ELECTRIC POWER RESEARCH INSTITUTE

Cooling Water Intake Debris Management: Jellyfish and Jellyfish-Like Organisms

Technical Update — *Cooling Water Intake Debris Management Interest Group*

Issue

Jellyfish, comb jellies, and salps (Phylum Cnidaria, Ctenophora, and Chordata, respectively) are gelatinous animals which live on the seafloor, swim within the water column, or drift with ocean currents. It is speculated that rising seawater temperatures, overfishing of predators, and the availability of more nutrients have aided in the population explosion of many species of jellyfish and other jellyfish–like organisms (Smithsonian 2013). Whether the causes are natural or anthropogenic, these aggregations, more commonly known as jellyfish "blooms", "swarms", or "outbreaks", have begun disrupting fisheries, marine recreational activities, and are an increasing issue at power plant cooling water intake structures (CWIS). Jellyfish populations can explode quickly and blooms can appear to come out of nowhere due to the organism's ability to grow fast, reproduce quickly, and survive in environments most marine organisms find uninhabitable (NSF 2013).

A pink meanie jellyfish feeds on a moon jelly (left, Smithsonian 2013). Hundreds of jellyfish block the trash racks (top right) and cover the floor (lower right) at the Orot Rabin Power Station in Hadera, Israel (www.dailymail.co.uk).

Biology

While jellyfish, comb jellies, and salps share a similar morphology, they are biologically very different. Salps, which are planktonic tunicates, are more closely related to vertebrates (Madin 2010). Jellyfish and comb jellies are comprised of two major cell layers: the external epidermis and internal gastrodermis. Between each cell layer, the mesoglea makes up a kind of internal skeleton containing some structural proteins, muscle cells, and nerve cells. Jellyfish and comb jellies have no stomachs, intestines, or lungs. Instead, the gastrodermis lines an all-purpose gut and an opening through which food enters, waste is eliminated, and reproductive cells are released (Smithosonian 2013).

Jellyfish and other gelatinous jellyfish-like organisms can pose a significant threat to power plant cooling water intake structures (CWIS). In sufficient quantities, jellyfish can block intake screening equipment (for example, bar racks and traveling water screens), which can lead to reduced cooling water flow or, in extreme cases, structural failure of the screening equipment. Furthermore, the passage of jellyfish into the circulating water system can result in plugging of the condenser tubes. Cooling water blockage is a concern because it negatively affects facility reliability and results in a loss of revenue. This technical brief provides background on jellyfish and jellyfish-like organisms as debris agents at power plant CWIS. It includes information on the organisms' biology, jellyfish blooms, and control strategies, as well as lists of external resources such as key literature, websites, and contact information for technical experts on jellyfish.

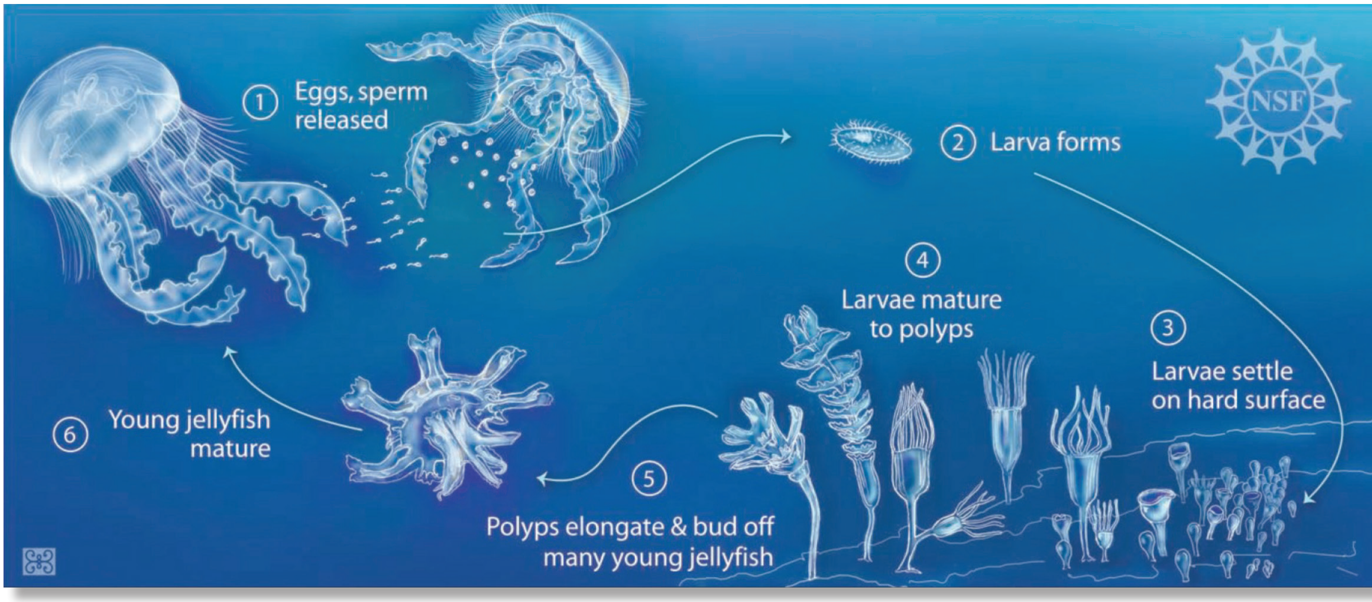

Figure 1. Jellyfish reproductive cycle (Image from National Science Foundation website: http://www.nsf.gov/news/special_reports/jellyfish/jelly_life.pdf)

Salps have gelatinous and transparent bodies that can be shaped like cylinders, spindles, or prisms. Salps move via jet propulsion by ingesting water at one end, passing it through its contracting hollow body, and ejecting it through a siphon on the opposite end. In the process, planktonic food items are filtered out using an internal mucous net (Sutherland and Madin 2010; Greenberg et al. 2010).

Globally, there are approximately 4,000 species of jellyfish and up to 150 species of comb jellies. Not all species swim and float through the water, but those that do can drift with currents for thousands of miles. Jellyfish are carnivorous and eat plankton, crustaceans, and small fish. There are also a number of marine animals known to eat jellies including some fish species and even endangered leatherback turtles (*Dermochelys coriacea*) (Smithsonian 2013).

There are approximately 50 species of salps throughout the oceans. Some look like tubes or long snakes, while others look more like chandeliers hanging in the water. They can exist as single animals called solitaries or as chains called aggregates and populations can grow rapidly under the right conditions (Madin 2010).

Jellyfish, comb jellies, and salps have very different reproductive cycles. Comb jellies have the least complex reproduction, relying on self-fertilization, since the majority of comb jellies are hermaphroditic (Smithsonian 2013). Salps represent the next level of reproductive complexity with solitary salps reproducing via asexual budding to produce the next generation. The offspring of asexual budding emerge as an aggregate from the parent. Aggregate salps can reproduce sexually, releasing solitaries into the water column (Rakow 2009). Reproduction of "true" jellyfish is more complex than that of salps (Figure 1). Adult female and male jellyfish release eggs and sperm, which unite to produce a larva (planula) that attaches to a hard surface. Living stationary (sometimes for decades) in the polyp phase, it awaits favorable conditions, at which point it elongates and buds off, releasing many young jellyfish. Though little is known about the polyps' formation (since they are rarely found or studied in the wild), it is believed that fields of polyps release jellyfish simultaneously, creating tens of thousands of jellyfish at a time. These juvenile jellyfish rapidly mature into adults and repeat the cycle (NSF 2013). Most jellyfish species live less than a year and some of the smaller species may only live a few days (http://www.jellywatch.org/blooms/facts).

Adult jellyfish are very adaptive and can survive well in varying environments and new ecosystems. They have broad diets, reproduce quickly, alter body size based on food availability, and tolerate low-oxygen water (Smithsonian 2013).

Extent and Occurrence of Blooms

Speculation that jellyfish blooms have increased in recent decades is under debate. Some scientists and conservationists believe that humans have influenced the marine ecosystem to such an extent that systems are out of balance, resulting in massive increases in global jellyfish populations (Schrope 2012). Still, the analyses of most existing data sets demonstrate that jellyfish populations naturally fluctuate over the long-term (8 to 100 yrs) with variation in climate (Purcell et al. 2007; Purcell 2012). For example, the northern sea nettle (*Chrysaora melanaster*), common in the Bering Sea, showed a dramatic increase in population during the 1990's, peaking in summer of 2000, and then declining and stabilizing at a moderate level after 2001, which coincided with warmer water temperatures (Brodeur et al. 2007).

One data set difficult to ignore is the growing reports of problems associated with jellyfish blooms (Figure 2). In Japan over the last 10 years, a dramatic increase in moon jellyfish (*Aurelia aurita*) has been noted by fishermen. A majority (65%) of those fisherman surveyed believe jellyfish populations have increased during the last 20 years (Purcell et al. 2007). Han and Uye (2010) note that since the first jellyfish-caused (*A. aurita*) shutdown of a Korean nuclear plant in 1996, the shutdowns have only become more frequent and the chronic blooms more commonplace. In 2006, the USS *Ronald Reagan* aircraft carrier was powered down while docked in Brisbane, Australia after thousands of jellyfish were sucked into the ship's water intake, diminishing its ability to condense steam from the ship's turbines (Hilburn 2007). A swarm of Australian spotted jellyfish (*Phyllorhiza punctata*) forced the closure of six Spanish beaches in the summer of 2011 after 100 swimmers were treated for jellyfish stings (NewScore 2011). In 2011 alone, jellyfish blooms shut down power plant facilities in Israel (Orot Rabin, a coal-fired plant), Scotland (Torness, a nuclear plant), Japan (Shimane, a nuclear plant), and the U.S. (St. Lucie, a nuclear plant in Florida) (Schrope 2012). In April 2012, a large swarm of salps caused a temporary shutdown of Pacific Gas and Electric Company's Diablo Canyon Nuclear Station. Diablo Canyon had also been previously shut down by jellyfish in 2008 (NRC 2008). In early September 2013, Sweden's largest nuclear power plant, Oskarshamn, on the Baltic coast, was shut down (similar shutdowns occurred in 2005) by an influx of jellyfish of the genus *Aurelia* (Mengewein 2013).

Scientists who believe blooms are on the rise have identified several possible causes of jellyfish population increase including: climate change, eutrophication, overfishing, and ocean sprawl – excessive development of the coast and open marine areas (Purcell et al. 2007).

Climate Change

Changing environmental factors may directly affect the size, location, and timing of jellyfish populations. Increasing ocean temperatures caused by climate change may be helping jellyfish populations reproduce at a faster rate (Purcell 2005; Han and Uye 2010). For example, the mauve stinger (*Pelagia nocephrae*) was found to have faster growth at a water temperature of 19°C than at 13.5°C (Purcell et al. 2007). Changing climates have also reduced rainfall in the temperate zones. With reduced rain runoff from land, coastal salinity levels remain high and allow better survival closer to shore, increasing jellyfish-human interactions (Dabir and Kale 2012). Reports indicate that increasing carbon dioxide concentrations in the atmosphere have led to a decrease in ocean water pH. It is speculated that ocean acidification could have detrimental effects on calcifying organism that build skeletons or shells of calcium carbonate. This could, in turn, benefit jellyfish and other non-calcifying gelatinous organisms that are able to thrive in more acidic environments (Purcell et al. 2007).

Eutrophication

An ecosystem's response to the addition of artificial or natural nutrients is eutrophication; it is characterized by an increase in biomass at all trophic levels. In most cases, increased nutrient loads in a marine environment are a result of human development in coastal areas and can be associated with pollution, fertilizers, sewage, and aquaculture (Dabir and Kale 2012). More nutrients means more food which results in greater reproductive output (Purcell et al. 2007). Eutrophication often results in lower dissolved oxygen levels as biomass increases, especially in bottom waters. Fish avoid or can die in environments with lower oxygen levels; however, many jellyfish species are tolerant of low oxygen and can take advantage of areas with reduced competition for resources (Purcell et al. 2007).

Overfishing

Overfishing of both predators and forage fish opens up ecological space for jellyfish. Commercial fishing reduces the number of jellyfish predators like chum salmon (*Onorhynchus keta*), butterfish (*Peprilus triacanthus*), and spiny dogfish (*Squalus acanthias*) (Purcell et al. 2007). Overfishing can remove the natural check that maintains jellyfish populations. In addition, jellyfish are known to prey on eggs and larvae of those same fish, and their increasing numbers may make it difficult for depleted fisheries to rebound (Stone 2010). The fishing industry also reduces forage fish populations which compete with jellyfish for resources. Fewer competitors results in increased zooplankton for a growing jellyfish population to feed on (Purcell et al. 2007).

Ocean Sprawl

Humans have disturbed the marine environment in many ways either through alterations to the shoreline or through construction in coastal waters. Docks, marinas, breakwaters, oil platforms, and artificial reefs all provide surfaces for jellyfish polyps to anchor and accumulate in large numbers (Purcell et al. 2007). These structures are often in shoreline areas and have the potential to increase both the presence of polyps and the probability that jellyfish blooms will occur. Coastal power plants' thermal discharges could perpetuate the problem by creating areas of elevated water temperature which is beneficial to the reproduction and growth of many jellyfish (Purcell et al. 2007).

Laboratory studies and SCUBA surveys conducted by Duarte et al. (2013) have linked the increase in jellyfish blooms to the proliferation of artificial structures in coastal zones from ocean sprawl. SCUBA surveys were conducted over a wide geographical range (Japan, UK, Spain, and Solvenia). In addition, Duarte et al. (2013) report on recently conducted field and laboratory experiments designed to determine the extent of jellyfish planulae settlement on various artificial surfaces. The field experiments were conducted in the Chesapeake Bay with sea nettles (*Chrysaora quinquecirrha)* and the lab experiments were conducted with Mediterranean jelly (*Cotylorhiza tuberculata*) under conditions simulating the Spanish Mediterranean Sea. Duarte et al. (2013) found that there was a significant difference in settlement preference for *C. tuberculata* and *C. quinquecirrha* polyps across substrates types and that recruitment on artificial substrates was similar to or greater than recruitment on natural ones. Potentially suitable artificial structures for polyp settlement commonly associated with ocean sprawl include pillars, platforms, walls, piers, floating docks, oil rigs, aquaculture structures, rip rap, bridges, buoys, moorings, ship hulls, and garbage (Duarte et al. 2013). Research by Tomaru et al. (2014) on the recruitment of moon jellies (*A. aurita*) reached a similar conclusion – that that the prevalence of artificial (particularly plastic) substrates may provide increased recruitment area for jellyfish. Lo et al. (2008) also concluded that the presence of floating aquaculture rafts was among the principal factors contributing to large populations of *A. aurita* in Tapong Bay, Taiwan.

Figure 2. Jellyfish blooms in the Gulf of Mexico (image from Monty Graham, Dauphin Island Sea Lab) and an Australian sign warning swimmers of jellyfish (inset image from Flickr user rezendi).

Control

Methods and mechanisms for the control or eradication of jellyfish blooms are somewhat limited. This is in part due to the difficultly in studying jellyfish and the limited historical data on the causes of blooms. Currently, there are a few documented control mechanisms under research and several initiatives being undertaken to identify and track jellyfish blooms worldwide.

Barriers and Diversion

Traditional debris screening and handling methods at intakes have proven to have limited success against jellyfish blooms, evidenced by the growing number of plant shut downs. In cases where carryover of jellyfish is an issue, operators are likely to consider switching from through-flow screens to other designs that minimize carryover (e.g., dual flow and Bilfinger Water Technologies - Passavant Geiger Multi-disc screens). In addition, some manufacturers (e.g., Bilfinger Water Technologies-Passavant Geiger) also offer automatically-raked bar screens that have been used to handle heavy jellyfish loads thereby reducing strain on the finer mesh downstream traveling water screens.

A growing area of research has focused on developing physical barriers or diversion technologies to reduce jellyfish impacts on water intakes. For example, Lo (1991) conducted a laboratory study to evaluate the effectiveness of an air bubble barrier on neutrally-buoyant floats (jellyfish surrogate) under various water depths, unidirectional currents, air discharge rates, and wave conditions. The results indicated that air bubbles alone were inadequate for preventing jellyfish ingress into intakes.

Later, Lo (1996) conducted additional laboratory studies to evaluate the use of a floating boom in concert with air bubbles to prevent the ingress of jellyfish under various current, wind, and wave conditions. Results indicated that the air bubble plume was able to lift the jellyfish to the water's surface and accumulate them behind the boom system where a suction pump could be used to move the jellyfish to safe discharge location away from the intake.

Detection and Removal

The growing issue and concern of jellyfish blooms disrupting power generation at power plants has fast-tracked research and development in many parts of the world. In Japan, the Higashi-Niigata Thermal Power Station has such an issue with jellyfish that engineers have developed an underwater image analysis system used to detect and remove jellyfish automatically (Matsuura et al. 2007). This system consists of an underwater camera mounted at the bottom of the CWIS, image analysis software to detect jellyfish, and a pump to remove detected jellyfish. In Malaysia, research has been conducted using an acoustic sensor to detect jellyfish (Samsuri et al. 2012). This preliminary study utilized jelly crystals as a surrogate and demonstrated success in detection with acoustics; however, further improvements are needed before full implementation on a larger scale is warranted. Brierley et al. (2004) also demonstrated the potential for using hydroacoustics to detect jellyfish and estimate abundance.

Tracking and Early Warning Networks

Marine biologist and jellyfish activists are turning to the web and social media to help develop a better understanding of how changes in the world's oceans are affecting jellyfish blooms. Jellywatch.org (Jellywatch) was created by the Monterey Bay Aquarium Research Institute in 2010 and is an active international collaborative project in which citizen activists can identify and record sightings of blooms (http://jellywatch.org/). Collaborative data collection sites like Jellywatch are being used to create scientifically-coordinated global jellyfish and environmental databases, such as the Jellyfish Database Initiative (JEDI) currently under construction by Jellywatch. The JEDI project will include data acquisition and statistical analysis, global maps of regional jellyfish blooms, information on jellyfish roles within the ecosystem, and discussions on the socio-economic ramifications of jellyfish blooms (Condon et al. 2013). The National Oceanic and Atmospheric Administration (NOAA) is taking this type of jellyfish bloom data a step further and creating tools for

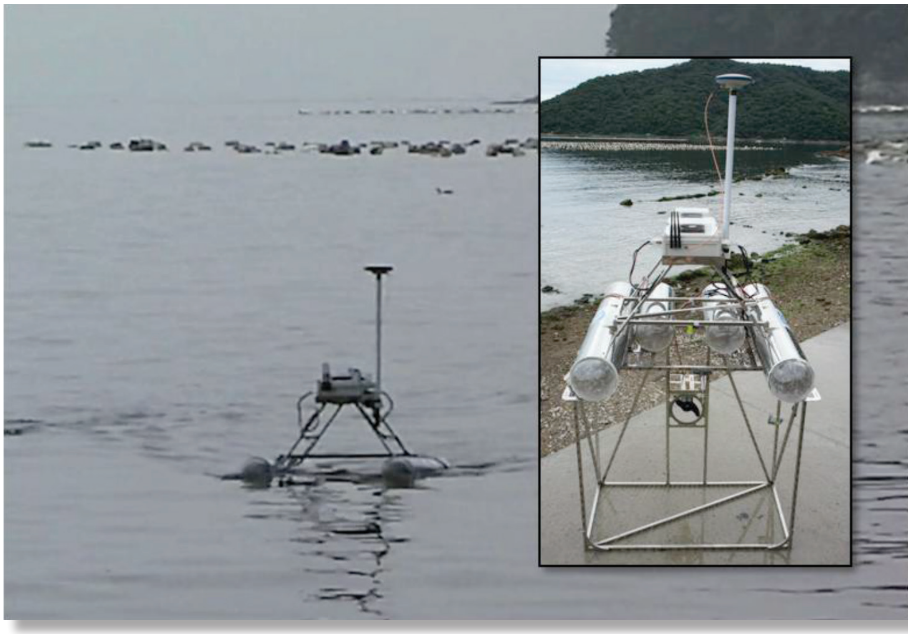

Figure 3. Jellyfish Elimination Robotic Swarm or JEROS was constructed by a group at the Korean Advanced Institute of Science and Technology (Ackerman 2013).

forecasting the presence of sea nettles within the Chesapeake Bay. This NOAA project utilizes the established relationship between salinity and temperature conditions and the presence of sea nettles within Chesapeake Bay. NOAA updates a map (hourly) illustrating probable distribution patterns of sea nettles to help minimize jellyfish encounters (http://chesapeakebay.noaa.gov/forecasting-sea-nettles). Japan has also implemented a forecasting project called STOPJELLY to better predict and control outbreaks of jellyfish that impact commercial fisheries (http://tnfri.fra.affrc.go.jp/kaiyo/POMALweb/e-stopjelly.html).

Eradication

Hyun Myung, a professor of robotics at the Korean Advanced Institute of Science and Technology (KAIST), and his group have developed a robot to combat jellyfish blooms (Figure 3). The Jellyfish Elimination Robotic Swarm (JEROS) is an autonomous vehicle equipped with navigation system, detection camera, and a grid for jellyfish removal (Kim et al. 2013). The JEROS camera system captures images which the on-board computer then processes to identify jellyfish. Once a group of jellyfish have been located, multiple JEROS are able to team up in formation to slice up approximately 900 kilograms (~2000 lbs) per hour of jellyfish through a grid system installed below each unit (Ackerman 2013). A prototype system has been tested in the field to demonstrate feasibility and more tests are planned to gather additional data (Kim et al. 2013). Though initial results appear promising, the prototype JEROS system may be limited in its effectiveness depending on the deployment location and the species being targeted. The sea walnut (*Mnemiopsis*), a type of comb jelly, is one of the more prolific breeders and even cut up bits will regenerate and resume normal life as whole adults in two to three days (Flannery 2013).

Key Resources

Literature

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Websites

Fourth International Jellyfish Bloom Symposium
http://home.hiroshima-u.ac.jp/~ijfs/index.html

Jellywatch
http://jellywatch.org/

National Center for Ecological Analysis and Synthesis: Jellyfish Group
http://www.nceas.ucsb.edu/projects/12479

National Oceanic and Atmospheric Administration (NOAA) Chesapeake Bay Office: Forecasting Sea Nettles
http://chesapeakebay.noaa.gov/forecasting-sea-nettles

Population Outbreak of Marine Life STOPJELLY Project
http://tnfri.fra.affrc.go.jp/kaiyo/POMALweb/e-stopjelly.html

Experts

Below is a list of experts in the area of jellyfish biology and bloom research.

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