RECLAMATION

Managing Water in the West

Effect of Electric Fish Barriers on Corrosion and Cathodic Protection

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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A main goal of Reclamation is the delivery of water and power. However, these water delivery systems could affect endangered and protected fish species. Electric fish barriers could control the movement of fish, thereby protecting them from adverse outcomes. Literature research revealed that electric fish barriers could cause electrical interference on nearby structures and electrical systems. This potential for electrical interference not only could cause corrosion on nearby structures but also create interference issues with cathodic protection systems.

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Preface

The primary objective of this scoping study was to develop an understanding of electric fish barrier operation and determine possible corrosion issues these barriers could create on nearby structures. Literature research revealed that electric fish barriers could cause electrical interference on nearby structures and electrical systems. The potential for electrical interference could not only cause corrosion on nearby structures but also create interference issues with cathodic protection systems.

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List of Acronyms and Units

AC	Alternating Current
DC	Direct Current
CP	Cathodic Protection
ICCP	Impressed Current Cathodic Protection
GFFB	Graduated-Filed Fish Barrier
Hz	hertz
m	meter
m/s	meter per second
µS/cm	microSiemens per centimeter
V/cm	volts per centimeter
V/in	volts per inch

Introduction

An electric fish barrier, also known as an aquatic electrical barrier, is a non-physical barrier that prevents fish passage from one location to another or induces fish movement from one area to another within a body of water using an electric current. Electrical fields are one of the methods to control the migration of native and/or invasive species [1-5]. This technology aids in preventing the movement of fish to protect them from entering potentially dangerous areas such as hydropower penstocks [4,6-7], prevent migration upstream such that fish avoid entry into a fish hatchery [1,8], and prevent movement into waterways [5,9-10], such as invasive species to protect native species in particular body of water. Electrical fields are also used to guide fish movement out of a navigation lock prior to the entry of a boat [11]. Reports on implemented barriers show their overall efficacy in preventing the movement of fish. The non-physical nature of these barriers make their application in many waterways practical as it does not impede the passage of boats and presents low risk to the environment.

Aquatic electrical barriers utilize the same principle as an impressed current cathodic protection (ICCP) system by passing an electrical current through a conductive liquid (e.g. water) creating an electric field. However, unlike the cathodic protection (CP) system, which prevents a structure from corrosion, the fish barrier causes a physiological reaction in the aquatic species. The field is created by placing a conductive anode and cathode in the water and passing a current between the conductors. Fish inside the field become part of the electrical circuit. Fish in contact with the electrical field can experience a reaction, such as: avoidance, electrotaxis (forced swimming), electrotetanus (muscle contraction), electronarcosis (muscle relaxation or stunning), or death [12]. The amount of current that passes through the fish depends on the relative conductivities between the fish and the water. Similar conductivity translates to more efficient power transfer to the fish [13]. Smaller fish are typically effected less by the electric fields than larger fish, because more power is transferred for a given voltage gradient (volts per unit distance) over the length of the fish [14-15]. The effects depend on the location of the fish in the field and on the fish species [15]. This is useful since all species and sizes of species (juvenile vs. adult) respond differently to the electric fields, allowing the field to be tailored to the species and size required.

Electrical barriers can use alternating current (AC), direct current (DC), or pulsed DC. Early fish barriers utilized alternating current, which has since been found to be injurious to fish because alternating polarity causes electrotetanus [15]. Recent applications of fish barriers use direct current or pulsed DC. When pulsed DC is used, peak voltage, peak current, pulse width, and frequency are adjusted to elicit the desired fish response [15]. Power requirements for barrier operation not only depend on the type of current selected but also increases with increasing water conductivity [15]. Constant DC barriers require more power than pulsed DC [15].

Conclusions

Electric fish barriers are an effective method to control fish movement, yet allow uninhibited passage of boats and debris when used to prevent fish from moving upstream. Barriers can be designed to completely prevent the passage of most types of fish into an area. Power requirements and the strength of the electric field depend on the type and size of fish being controlled. The current type, length and amount also alter the field strength.

While these barriers are highly effective, they do pose a number of possible safety hazards. For this reason, monitoring of the barriers and safety precautions must be employed. When designing the specifications for the electric barrier, the biological factors of the fish response must also be considered to minimize any injurious impacts caused by the barrier.

Electric barriers may cause stray current corrosion on nearby structures and the interaction between an electric barrier and cathodic protection system has never been examined. In addition, although pulse cathodic protection is not normally utilized on submerged structures it should be examined as to whether a pulsed DC electric fish barrier can also be used to protect the structures near the barrier.

Discussion

How Barriers Work

The basic electric fish barrier is an array of electrodes submerged in the water perpendicular to flow, connected to pulse generators and a power source above the water. When the pulse generators release current, voltage is applied between two electrodes, creating an electric field across the section of water. The electrical field lines run parallel to the direction of flow and when fish are upstream they are oriented head-to-tail fin along the maximum voltage gradient [2,16]. As fish enter the electric field, they become part of the electrical circuit and they experience electric current flow through their body. As the fish approach the anode they experience increasing field intensities [2]. When the fish encounter the electric current, they generally turn around and swim away from the electric barrier. However, if they continue to swim through the barrier the electric current overwhelms their sense of orientation [2,6]. This loss of orientation results in the fish aligning themselves perpendicular to the current to avoid a continued passage of current through their body [2,6]. This is called rheotaxis. If the fish are traveling upstream into the barrier, rheotaxis causes the fish to drift back downstream by default. In barriers preventing downstream travel, fish who continue to swim through the barrier can become immobilized and swept downstream through the barrier. It is thus more difficult to block downstream migration than upstream migration.

The greater the voltage gradient, the higher the voltage drop across the body of the fish. Thus, barriers with higher voltage gradients elicit stronger reactions from the fish and are more effective in preventing passage through the barrier. The length of the fish also affects the voltage drop across their body; the longer the fish, the greater the voltage drop. Therefore, a higher voltage gradient is required to prevent the passage of smaller fish through a barrier. The accepted range of threshold for tolerable voltage gradients for freshwater fish was determined to be between 0.05 and 5.5 V/cm [2,15-16]. It should be noted that a barrier with this voltage gradient will only be effective if it extends the entire depth of the body of water [2,16].

Electrical Interference

The term "interference" is electrical interference and is defined as "*any detectable electrical disturbance on a structure caused by a stray current where a 'stray current' is defined as a current in an unintended path*" [17]. The structure could be any metallic network, such as electrical power grids and communication systems. Although the source of the interfering current is often DC from an impressed current cathodic protection system, the current can also originate from any electrical system that uses the earth or water intentionally or inadvertently as a current path. AC can also cause electrical interference. However, since most electric fish barriers are DC this document will only focus on DC interference.

Stray currents from nearby electric installations may flow to and from a structure if they are located in the same electrolyte (water) or connected electrolytes (e.g. water-to-soil). The potential of the structure will be lowered (made more negative) at points where the stray current enters the structure, providing partial cathodic protection. Corrosion may occur when the potential becomes more positive where the stray current leaves the structure. Stray currents on other buried or submerged structures are considered a part of the design and operation of all CP systems. If a potential for stray current interference exists, without mitigation measures accelerated corrosion may occur. Design features used to minimize the risk include anode bed location and installation of additional CP systems.

Barrier Set-Up and Construction

Electrodes

An electric fish barrier is created with a series of electrodes, alternating anodes, (positive electrodes), and cathodes (negative electrodes), spanning across a body of water [18]. These are connected by cables to an above-ground power supply. Electrodes can be arranged in a vertical formation, anchored into an insulated material at the bottom of the water, or they can be evenly spaced horizontally along the bottom of the waterway. The electrodes arranged vertically in the water create an electric field of a uniform strength at any depth. The vertical arrangement often causes debris buildup along the electrodes and therefore avoided in locations with swift currents or much debris.

Electrodes arranged horizontally across the bottom of the water, (flush-mounted electrodes), do not collect debris or inhibit the passage of boats [9,19]. These are used in areas with high water traffic, lots of debris, fast water current, and in temporary barriers [9,19]. In the construction of flush-mounted electrodes, the electrodes are placed in a weir built across the bottom of the canal or channel. The weirs are usually composed of concrete with high silica content for insulation [16]. An example of flush mounted electrodes in a weir is shown in Figure 1a and 1b. Temporary fish barriers can be made using this construction, which allows for portability. In some cases where the bottom of the body of water is uneven, electrodes are placed in weirs to create a barrier with uniform field strength. When the electrodes are placed horizontally over the ground, they create a weaker electric field towards the surface of the body of water. The field strength increases with the depth of the water and the power supplied to the electrodes, calculated based on the desired gradient at the water surface to prevent fish passage.

a **b**

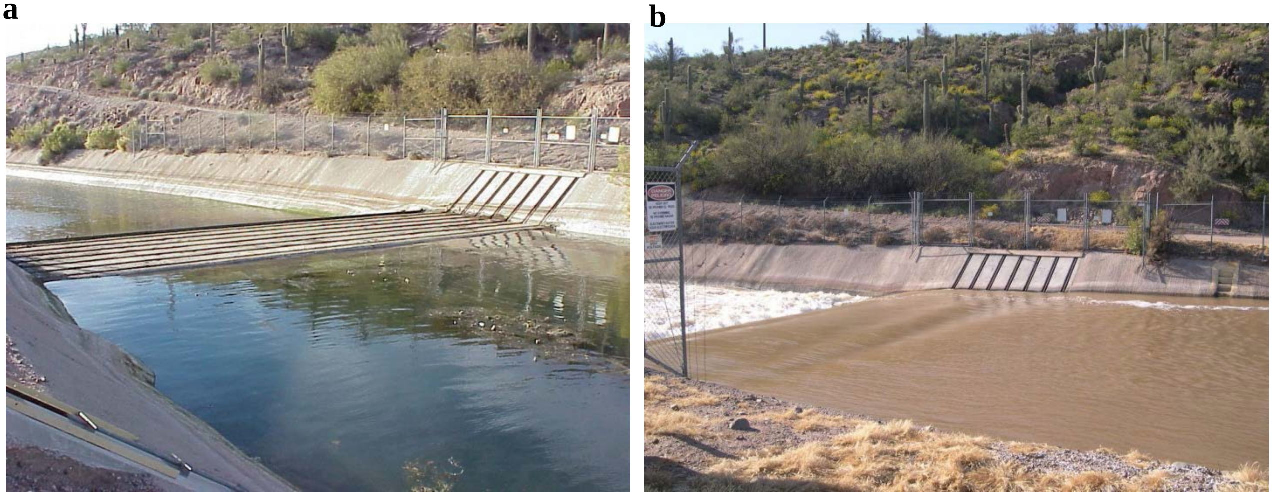

Figure 1. Granite Reef Dam on the Salt River fish barrier using railroad iron electrodes bottom-mounted to the concrete deck. The barrier prevents migration of Colorado River striped bass and grass carp via the Central Arizona Project canal from entering the Salt and Verde Rivers. The electric fish barrier is considered 100% effective. [20]

Sediment deposits on the electrodes can render them ineffective in sediment deposits greater than 0.6m [21]. For this reason, vertical electrode arrays are sometimes embedded in the sides of a geographical formation around the barrier.

The electrodes must be placed across the body of water so the electric current produced is parallel to the stream flow (Figure 2) [21]. The physical electrodes are therefore placed perpendicular to the current flow. This arrangement produces voltage potentials that are also perpendicular to the flow of the water. Thus, when a fish swims into the electric field, their body is also perpendicular to the equipotential lines. The fish therefore experience a voltage drop across their body as it spans different equipotential lines. The electric fish barrier is not as effective when the fish swim parallel to the electric field, in an alignment perpendicular to the current flow because their body does not span different voltage gradients. In this case, the fish experience only one voltage gradient and do not experience the shock caused by a voltage drop over their body.

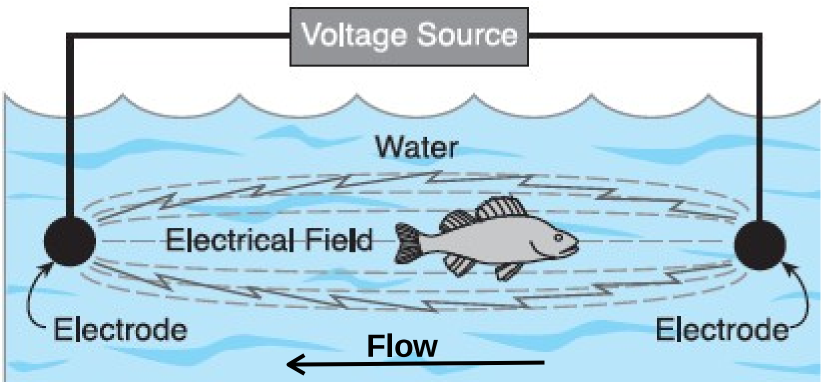

Figure 2. Electric field lines shown parallel to fish between two electrodes. [21]

The electrodes are commonly made out of ferrous materials. In the electric barriers that were part of the Central Arizona Project (Figure 1), the electrodes were made from iron and high-carbon steel railroad rails [16]. Copper electrodes should not be used because they easily produce copper sulfate compounds, which are poisonous to fish. To avoid high-maintenance costs, the electrodes should not be made out of a highly-corrosive material. Due to erosion and electrolytic buildup on the electrodes, electrodes will eventually lose their effectiveness.

Electric Current

Most electric fish barriers use pulsed direct current. Electric fish barriers can be designed using both alternating currents and direct currents. However, fish are more sensitive to alternating current, which was used in many of the older barriers. However, the field produced by AC causes high levels of muscle contraction in the fish, resulting in immobilization [15]. Fish are exposed to more electric current when immobilized, causing greater injury to their body. Barriers using only DC cause a type of seizure or galvanotropism. This causes the fish to move towards the anodes away from the strongest part of the field [22]. When compared to a constant current, pulsed DC resulted in a lower number of internal vertebral injuries [15]. The length of the fish also affected the number of vertebral injuries with both constant and pulsed DC [22]. Direct current can cause heavy corrosion of the anode and oxidation and electrolytic buildup on the cathode, which reduces the ability to pass electricity. Pulsed DC limits the amount of electrolytic buildup on the cathode while posing the least risk of injury for the fish [11].

Pulsators

The current to the electrodes is supplied through a series of pulsators, which release an electric current at specific intervals. The current from the pulse generator creates the voltage differential between the cathode and the anode, which starts the barrier. The pulsators are connected to a capacitor, which stores the energy from a power source and discharges the current through the electrodes at specific intervals [21]. The more pulsators connected in series, the more efficient the barrier system is. Typical barriers consist of six pulsators but when only one pulsator is used, its energy can be split and supplied to up to three electrodes [21]. Figure 3 shows an example of a bank of pulsators.

Figure 3. Pulsator system for electric fish barrier at Strawberry Reservoir and Recreation Area. [23]

Pulsators allow for a number of types of waveform releases including standard pulses, sweeping pulses, sweeping frequencies or gated bursts [21]. Standard pulses and gated bursts are most commonly used in electric fish barriers. A standard pulse is one with a consistent frequency and duration whereas gated bursts are a group of standard pulses with long off times between each group [21]. The gated bursts are as effective as the standard pulses and found to be less stressful for the fish [21]. Sweeping pulses include pulses that gradually increase or decrease in frequency or duration. Soft-start pulses are occasionally utilized since they can cause the dispersion of fish away from electrodes without an intense biological reaction to the full electrical current of the barrier [15].

When multiple pulsators release an output simultaneously, it is possible to induce a stray current within the insulating material in which the electrodes are placed [24]. This current can then flow through the ground, creating a ground current with the potential to interfere with nearby structures and electronics. This was the reason cited for the malfunction of a traffic signal at a railroad crossing on Old Romeo Road near the electric barriers at the Chicago Ship and Sanitary Canal [24]. In order to prevent possible interference with nearby structures, the pulsators are de-synchronized. It is especially important to de-synchronize the pulsators when there are multiple barriers in one location, as with the Chicago Ship and Sanitary Canal, to prevent the induction of any ground currents.

Other Conditions for Barrier Specifications

The property of the water where the barrier is constructed is important in determining the voltage requirements for the barrier and CP systems. Electric barriers have been successful in blocking fish moving upstream in water with velocities between 0.6-3.0 m/s [21]. However, barriers have only been effective in water with velocities under 0.5 m/s for blocking fish moving downstream [21]. Therefore, electric barriers are more effective preventing upstream movement of fish than downstream movement in areas with faster-moving water.

There is an inverse relationship between water velocity and the likelihood of a fish breaching the barrier for upstream passage of fish [25]. The faster the velocity the less likely it is that a fish will be able to swim across the barrier. This is due to the time required to traverse the distance and the lengthening of their exposure to the field [25]. The over-exposure to the electric current causes fish to align perpendicular to the current flow, (rheotaxis), allowing the current to sweep them downstream. The water velocity, at which the fish experienced immobilization and rheotaxis while attempting to cross the barrier at the Chicago Ship and Sanitary Canal, was 0.07 m/s [25]. Placement of the barrier is critical for preventing increases in exposure time and potential risk of injury if the fish are trapped in the barrier in slow or stagnant water, such as eddies.

The design of electric barriers must consider the conductivity of the water since the ability and efficiency of passing current from the water to the fish is determined by the conductivity of both the water and the fish [15]. Electric barriers are the most effective when the conductivity of the fish matches that of the water, thus the voltage gradient in the water matches that in the body of the fish. Water with a higher conductivity allows a better flow of the electric current because it behaves like a resistor in the electric circuit created by the barrier and the fish. Therefore, a higher current is required to maintain the electric field [21]. Most electric barriers can now operate effectively in water with conductivity up to 5,000 µS/cm [21]. The conductivity of water is related to salinity and sediment deposits as well as changes in water temperature. Because of the temperature effect it is necessary to monitor the system and change the amount of electrical current supplied to maintain the desired voltage across the barrier.

Graduated Field Fish Barriers

Graduated field fish barriers are designed with the intention of improving the fish deterrence levels while causing less biological harm to the fish [6]. These are created by a series of parallel electrodes placed perpendicular to the flow but graduated in power intensity [6]. Each successive electrode generates a stronger voltage gradient (Figure 4), creating a stronger electric field as the fish swims farther into the barrier. The lowest voltage gradient is located at the edge of the graduated field barrier, creating an area mildly uncomfortable or annoying to the fish. This causes them to turn around before they experience electrotetanus, electronarcosis or euthanasia [6]. The graduated increase in the voltage gradient is effective in preventing the passage of different sized fish and has a high deterrence rate for preventing both the upstream and downstream passage of fish [6]. It is difficult to maintain an electric field with a low voltage gradient over a large depth therefore; these barriers are less effective in deep water applications [6].

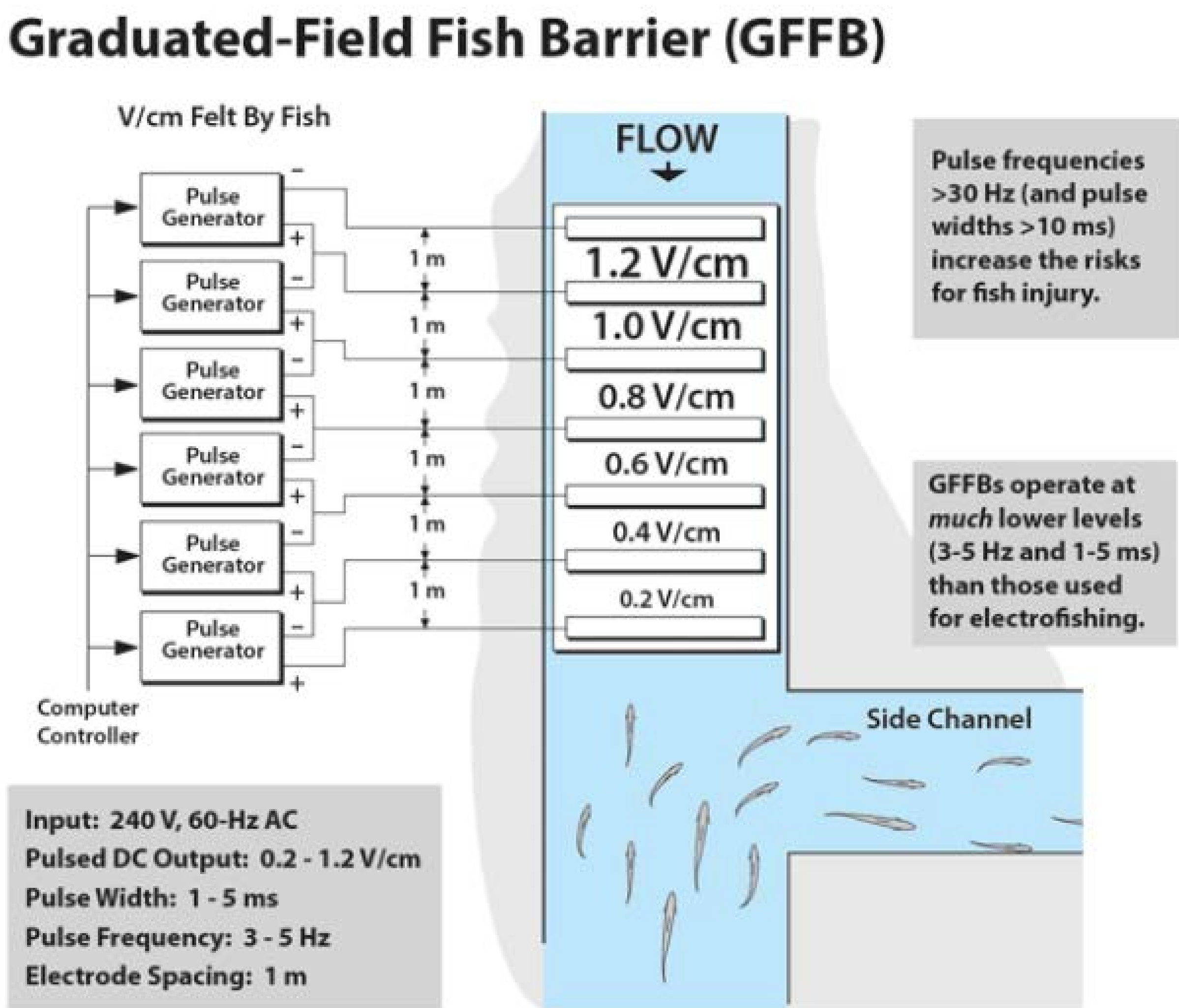

Figure 4. Conceptual Drawing showing specifications and graduated-field technology used to guide fish away from unintended areas. [6]

Pulse Cathodic Protection

Pulse direct current technology has been used on well casings for CP since the late 1960's. However, it recently been applied on reinforced concrete to protect the reinforcing steel from corrosion [26-27]. A method has been developed to cathodically protect buried ferrous structures, such as well casings and pipelines [28-29]. Similar to traditional constant DC impressed current cathodic protection systems, a cable is attached to the structure and another one is attached to the anode and then connected to terminals in the power source. DC voltage is applied across the terminals to cause current to flow to the anode providing electrons at the structure surface effectively inhibiting corrosion. With a pulse system the voltage is only applied periodically.

A typical constant DC cathodic protection system offers good protection but only for a limited area along the structure to be protected [28-29]. Increasing the amount of current supplied by increasing the voltage, will increase the amount of protected area [28-29]. However, the average current must be low enough such that an excess of hydrogen gas is not generated at the structure damaging the coating that may be present. A pulsed DC voltage source provides a much greater coverage and greater redistribution of the current along the structure due to the inductive and capacitive reactance of the anode and structure system [28-29].

The concrete resistivity and applied current density are important for the proper distribution of electrical current in a reinforced concrete. CP current causes alterations in the bulk concrete and pore space, which leads to micro-cracking [27]. That along with softening of the C-S-H leads to decreased concrete durability [27]. The largest problem in terms of concrete microstructure is enlarging the gap between cement paste and aggregate in the interfacial transition zones [27]. Conventional steady state DC current increases the likelihood of modifications of the structure both in the bulk (reducing porosity) and in the interfacial transition zone significantly [27]. In the case of reinforcement in concrete, DC pulse cathodic protection achieves adequate protection of the steel, but is less detrimental to the concrete microstructure and beneficial for ion transport mechanisms and electrical properties [27]. In addition, pulse CP is a cost-effective technique for corrosion prevention and protection, due to better performance of CP protected reinforced concrete structures [27].

Case Study

Chicago Ship and Sanitary Canal Barrier System

The largest system of electric fish barriers is located in the Chicago Ship and Sanitary Canal to prevent the migration of Asian carp from the Mississippi River into the Great Lakes. This system, operated by the US Army Corps of Engineers, contains three active barriers and a demonstration barrier as shown in Figure 5.

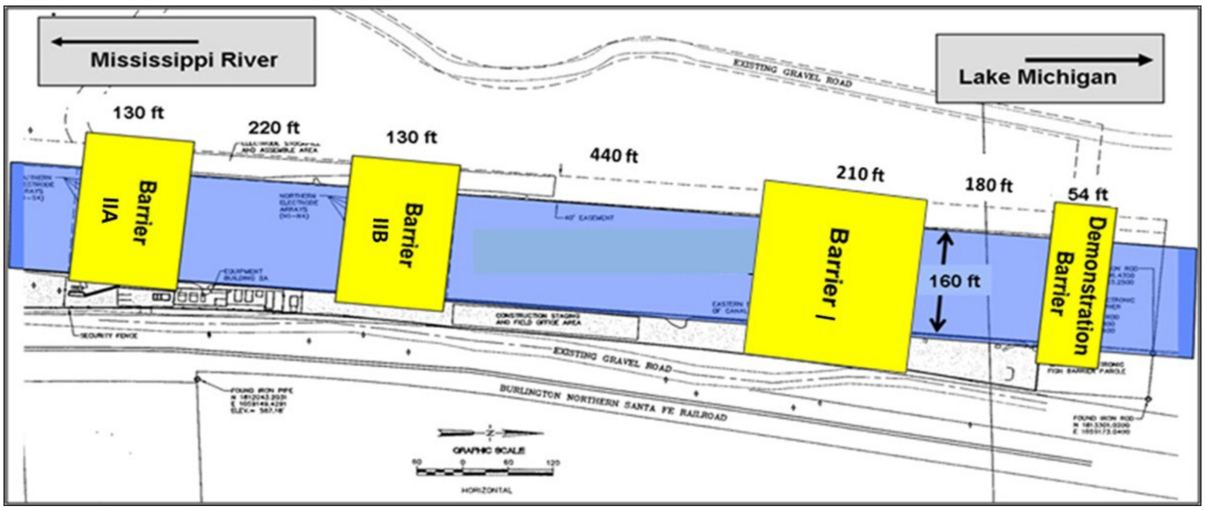

Figure 5. **US Army Corps of Engineers electric fish barrier set-up at the Chicago Ship and Sanitary Canal. [30]**

The demonstration barrier proved effective in preventing movement of large common carp but operation and monitoring identified needed improvements in system design and longevity [19]. Figure 6 shows a schematic of the design of the demonstration fish barrier. Additional augmented barrier technologies required to maximize the effectiveness of the electric fish barrier on more fish species and sizes. The demonstration barrier was not effective on smaller carp. The steel cable electrodes were determined to have a useful lifetime of only 3-5 years due to corrosion [19]. Significant maintenance and cost would be associated with a barrier of this design making it ineffective over the long term.

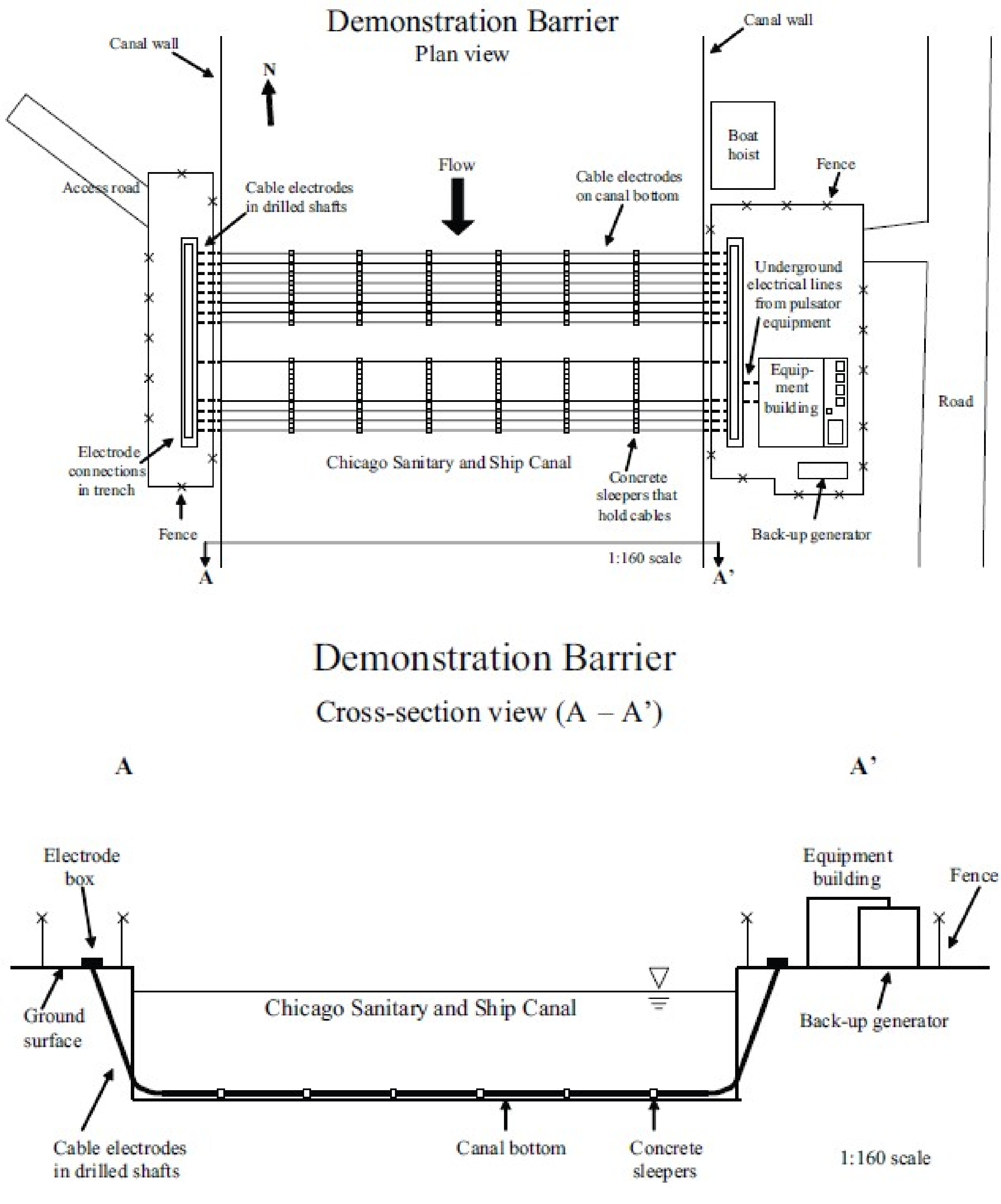

Figure 6. **Schematic plan view and cross-section view of Chicago Sanitary and Ship Canal demonstration electric fish barrier. [19]**

Barrier II is almost completely effective in preventing passage of the juvenile carp with the exception of one juvenile Asian carp found on the other side of the barrier in 2009 [30]. An illustration of Barrier II is shown in Figure 7. The conductivity of the water in the canal typically averages around 981 µS/cm and these barriers are the most effective in water conductivities of 100 µS/cm to 4000 µS/cm [25]. In order to combat the corrosion issue and increase the longevity of the system all of the electrodes are solid steel billets to extend service life to approximately 20 years [19]. The augmentations implemented not only increased the life of the barrier system but also is capable of creating a higher voltage electric field than the demonstration barrier. [18].

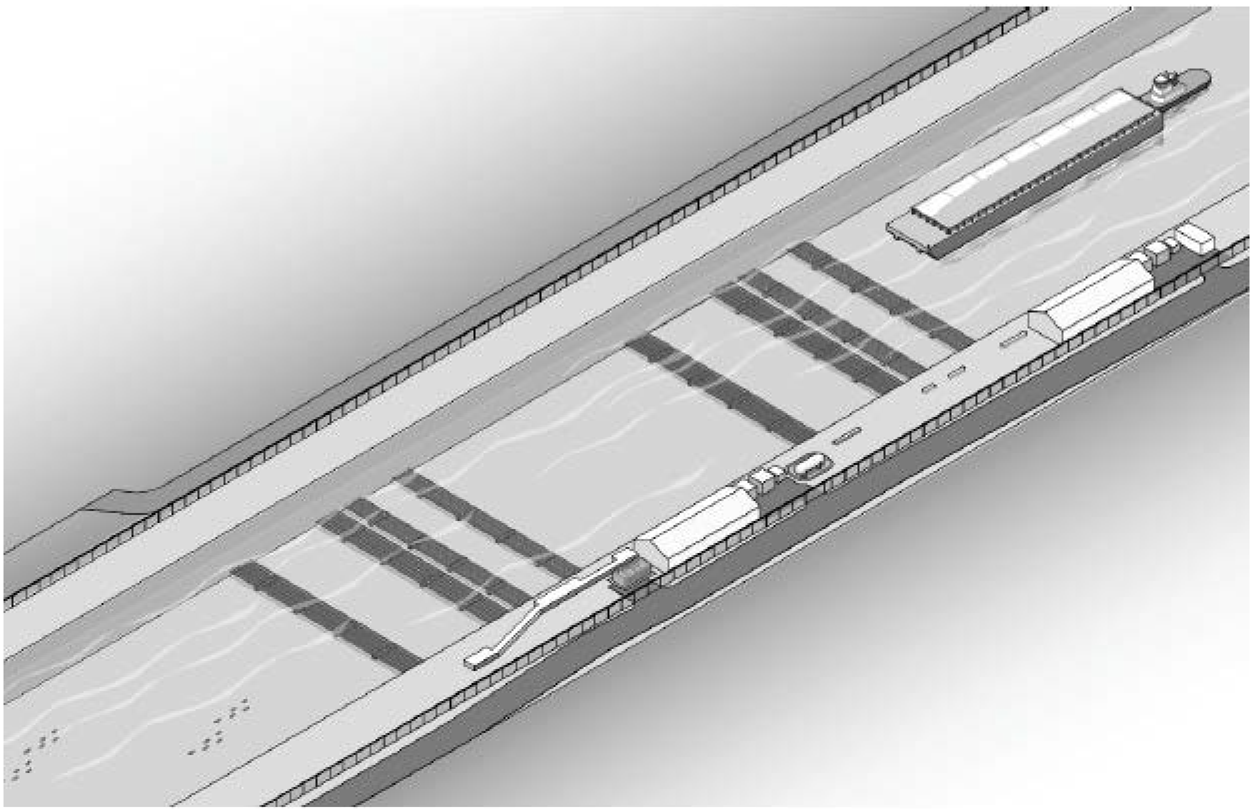

Figure 7. Illustration of Barrier II showing electrodes and control houses. Flow is right to left. [19]

However, various problems with the operation and design of the barriers were perceived and are listed below along with the planned solutions determined in 2013 [24]:

- At times when Barriers IIA and IIB operate simultaneously, the traffic signal at the railroad crossing on Old Romeo Road (the road parallel to the barriers) has malfunctioned [24]. To fix the issue USACE planned to prevent overlap of pulses from the barriers and perform upgrades and operational changes to the signal [24].

- There is some concern over a pipeline in the vicinity however; preliminary in-line inspections have shown no deleterious impact on the pipeline due to the electric barriers. Installation of new test stations to monitor corrosion rate and potential along the pipeline is planned [24].

- Imperceptible readings for electricity have been measured on some of the fences near the barriers and are currently being monitored however; the electrical readings measured are deemed not to be unsafe [24]. If monitoring determines mitigation methods are required, one option is replacing the metal fencing with non-conductive fencing [24].

Current monitoring of the electrical potential and corrosion of many structures nearby has determined thus far, no detrimental electrical potential or heightened corrosion has been reported [24].

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