing a threat to the biosecurity of the entire Marine ecosystem [7].

4. The impact of nuclear-contaminated water discharge on benthic organisms

4.1. Effects on growth and reproduction

Benthic organisms have long lived in the bottom environment of the sea area. After nuclear-contaminated water is discharged into the ocean, radioactive nuclides are prone to settle in the bottom sediment, forming high-concentration contaminated areas, which seriously inhibit the growth and reproduction of benthic organisms such as mollusks, benthic crustaceans and polychaetes [4]. Radionuclides can enter the bodies of benthic organisms through surface absorption, ingestion and enrichment, etc., inhibiting their cell division and the development of tissues and organs, leading to a slowdown in the growth rate of mollusks, abnormal shell development, reduction in individual size, prolonged molting cycle of benthic crustaceans, and delayed body development. Alexeev and Galtsova (2012) found in their research on the benthic ecosystem of the Russian Arctic shelf that in areas affected by radioactive contamination, the average biomass of benthic organisms decreased by approximately 30% compared to clean areas, individual sizes were generally smaller, and growth rates significantly slowed down [4]. The average weight and body length of benthic organisms in contaminated sea areas have decreased by more than 25% compared with those in clean sea areas, and their growth conditions have deteriorated significantly.

At the reproductive level, nuclear radiation has a direct damaging effect on the reproductive organs of benthic organisms. Take shellfish as an example. Strontium-90 accumulates in the gonadal tissue and replaces calcium ions, interfering with the synthesis and deposition of ovoproteinogen, leading to the arrest of oocyte development and vacuolation of the cytoplasm. Under cesium-137 exposure, the gametes release synchrony of benthic polychaetes is disrupted, and the fertilization rate drops by approximately 35%. Research has found that the rate of deformities in benthic crustacean larvae in radioactive contaminated sea areas has significantly increased, manifested as incomplete appendage segments and pigment loss in compound eyes, which directly leads to the loss of swimming ability and the ability to escape from predators of the larvae. The mortality rate is 2.3

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times higher than that in clean sea areas [7]. Under long-term pollution stress, the reproductive capacity of benthic organism populations continues to decline, and the population size gradually decreases, directly affecting the stability of benthic organism communities [7].

4.2. Changes in appearance and community

The discharge of nuclear-contaminated water can cause obvious appearance distortion characteristics in benthic organisms and simultaneously alter the composition and structure of benthic biological communities [4]. Due to the influence of radioactive nuclides, shellfish are prone to uneven shell thickness, irregular shape, and shell surface damage. Benthic crustaceans, on the other hand, may experience appendage deformities, shell discoloration, and body damage. These appearance distortions not only affect the normal survival and activities of organisms but also reflect the severe radiation damage to their bodies.

In terms of community structure, the number of sensitive benthic species has decreased rapidly, and pollutant-tolerant species have gradually become the dominant group. The richness, diversity and uniformity of benthic communities have all shown a downward trend [4]. The research data of Alexeev and Galtsova show that in the Arctic sea area with heavy radioactive contamination, the number of benthic species has decreased by more than 40%, the community structure tends to be single, and the concentration of dominant species has significantly increased [4]. The benthic biological community in polluted sea areas has a single composition, with dominant species concentrated. The stability of the community has been significantly reduced, and the habitat density and biomass of benthic organisms have decreased significantly compared with those in clean sea areas. The imbalance of benthic organism community structure will disrupt the stability of the Marine bottom sediment environment, reduce the ecological functions of benthic organisms such as water purification and bottom sediment restoration, and further aggravate the degradation of the Marine ecosystem [5].

4.3. The effects caused by specific chemical elements

Strontium-90, cesium-137, carbon-14 and other nuclides are the core chemical substances that cause damage to benthic organisms, and the hazard mechanisms of different nuclides are significantly different. The chemical properties of strontium-90 are similar to those of calcium. It is prone to accumulate in calcified tissues such as bones and shells of benthic organisms, replacing calcium elements and causing abnormal calcification in organisms, resulting in fragile shells and deformed bone development. At the same time, it can also damage the hematopoietic function of the body and increase the probability of disease [3]. Cesium-137 is mainly enriched in the muscle tissues of benthic organisms, interfering with the electrolyte balance of the body, damaging the structure of muscle cells, affecting movement and feeding functions, and simultaneously inhibiting enzyme activity and disrupting metabolic processes. Bezhenar et al. found through model research that after the Fukushima nuclear accident, cesium-137 in sediments could be efficiently transferred to benthic organisms through the benthic food chain, and the bioenrichment factor could reach more than 200 in specific benthic invertebrates [7]. Carbon-14 can participate in the synthesis of organic matter in benthic organisms, remain in the organisms for a long time and continuously release radiation, causing DNA damage, gene mutations, and chronic physiological damage. Moreover, this damage can be passed on to offspring through reproduction, causing intergenerational harm [3]. In addition, although the concentrations of transuranuclides such as plutonium-239 accumulated in sediments are extremely low, due to their high toxicity and long half-life, they pose a potential threat to the long-

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term genetic diversity of benthic populations [10]. The long-term accumulation of these radionuclides in benthic organisms not only affects individual survival but also is passed on to upper predators through benthic organisms, expanding the ecological impact range of radioactive pollution [7].

5. Conclusion

The Marine discharge of nuclear-contaminated water is a continuous and multi-stage ecological risk event. This paper systematically analyzes the types and contents of the main radioactive nuclides discharged from nuclear-contaminated water, and based on the research results at home and abroad, explores the harmful mechanisms to the growth, reproduction, community structure and physiological functions of plankton and benthic organisms. Studies have shown that nuclides such as tritium, carbon-14, strontium-90, and cesium-137 can have multi-level and long-term negative impacts on Marine ecosystems through pathways such as water diffusion, biological absorption, and food chain transfer. Plankton and benthic organisms, as the fundamental links of the Marine food web, are highly sensitive to radioactive contamination. Radionuclide exposure not only directly inhibits their growth and reproduction, induces appearance distortion and simplifies community structure, but also transmits radioactive risks to higher trophic levels through bioaccumulation and food chain amplification effects. At present, the regulatory system for the discharge of nuclear-contaminated water still has problems such as insufficient data transparency and an imperfect cross-border coordination mechanism, and it is urgent to strengthen international monitoring cooperation and ecological risk assessment. Future research should further focus on the chronic ecological effects of low-dose long-term exposure, the synergistic toxicity mechanism of multi-nuclide complex pollution, and the construction of prediction and early warning systems based on ecological models, providing a scientific basis for the control of nuclear-contaminated water discharge and Marine ecological protection.

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