The ecological mechanisms of *Acetes* blooms as a threat to the security of cooling systems in coastal nuclear power plants

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Abstract

Recently, there have been an increasing number of reports on the shutdown of coastal nuclear power plants because of outbreaks of marine organisms, such as jellyfish and fish. These organisms clog the pipes during an outbreak or when they accumulate near nuclear power plants in coastal regions. The safety of nuclear power plants is threatened by *Acetes* blooms. Thus, based on the physiology and ecology of *Acetes*, including the biology, auxology, feeding ecology, population dynamics, environmental suitability and effects of nuclear power plant thermal effluents, three hypotheses were proposed by previous studies to explain the ecological mechanisms of an *Acetes* bloom: (1) the wintering ground hypothesis, (2) the population dynamics hypothesis and (3) the ecosystem dynamics hypothesis. The main content and prevention measures used in previous studies were introduced and reviewed. Ecological protection combined with relevant environmental protection policies and laws in coastal areas are the long-term goals for the management of *Acetes* blooms.

Keywords *Acetes* · Cooling system in nuclear power plants · Blooms of marine organisms · Ecological mechanism

Introduction

According to the 2015 global nuclear industry report, nuclear power plants around the world in 2014 generated a total of 2410 billion kilowatt-hours, accounting for 10.8% of the world's total power generation, which was a 2.2% increase compared to that in 2013 (Schneider et al., 2015). The global distribution map of nuclear power plants

indicates that most of the nuclear power plants are located in coastal areas (Fig. 1). The cooling technology used in these plants mainly adopts the single-cycle cooling and direct discharge modes. A typical large-scale nuclear power plant uses 800–1000 million gallons of cooling water every day.

In recent years, due to the impacts of the eutrophication of coastal waters and global warming, clusters of marine organisms have been developing in these areas, such as algal blooms, red tides, green tides, brown tides and jellyfish blooms. Among the multiple impacts caused by the outbreaks of these marine organisms, blockage of the cooling water inlet of a nuclear power plant is the most prominent and serious one.

Recently, there have been occasional threats due to marine organism outbreaks that impact the safety of the cooling system of coastal nuclear power plants. The most common issue occurs when jellyfish block the water intake filter screen and even cause the reactor to shut down (Table 1). For example, in September 2013, a jellyfish clogging incident at the Oskarshamn plant in Sweden was caused by a large number of *Aurelia aurita*. There have also been reports of jellyfish invasions at Diablo Canyon in California, St. Lucie in Florida, Hadera in Israel, and Torness in the United Kingdom. Clogging events often occur during the mass reproduction

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Fig. 1 The distribution of global nuclear power plants. (Christoudias et al., 2014)

Table 1 List of shutdown cases or threats to nuclear power plants caused by blooms of marine organisms

Year	Nuclear power plant	Country	Species
June 2003	Uljin nuclear power plant	Korea	<i>Euphausia pacifica</i> <i>Salpa fusiformis</i>
August 2005	Stockholm's Oskarshamn plant	Sweden	<i>Aurelia aurita</i>
October 2008	Diablo Canyon 2 reactor in California	US	Jellyfish
December 2009	CRUAS	France	Seagrass
June 2011	Torness nuclear power station	UK	Jellyfish
July 2011	Hadera	Israel	Jellyfish
August 2011	St. Lucie Nuclear Plant in Florida	US	<i>A. aurita</i>
July 2012	San Luis Obispo in California	US	<i>S. fusiformis</i>
September 2013	Stockholm's Oskarshamn plant	Sweden	<i>A. aurita</i>
July 2014	Hongyanhe Plant Unit 1/2	China	Jellyfish
August 2015	Ningde Plant Unit 3	China	<i>Acaudina molpadioides</i>
January 2016	Ling'ao Plant Unit 2	China	<i>Acetes</i>

and growth of jellyfish in summer. Cloggings that resulted from impinging sea squirts and krill also occurred at the Uljin nuclear power plant in Korea. In addition, a large-scale population explosion of algae, such as *Cladophora*, combined with climatic events such as storm surges, also caused a shutdown of the FitzPatrick nuclear power plant in the United States from September to November 2007 (Deretz, 2007).

In recent years, nuclear power plants in China have faced increasing risks caused by marine organism outbreaks, which threaten the safety of cooling water systems. For example, three nuclear power plants at Hongyanhe, Ningde and Fangchenggang were shut down due to blockages of the cooling water intakes resulting from blooms of jellyfish, sea cucumbers (*Acaudina molpadioides*) and algae (*Phaeocystis globosa*), respectively. In addition, on January 9, 2016, an outbreak of *Acetes* shrimp occurred at the water intakes of the Ling'ao Nuclear Power Plant in western Daya Bay (Fig. S1). The main threat during the

incident came from three species, *Acetes chinensis*, *Acetes erythraeus* and *Acetes japonicus*, with an abundance ratio of 41:50:9 (unpublished data).

At present, there are few studies on the relationship between environmental factors in waters surrounding nuclear power plants and the blooms of plankton or nekton causing blockages of cooling water systems. As the safety of the nuclear power plants in western Daya Bay is potentially threatened by *Acetes* blooms at its water intake points, the Daya Bay nuclear power plant was chosen as a case study. The composition, distribution and abundance of *Acetes* are evaluated based on information in the literature on the physiology and ecology of *Acetes*. Based on this information, which includes environmental parameters, we provide a synthesis of the potential mechanisms and control factors of *Acetes* outbreaks from the perspective of ecological system dynamics. Possible ecological strategies to respond to the threats posed by

these outbreaks are also discussed, and these strategies have very important practical and scientific significance.

Advances in physiological and ecological research of *Acetes*

The *Acetes* genus includes 14 species belonging to the Sergestidae family of Crustacea. The body length of *Acetes* is generally 1 to 4 cm, and the carapace is translucent (Fisher, 1984). The common species in the northern coastal areas of China is mainly *A. chinensis* (Liu, 2013), while in the subtropical sea area of South China, *A. japonicus*, *A. erythraeus* and other species also produce high biomasses (Lei, 1984). Although the organisms are small, *Acetes* is an important fishery product in China and Southeast Asian countries because of its large biomass upon accumulation. In 2007, the total output of *Acetes* in China exceeded 600,000 tons, accounting for 40% of the total output of shrimps and 5.5 times that of prawns (Liu, 2013). According to data from the Food and Agriculture Organization of the United Nations (FAO), the annual production of *A. japonicus* was between 550,000 and 600,000 tons from 2009 to 2013, ranking 15th in terms of the production of major fishery products (FAO, 2015). These figures reflect the importance of fishery resources and aquatic products.

Biology and development of *Acetes*

The biology and life history of the genus *Acetes* was reported by Omori (1975). The larval development of *A. chinensis* was studied by Liu & Zhang (1981), who discussed the spawning in Liaodong Bay that occurs twice per year. The spring spawning period begins in late May and reaches its peak in June; the summer spawning period reaches its peak in August and ends in late September. The initial water temperature for spawning is approximately 18 °C, and the spawning period usually occurs after the water temperature reaches 20 °C (Liu & Zhang, 1981). The larval development of *A. chinensis* undergoes 4 nauplius stages, 3 zoea stages, 2 mysis stages and 4 postlarval stages (Liu & Zhang, 1981). *A. japonicus* in southern China usually has a summer generation that occurs from July to October and then a winter generation that occurs from November to May of the following year. The life span of *A. japonicus* in the summer generation is 2.5 to 3 months. The individual lengths of both females and males are larger in the older generations than in the younger generations, and the maximum length (36.5 mm) appears in April to May and then decreases. In July, the lengths of individuals reach a subpeak and decline to a minimum in September (Lei, 1984). Individual organisms that reach maximum length in July usually hatch from the beginning of April to May. After 2.5 to 3 months of

development, the growth rate is approximately 7~8 mm per month. The temperature is the most important factor that impacts the spawning and development of *A. japonicus*. The average annual water temperature in the subtropical zone of eastern Guangdong is 21.4 °C. Compared with *A. japonicus* development in the temperate zone, the starting and ending times of spawning will be accelerated by 15~30 days, and the end times of spawning will be delayed by 15~30 days (Lei, 1984). Based on these considerations, an increase in temperature, especially due to the cumulative temperature effects of thermal discharge near a nuclear power plant, may change the temporal rhythm of spawning-incubation-larval development of *Acetes*, thereby accelerating spawning and larval development and resulting in a large-scale bloom of its population.

Feeding ecology of *Acetes*

In a previous study on the feeding behavior of *Acetes sibogae*, it was found that *Acetes* uses its third pair of maxilliped and its first three pairs of ambulatory legs to capture prey, and then it uses the second pair of maxilliped to sort, screen and insert the prey into the mouthparts (McLeay & Alexander, 1998). A field study on the feeding of *Acetes* indicated that the medium-sized species (*Acetes intermedius*) in the coastal area of southwestern Taiwan mainly fed on phytoplankton. Among phytoplankton, dinoflagellates (mainly *Prorocentrum* spp.) are the main food source, followed by diatoms (mainly *Pinnularia viridis*) and green algae (mainly *Hydrodictyon* spp. and *Pediastrum* spp.) (Chiou et al., 2005). In addition, the feeding activities of *Acetes* show obvious diurnal rhythms and seasonal variations. In July, approximately 76% of feeding took place at night; in September, approximately 98% of feeding took place at night. These patterns show that *Acetes* exhibits diel vertical migration and feeds in the upper water column layer at night to avoid being attacked by predators during the daytime (Chiou et al., 2005). Similarly, the annual observation data of midsized *Acetes* near the Philippines coastal area indicated that midsized *Acetes* could feed on 13 major classes of organisms or amorphous substances, including phytoplankton and zooplankton, among which *Peridinium* spp. and *Dinophysis* spp. were the major food components of phytoplankton (Metillo, 2011). Researchers who analyzed the gut contents of *A. serrulatus* on the coast of Malaysia indicated that decapod appendages accounted for 31.87%, phytoplankton accounted for 16.48%, and zooplankton accounted for 14.18% of contents (Oh et al., 2011). In the coastal area of the Tanjung Dawai estuary (Malay Peninsula), researchers found that the gut contents of *A. japonicus* were mainly composed of vegetative matter (28%) and crustacean appendages (19%), and dinoflagellates were the most frequent phytoplankton. From the perspective of

annual variations, a phenomenon was observed in which the gut content consisted of a succession of dinoflagellates and diatoms. This finding may be due to the succession of phytoplankton community composition in water; however, it may also be caused by a periodic selective feeding behavior of *A. japonicus* (Amani et al., 2012). In conclusion, the composition of *Acetes* food is diverse and exhibits diurnal variations. In general, the omnivorous feeding behavior of *Acetes* has an effect on primary producers such as phytoplankton and secondary producers such as copepods and other crustaceans. These prey organisms, occupying the lowest trophic levels, are very abundant, and thus, their predators (*Acetes*) have a great chance of accumulating at high biomasses. Therefore, understanding the relationship among primary production dynamics, environmental factors and prey-predator dynamics is the core of studying *Acetes* outbreaks.

Reproduction and population dynamics of *Acetes*

The reproduction of *Acetes* is the most important process in maintaining the population. An annual study on the reproductive biology of *Acetes indicus* in the Straits of Malacca found that its population had a male:female ratio of 1.0:2.1. The average body length of mature females was approximately 23 mm, and the fecundity was 1135~2235 spawn eggs, with an average of 1666.30 ± 262.10 spawn eggs. The sexual maturity coefficient of females showed a significant positive correlation with conductivity, salinity and total suspended matter concentration in water, but there were no significant correlations with temperature and dissolved oxygen. The sexual maturity index of *A. indicus* fluctuated annually, with the highest value occurring from June to August (Amin et al., 2009). A study of the population dynamics of *Acetes americanus* in the coastal upwelling area in Brazil found that the body lengths of females were significantly longer than those of males, and showed a substantial predominance (77%) in female abundance (Santos et al., 2015). Compared with high latitude regions, individuals (*A. americanus*) in low latitudes have significantly longer body lengths and lifespans (Santos et al., 2015). In a study of the reproductive biology of *A. chinensis* on the western coast of the Korean Peninsula, mature female individuals appeared at the beginning of April and reached their maximum abundance in July, and there were no mature females after September (Oh & Jeong, 2003). The researchers also performed anatomical studies and found that the two main periods of sexual gland maturation occurred during June and early September. Overall, female individuals were larger than males, and they reached body length maximums in different seasons, which reflects the regulation of the reproduction strategy of the organism. In addition, according to a previous study, the mortality rate of *A. chinensis* is relatively high (Oh & Jeong, 2003). This high mortality rate may be due mainly to fish

feeding and migration habits. Therefore, a large-scale *Acetes* bloom reflects the observable seasonality and its short duration (Oh & Jeong, 2003). The migration of *A. chinensis* in the coastal regions of southern Zhejiang was also one of the most important factors affecting its biomass (Shi, 1986). In terms of population mortality, the biomass of *A. chinensis* in the Kutubdia Strait in Bangladesh was found to be high from March to August, and the maximum biomass was produced from March to April and from July to October (Zafar et al., 1998). Previous studies indicated that the natural mortality, fishing mortality and total mortality of *A. chinensis* in the sea area were 4.26, 1.13 and 5.39, respectively (Zafar et al., 1998). This result implied that natural death is the main cause of the fall in *A. chinensis* biomass (Zafar et al., 1998).

Effects of environmental factors on the distribution of *Acetes*

Different species of *Acetes* have different optimum temperatures for growth. However, there are significant differences in the temperature optima for growth in different geographical regions for the same species. For example, *A. americanus* in the coastal upwelling region of Brazil, where chlorophyll concentration was high, had an optimum growth temperature of approximately 20 °C (Santos et al., 2015). On the other hand, *A. americanus* distributed in the nonupwelling region of the southeastern coast of Brazil had an optimum growth temperature ranging from 24 to 26 °C during summer, when its biomass was the highest (Simões et al., 2013). In addition to temperature, rainfall and runoff also have a large impact on the biomass of *Acetes*. A study of *A. intermedius* in southwestern Taiwan found a significant positive correlation between its biomass and river runoff or rainfall. In addition, at different stages of development and reproduction, *A. intermedius* also congregated in different salinity zones. In July, *A. intermedius* was mainly concentrated in the shallow coastal area and then moved offshore toward higher salinity from August to September, after which the population then returned to the nearshore low-salinity area in October. The shrimp's spatial distribution in the estuary and shelf was mainly caused by the reproductive migration of species to offshore shelf waters and its demand for food in the estuary (Chiou et al., 2000). In an experiment on the hatching rate of *A. intermedius* eggs under different temperature and salinity gradients, *Acetes* eggs were not able to hatch normally at low temperatures (15 °C) and low salinities (0~10). Above a salinity of 25, the hatching rate of eggs reached more than 90% and the time required for incubation was reduced at high temperatures, i.e., 10 h at 30 °C, 14 h at 25 °C and 29 h at 20 °C (Chen & Chen, 1999). Temperature and salinity also had a significant effect on the posthatching of the shrimp, from nauplius to zoea. At salinities in the range from 25 to 30, the development time increased with

decreasing temperatures, i.e., 28 h at 30 °C, 45 h at 25 °C and 4–5 days at 20 °C. At 25–30 °C and salinities between 20 and 30, the metamorphosis of nauplius into the zoea rate reached 90–100% (Chen & Chen, 1999). Studies on the relationship between hatching, larval development, the natural distribution of *A. chinensis* eggs and environmental factors such as temperature and salinity are rare, especially in subtropical sea areas such as Daya Bay. Research on the mechanisms of the development and blooms of *A. chinensis* is extremely important.

Effects of thermal discharge from nuclear power plants on the structure and biomass of plankton communities

According to the abovementioned results of the physiological and ecological research on *Acetes*, warmer temperatures and the food composition are the key factors that cause an outbreak of *Acetes*. Thus, the thermal discharge from a nuclear power plant provides a “hotbed” for the growth and reproduction of the organisms. On the other hand, discharge will also affect *Acetes* food, especially plankton, whose composition and abundance are known to be responsive to thermal changes. Hence, research on the ecological mechanisms of *Acetes* outbreaks cannot ignore the effects of thermal discharge on the biomass and community structure of plankton in the area.

The impacts of thermal discharge on the nearshore ecosystem are mainly reflected by a reduction in dissolved oxygen (DO), increased concentrations of nitrogen and phosphorus in water, changes to the physiological activity and function of marine organisms, and reduced biodiversity (Chen et al., 2010). Thermal discharge has the most obvious impact on primary producers such as phytoplankton. Analysis of the long-term changes in the composition of phytoplankton groups in the waters adjacent to the Daya Bay nuclear power plant (1982–2005), (Li et al., 2011) found that the temperature around the thermal discharge outlets was approximately 6.8 °C higher than the temperature of the offshore water, and the temperature increased by approximately 5.6 °C in 23 years (Li et al., 2011). The N/P ratio in water also increased significantly, from 1.38 in 1985 to 49.09 in 2004; the corresponding change was also reflected in the reduction of biodiversity, as phytoplankton showed a decrease from 46 genera and 159 species in 1982 to 44 genera and 126 species in 2004 (Wang et al., 2008). The abundances of diatom cells showed a significant negative correlation with temperature, while dinoflagellates showed a significant positive correlation, resulting in more dinoflagellate cells being found close to the outlet. The percentage of diatoms decreased from 82.0% in 1982 to 53.1% in 2005, and the abundance of dinoflagellates increased by 50% over

the same period of time. Therefore, under the influence of thermal discharges, the phytoplankton community in the waters around the Daya Bay nuclear power plant showed a clear trend of transformation from diatoms to dinoflagellates (Li et al., 2011). Similarly, in a study of the long-term changes in phytoplankton in the waters near the Loviisa nuclear power plant in southern Finland (1971–1994), it was found that the nutrient concentration increased each year after the opening of the nuclear power plant in 1977, causing significant increases in the Chl *a* concentration and primary productivity. In particular, warming caused a significant increase in the biomass of cyanobacteria *Aphanizomenon* spp. (Ilus & Keskitalo, 2008). In a study of the waters adjacent to the Kuosheng Bay nuclear power plant in northern Taiwan, it was found that the concentration of the phytoplankton Chl *a* near the outlet was significantly lower than that near the inlet, but the concentrations of algae attached to drain pipes and benthic phytoplankton Chl *a* were significantly higher at the outlet than at the inlet. The algal species composition consisted mainly of *Ulva* spp., *Nitzschia* spp., and *Achnanthes* spp. (Chuang et al., 2009; Lo et al., 2004). In the waters around the Madras nuclear power plant on the eastern coast of the Indian Peninsula, the outlet waters were heated by approximately 7–8 °C relative to the inlet waters, and the concentration of Chl *a* and primary productivity near the outlet were reduced by approximately 50% relative to the inlet. Although there was no significant difference in phytoplankton species diversity between inlet and outlet waters, there was a significant difference in species composition (Poornima et al., 2006). Field observations from the Madras plant also revealed that the concentration of phytoplankton Chl *a* and primary productivity increased gradually from the outlet drain to the warm-drain mixing zone to the inlet. In addition to the warming effect, residual chlorine also had a relatively significant impact on phytoplankton growth and carbon fixation, and phytoplankton biomass and growth rate were significantly reduced under high temperatures and high residual chlorine concentrations (Poornima et al., 2005).

In addition to on-site research in areas affected by the thermal discharges of nuclear power plants, many laboratory simulation experiments have also been carried out to explore the effects of temperature and residual chlorine on the growth and physiological activities of phytoplankton. Sanders et al. (1981) noted that the phytoplankton biomass was slightly increased due to thermal discharge, but the phytoplankton biomass was still reduced under the synergistic effects of residual chlorine and copper (Sanders et al., 1981). Laboratory simulation of the thermal discharge of 28–40 °C from the Madras nuclear power plant in India showed that the growth rates of both diatom species *Chaetoceros wighamii* and *Amphora coffeaeformis*, isolated from the outlet and inlet waters, decreased slightly with an increase in temperature, but *A. coffeaeformis* was more adaptable than *C.*

wighami to high temperatures; therefore, this species could become the dominant species in the high-temperature zones (Rajadurai et al., 2005).

The changes in the phytoplankton community structure and biomass are directly related to the population dynamics of its predators; the growth, development, and reproduction of zooplankton cause changes in the material circulation pathways and rates between various parts of the ecosystem, which, in turn, generates feedback for the phytoplankton community. In a study of the waters adjacent to the Kapar power plant in Malaysia, the researchers noted that under the conditions of warming and a pH reduction caused by thermal discharges over the past 30 years, smaller zooplankton tended to be favored, especially small bodied crustaceans, salps and larvaceans, which were more tolerant to sea warming, while larger copepods exhibited significantly reduced biomass (Chew et al., 2015). *Temora discaudata* and *Temora turbinata* were the dominant species of copepods in northern Taiwan. Their biomass was significantly lower than that in areas unaffected by thermal discharges (Tseng et al., 2011). Studies on the waters adjacent to the Martigues-Ponteau power station along the Mediterranean coast found that the rate of respiratory metabolism of *Acartia clausi* was significantly reduced under the impacts of increased temperature in the outlet drain (Capuzzo, 1980). At the Millstone Nuclear Power Station in Long Island, USA, thermal discharges in the outlet caused nearly half of the copepods to die within 3.5 days, while the copepod mortality rate was as high as 70% within 5 days, and the corresponding inlet water mortality rate of copepods within 5 days was only 10% (Carpenter et al., 1974). Similar to those of copepods, the feeding rates of bacteria and heterotrophic dinoflagellates were also affected by the synergistic effects of thermal discharge and residual chlorine. Experimental data showed that under hypochlorite concentrations of <0.03 ppm and elevated temperatures, the bacterial productivity decreased by 23~69%, while the feeding rate of heterotrophic dinoflagellates decreased by 31~36% (Dominguez-Faus et al., 2009).

Although there is no consistent conclusion on whether thermal discharges can cause a reduction in phytoplankton species diversity, the species adaptation to increased temperatures will inevitably lead to a competitive advantage in the area affected by thermal discharges, which may lead to a single large-scale algal bloom. At the same time, however, most of the current research uses microscopic examinations or mainly Chl *a* as an evaluation index, which may neglect pico- and nanophytoplankton to some extent, thus underestimating the phytoplankton composition diversity and only slightly describing the structure of the phytoplankton. On the other hand, changes in phytoplankton biomass and community structure at the food web and microbial loop levels are bound to change the quantities and compositions

of zooplankton and higher trophic organisms, thus causing changes in the feeding behaviors of organisms including *Acetes*. Current research lacks understanding of the mechanism and effects of thermal discharges on phytoplankton in food webs and microbial loops. Therefore, the study of the dynamics and response mechanism of ecosystems under thermal discharge has become a key scientific problem to be solved, especially with respect to phytoplankton.

Analysis of the ecological mechanism that may lead to *Acetes* blooms

According to the abovementioned basic biological and ecological characteristics of *Acetes*, combined with an analysis of the changes in the main environmental factors and their ecological impacts, three hypotheses on the ecological mechanism of *Acetes* blooms in coastal ecosystems can be advanced.

- (1) “Hibernate hypothesis”: that is, the seawater temperature increases in the area affected by thermal discharges of coastal nuclear power plants, and in winter, *Acetes* accumulates in the thermal discharge areas for wintering. During this process, there is no obvious growth or decline in its population. The blooms are mainly caused by the aggregation of shrimp resulting from thermotaxis, which occurs close to the cooling water inlet of the coastal nuclear power plant and has an impact on the cold source safety of the nuclear power plant.
- (2) “Ripen hypothesis”: that is, the regional warming of the coastal nuclear power plant leads to spawning and early larval development of *Acetes*, and food does not become the main limiting factor during its development.
- (3) “Feast hypothesis”: under the conditions of coastal eutrophication, the phytoplankton community structure in subtropical coastal waters changes from small particles to large particles; namely, pico- and nanodinoellates and *Synechococcus* transform into small diatoms and dinoflagellates, and this community succession is more obvious under winter wind mixing. Changes in the phytoplankton community structure lead to differences in the particle-size composition of zooplankton, and thus, the dominance of medium-sized zooplankton (such as copepods) increases so that a shorter food chain can be used for the growth and larval development of *Acetes*, providing nutritional conditions for the outbreak of *Acetes*. At the same time, the regional thermal discharges from the nuclear power plant provide a more suitable environment for the development of *Acetes* larvae, which leads to shortening of the *Acetes*

development time, and the population biomass becomes very large even as bloom occurs (Fig. 2).

According to the above scientific hypotheses, the following four aspects need further study.

- (1) The nutrient sources (nutrient salts, phytoplankton, zooplankton) that affect the growth of *Acetes* are examined. Physical factors such as temperature, salinity, surface flow and other chemical elements such as dissolved oxygen, pH, and nutrient salts of the water body before, during and after an outbreak in the area are monitored, and the Chl *a* and primary productivity of the water body and the dominant species of phytoplankton are analyzed. The abundance of cells, the biomass of typical red tide algae (dinoflagellates, diatoms, and *Phaeocystis*), the biomass of zooplankton, and other parameters are analyzed, and the preconditions required for changes in the biomass of *Acetes* are analyzed from the perspective of nutrient sources for growth and development.
- (2) The function and role of *Acetes* in the food web are analyzed, including the feeding rate of nanozooplankton, the growth rate of phytoplankton, and the feeding rate of meso-zooplankton (copepod); the length, weight and stomach content of *Acetes* are qualitatively and quantitatively analyzed; and the effects of environmental factors on the feeding rate, development and metamorphosis rate of larvae are determined.
- (3) The population dynamics of *Acetes* under the effects of thermal discharge and the environmental factor control experiment in the main stage of the life history

of *Acetes* are determined, and the changes in spawning amount and hatching rate and changes in the larval development and metamorphosis of *Acetes* under the influence of temperature-residual chlorine interactions are analyzed. Combined with hydrodynamics, we can analyze the characteristics of migration and vertical migration of *Acetes*.

- (4) The genetic diversity of the *Acetes* populations in different geographical regions is evaluated. Molecular biological analysis of the samples collected from China's offshore areas to reveal the population differentiation and genetic structure characteristics, to determine the phylogenetic and evolutionary relationships among populations, and to evaluate the genetic relationship between *Acetes* in the study area and other geographic regions.

Main prevention and control measures

Although there have been many studies on the biological and ecological threats to the safety of cooling water sources in coastal nuclear power plants, the process of transforming scientific achievements and directly applying them to specific environmental safety projects is still ongoing. Therefore, prevention and control of biological elements related to the water intake safety of nuclear power plants are mainly based on prevention and elimination of biofouling on metal screens. The two main problems are caused by impingement of large organisms and entrainment of small organisms on the metal screens. Common large organisms on cold-source filter screens are mainly composed of attached organisms such as barnacles, hydroids, ascidians, sea anemones, and mussels but also include pelagic euphausiids, copepods, fish larvae and seaweed (Satpathy et al., 2010; Turnpenny et al., 2010). At present, the removal of these organisms mainly utilizes the following methods:

- (1) Physical isolation method, which involves using filter impingement screens with different mesh sizes to provide isolation; the world standard varies from 4 to 25 mm in diameter (Satpathy, 1990);
- (2) High flow rate method, such as that used at the Italian Vado Ligure power plant. At this plant, a high flow rate of $2.5 \sim 3.0 \text{ m s}^{-1}$ is used to prevent blockage; this method ensured no blockage for 14 years (Whitehouse, 1975) because at high flow rates, the shear stress of the water often exceeds the shear strength of many organisms, and this mechanism is used to control biofouling (Satpathy, 1990).
- (3) Heat treatment, which uses warm drainage after cooling of the filter screen. It has been reported that attached

Fig. 2 The food abundance hypothesis of *Acetes* blooms under the combined influence of eutrophication, ingestion, salinity, migration and thermal discharge

organisms such as mussels can be removed after 1 h at 40 °C (Fischer & Bianchi, 1984);

- (4) Mechanical removal method, which involves the manual or automated wiping of the filter screen with a sponge rubber ball to achieve the purpose of removal (Satpathy, 1990);
- (5) Osmotic pressure control method to kill low-salt organisms by reducing the salinity of the inlet channel surface (Satpathy et al., 1999);
- (6) Bromide removal method, which uses bromide toxicity to kill organisms and their larvae in water (Satpathy, 1990);
- (7) Ozone removal method, which uses the strong oxidizing properties of ozone to kill organisms (Nair et al., 1997);
- (8) The active compound method, such as the use of pyridyl alkaloids extracted from the nemertean that can inhibit the development of *Balanus amphitrite* larvae (Nair et al., 1997).

For different organisms that pose a threat, there are also corresponding facility layouts and prevention methods that are different in different countries. Although the methods can be effective for specific organisms, there are currently no effective methods to prevent and control outbreaks of organisms such as *Acetes*, which have few cases of outbreaks worldwide. *Acetes* blooms are a potential threat given current environmental changes. Therefore, the treatment and prevention of organisms that threaten cold water sources for nuclear power plants need to be studied based on the fundamental principles of ecology to prevent and control outbreaks of *Acetes*.

Environmental management or protection policies and laws for coastal nuclear power plants

With the accelerated development of nuclear power plants along the coastal areas since the 1970s, the environmental issues of coastal nuclear power plants have become increasingly prominent and are now an important aspect of coastal zone management.

In April 2016, the National Nuclear Safety Administration in China issued the Circular of the National Nuclear Safety Administration on the recent incidents of marine organisms or foreign bodies affecting the water intake safety of nuclear power plants (National Nuclear Safety [2016] No. 91). Its annex, “typical incidents of marine organisms or foreign bodies affecting the water intake safety of nuclear power plants”, explains the causes, processes, influencing factors and corrective actions of the incidents. Five suggestions are put forward for the operators of nuclear power

plants, which can be referred to as the work plan of nuclear power plants in response to marine biological outbreaks. The five suggestions are as follows. (1) Attribute great importance to the impacts of marine organisms or foreign bodies on the seawater system, especially the safety of the plant water system in previous cases, and analyze the possible problems of the current case. (2) Cooperate with relevant departments to study the movement of marine organisms or foreign bodies and establish early warning and prevention mechanisms. (3) Address the design or construction problems that may exist in the water intake and filtration systems to enhance the ability to resist marine organisms or foreign bodies. (4) Regularly check the water intake structures, systems and equipment, and conduct sufficient daily maintenance, cleaning, desilting and other work. (5) Improve the response plan for the blockage of the water intake system by marine organisms or foreign bodies and strengthen exercise, with a focus on ensuring the safety of important plant water system functions.

Relevant management policies provide good suggestions for the improvement and treatment of the water intake of nuclear power plants during subsequent marine organism outbreaks. However, marine organism outbreaks are associated with great uncertainty. In terms of preventive measures, relevant domestic and international regulations for nuclear power plants should continue to establish guidelines and integrate multiple prevention methods.

Summary

In conclusion, considering the current situation, in which *Acetes* outbreaks are a serious threat to the safety of nuclear power plants, it is necessary to implement control measures based on the biology and ecology of *Acetes chinensis* and *Acetes erythraeus* under the effects of temperature elevation, salinity changes, food availability and the hydrological regime of the study area. We comprehensively analyzed the causes and mechanisms of the outbreaks from the perspectives of physical and chemical conditions, phytoplankton biomass and community structure, dynamic changes in food webs and the population dynamics of *Acetes*. These results will provide the necessary scientific data for the control of large-scale *Acetes* outbreaks and aid in the prevention of potential entrainment hazards in cooling water intakes of nuclear power plants.

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