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Water for a Warming Climate:

A Feasibility Study of Repurposing Diablo Canyon Nuclear Plant for Desalination

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A Feasibility Study of Repurposing Diablo Canyon Nuclear Power Plant for Desalination

An MIT Technical Report

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Executive Summary

We consider the techno-economic feasibility of constructing a large-scale reverse osmosis desalination plant at the Diablo Canyon Nuclear Power Plant (DCNPP). This arrangement integrates the desalination plant with the nuclear power plant by sharing infrastructure and receiving feedwater and power from the nuclear power plant, forming a water-power coproduction system.

A key challenge for continued operation of DCNPP and for any desalination plant is compliance with California's regulations protecting marine organisms from large intake structures. We show how a new brushed-screen intake structure, serving both the nuclear power plant and the desalination plant, achieves compliance. Our understanding is that there are no other technical obstacles to DCNPP's license extension. The cost of the new intake is reflected in the cost of power. In our design, warm condenser water from the nuclear power plant flows into the desalination plant, which consists of a pretreatment system similar to that of the existing small-scale desalination plant at Diablo Canyon, followed by a partial two-pass reverse osmosis system and remineralization. Depending on the scale of the plant, either the discharged brine from the desalination system may be commingled and diluted with the excess cooling water, using the existing plant outfall, or a new advanced high-energy diffuser system may be required.

The focus of our analysis is a hypothetical plant of the same size as the existing plant in Carlsbad, CA, but we also include additional analyses of significantly larger plants. When we consider the cost of desalinated water from this arrangement, compared to other desalination plants in California, we find that there are significant economic advantages for a DCNPP-desalination coproduction plant. At smaller scales, savings result primarily from reduced power costs and the sharing of the new intake and existing outfall structures. At larger plant capacities, there is potential for additional cost savings from economies of scale. However, at larger capacities, other challenges arise, including increased infrastructure needs, especially around the plant outfall, as well as practical challenges in siting and building a very large plant on the DCNPP premises.

Key findings of this study include:

- The cost of electricity paid by the desalination plant is expected to be 5.4 cents per kWh, a significant reduction from the price of power purchased from the grid.
- The levelized cost of water falls in a range from \$0.77 to \$0.98 per m^3 of fresh water at the plant outlet, with distribution costs adding an additional \$0.02 to \$0.21 per m^3 to transport the water an additional 20-185 km to offtakers. For comparison, the cost to build additional Carlsbad-sized plants in California as stand-alone desalination plants is approximately \$1.84 per m^3 of fresh water at the plant outlet.
- Additional key data are shown in Table 1.

Table 1. Table of key results from technoeconomic analysis.

	Large-scale at Diablo	Mega-scale at Diablo	Carlsbad Estimated
Capacity (m^3/d)	**189,270**	**4,752,000**	**189,270**
Capacity (AFY)	**56,000**	**1,406,000**	**56,000**
Total Capex (Million $)	599	11,571	1,235
Energy consumption (kWh/m^3)	3.5	3.5	3.5
Electricity price ($/kWh)	$0.054	$0.054	$0.139
Water cost breakdown ($/$m^3$)			
Capital costs and amortization	$0.53	$0.41	$1.10
Operating costs (excluding energy)	$0.26	$0.19	$0.26
Energy costs	$0.19	$0.19	$0.49
Water price at plant outlet ($/$m^3$)	**$0.98**	**$0.79**	**$1.84**
Water price at plant outlet ($/AF)	**$1,207**	**$978**	**$2,269**

In light of these findings, we believe that building a desalination plant at Diablo Canyon is feasible. The scope of our analysis has been limited to techno-economic feasibility, but of course myriad additional factors should be considered. Consequently, we do not claim that a desalination plant at DCNPP is the preferred solution for water needs of the California Central Coast or for wider parts of the state.

Acknowledgements

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Contents

Scope and purpose

The purpose of this report is to explore the technical feasibility, cost, and economic benefits of utilizing Diablo Canyon Nuclear Power Plant (DCNPP) as an energy and feedwater source for a collocated reverse osmosis (RO) seawater desalination plant that would supply potable water to the state of California.

Nuclear power, seawater desalination, and the use of the lands on which DCNPP sits are all contentious issues in the state of California. This report is not intended to present a policy recommendation or endorsement of any particular course of action. We leave that work to the elected and appointed representatives of the people of California. This report is intended as an investigation of the technical and financial feasibility of one approach to repurposing DCNPP if it continues to operate beyond its current license.

Context and reason for study

The water crisis in California

California has a pressing need for additional sustainable fresh water supplies. Historically, California's network of water storage, rivers, and large infrastructure have allowed surface water supplies to meet the needs of those in central and southern California. However, due to increased demand for water and changes in fresh water supply, exacerbated by climate change, unsustainable groundwater pumping has become much more common [1,2]. In many groundwater basins, increased pumping is leading to rapidly deteriorating groundwater supplies [3–6]. In response, the State of California enacted the Sustainable Groundwater Management Act (SGMA) in 2014 [7]. This legislation requires critically over-drafted groundwater basins to achieve sustainability by 2040.

As an example of the challenge faced by different localities in Central California, Cuyama Basin is a critically over-drafted basin that is just under 100 miles away from DCNPP. In their most recent Groundwater Sustainability Plan [8], the Cuyama Basin Groundwater Sustainability Agency found that a pumping reduction of 135,000 m^3/day (40,000 acre-feet per year) would be required to reach sustainable pumping levels. The Cuyama Basin Groundwater Sustainability Plan proposes to enhance water supply through rainfall enhancement (cloud seeding) and stormwater recharge. However, this would only account for a fraction of the deficit. The current plan envisions pumping reductions of 50-67% from current levels in order to reach sustainable limits by 2038.

The challenges in Cuyama Basin are not unique. Groundwater basins all over California face re-evaluation of different approaches to achieve sustainable water withdrawal levels. Efficiency projects, infrastructure improvements, or shifting to more water-efficient crops can help to reduce demand. Direct or indirect potable reuse, water transfers, and rainwater capture can help to increase supply. Integrated water management across a diverse portfolio of projects and technologies will be required to bring California’s water usage to sustainable levels. Still, on a case-by-case basis, only some of these options may be possible, economical, politically palatable, or adaptable to the changing needs of the population and the planet.

Table 2. Summary of sustainability actions proposed by the Cuyama Basin Groundwater Sustainability Plan compared to desalinated water from Diablo Canyon. Diablo Canyon water cost includes distribution.

Project	Flow rate m^3/day (AFY)	Estimated cost $/m3 ($/AFY)	Note
Rainfall enhancement (cloud seeding)	13,500 (4,000)	$0.50-0.65 ($600-800)	
Stormwater recharge	13,5000 (4,000)	$0.016-0.025 ($20-30)	Water/land rights is a challenge
Water supply transfers or exchanges	-	$0.50-2.3 ($600-2,800)	Exchange w/ downstream users, facilitating stormwater recharge
Pumping reductions	-	-	Requires up to 67% reduction
Required reduction	135,000 (40,000)		
Diablo desalination plant	135,000+ (40,000+)	$1.17 ($1443)	Drought-proof

In 2019, Californian Governor Gavin Newsom issued an Executive Order directing state agencies to develop recommendations to ensure water security for all Californians. This came in response to challenges of droughts, floods, rising temperatures, over-drafted groundwater basins, aging infrastructure, and other water challenges, all amplified by climate change. The resulting report, the 2020 Water Resilience Portfolio [9], encourages the consideration of desalination as a means to supply water where it is cost effective and environmentally appropriate.

The potential desalination solution

For locations near the ocean, one means of increasing water supply is seawater desalination, a drought-proof source of water that could help Cuyama Basin and the surrounding areas to manage their groundwater sustainably without requiring extensive reductions in water use. Although the Water Resilience Portfolio explicitly encourages the consideration of desalination, developing and building desalination plants in California is a contentious issue in practice. There are challenging environmental regulations, a difficult permitting process, and many community and special interest organizations that passionately argue for or against the development of desalination projects. All of these factors can make it difficult, time consuming, and costly for new plants to be permitted and constructed.

Despite the challenges of developing desalination projects in California, desalination also offers some unique benefits compared to other means of addressing the water crisis. Desalination is a drought-proof source of water with an inexhaustible supply of feedwater. Regardless of the season or weather, a desalination plant can reliably produce a nearly constant supply of high-quality fresh water. Seawater desalination does not reduce the amount of fresh water available to local ecosystems, fish, other organisms, and the environment at large. When using reverse osmosis, as is proposed in this analysis, all the energy used is electrical energy, meaning that with carbon-free electrical power sources, the water produced by desalination would have a minimal carbon footprint.

Seawater desalination is most commonly performed by forcing water through a semipermeable membrane that blocks the passage of salt, as in reverse osmosis (RO). Evaporation of seawater, with capture of the pure condensate, is also used, as in multi-effect distillation. Seawater desalination is already practiced in California, most notably at the Claude "Bud" Lewis Carlsbad Desalination Plant in Carlsbad, California. This RO plant has a capacity of approximately 190,000 m^3/day and has been operating since 2015. Two other large desalination projects are being developed in California at Huntington Beach and Camp Pendleton [10]. There are also a number of other smaller desalination plants in operation in California, including a plant at DCNPP, which provides water for fire and dust suppression, makeup water for the nuclear reactors, and potable water for human consumption and use.

In many places around the world with limited water resources, desalination has become even more prevalent. Seawater desalination is ubiquitous in the Middle East and North Africa (MENA) region, which contains approximately half of the total global seawater desalination capacity. In this region, Kuwait is an extreme example, with seawater desalination providing nearly all the country's fresh water [11]. Singapore, another country with limited natural water resources, has turned to a combined strategy that employs water recycling, desalination, and rainwater capture to help reduce water imports from outside the country. Singapore aims to be water independent by 2060, with desalination expected to meet up to 30% of water needs [12].

The central requirement of energy for desalination

Seawater desalination has the potential to produce massive amounts of water to augment existing water resources, but desalination is also inherently energy intensive. Thermodynamic limitations mean that pure water cannot be separated from seawater with less than 0.71 kWh of energy per m^3 of fresh water [13]. As fresh water is removed from a given volume of seawater, and the remaining saltwater becomes more concentrated with salts, the energy required to extract more freshwater steadily increases. Seawater reverse osmosis plants typically operate at a recovery ratio of approximately 40-50% (meaning they recover 40-50% of the incoming feedwater as fresh product water, while 50-60% of the feedwater is turned into concentrated brine, which is disposed of). At this recovery ratio, a perfectly efficient, thermodynamically reversible plant would still consume around 1.1 kWh/m^3 [14]. Most new plants, with advanced pressure recovery and highly efficient membranes require 3-4 kWh/m^3. This energy consumption includes all elements of the desalination plant, such as intake pumps, pretreatment, the actual reverse osmosis system itself, post-treatment, and other plant operations. Additional energy is required for distribution. Distribution energy can become very significant when water is moved over large distances, such as in California's vast network of aqueducts and channels. These energy consumption numbers are put into context in Table 3.

Because of the energy intensity, desalination is generally more expensive than freshwater sources. Approximately 25-50% of the total cost of water from new RO plants is attributable to electricity [11]. There are several other mature desalination technologies that could be considered for a desalination plant at Diablo Canyon, but we focus on seawater RO in this analysis, as RO is the most commonly installed desalination technology today due to its relatively low cost compared to other large-scale desalination technologies.

Table 3. Energy consumption of water transfer and water treatment processes

Name of water transfer project	Length (km)	Energy consumed (kWh/m^3)	Energy use per unit distance (kWh/m^3 km)	Reference
West Branch Aqueduct, CA	502	2.07	0.004	[15]
Coastal Branch Aqueduct, CA	457	2.31	0.005	[15]
Transfer from Colorado River to Los Angeles, CA	389	1.6	0.004	[15]
Water treatment process (excluding pretreatment, post-treatment, etc.)	**Energy consumed (kWh/m^3)**			**Reference**
Conventional treatment of surface water	0.2–0.4			[16]
Water reclamation	0.5–1.0			[16]
Indirect potable reuse	1.5–2.0			[16]
Brackish water desalination	1.0–1.5			[16]
Desalination of Pacific Ocean water	2.5–4.0			[16]

The planned closure of Diablo Canyon

The Diablo Canyon Nuclear Power Plant

The Diablo Canyon Nuclear Power Plant comprises two identical units (Westinghouse 4-loop pressurized water reactor design) with a combined power output of 2240 MW_e. DCNPP is located near Avila Beach on the Central Coast of California, and is owned and operated by Pacific Gas and Electric (PG&E). The facility directly employs some 1,500 workers with an annual payroll of about $226 million. The facility pays an estimated $26.5 million in state and local taxes annually. DCNPP started commercial operations in the mid-1980s. Its Nuclear Regulatory Commission (NRC) licenses are set to expire in 2024 (Unit 1) and 2025 (Unit 2). Both units are currently in the so-called Column 1 of the NRC Action Matrix, i.e., there are no ongoing nuclear regulatory issues. Each unit runs nearly continuously, except for an outage of 2-4 weeks every 18 months during which the reactor is shut down for refueling and maintenance. The 3-year-average capacity factor for DCNPP is about 90%. The DCNPP generation cost is about 40 $/MWh (including fuel, O&M, and Capex) [17–20], thus we estimate that the plant is an economically viable electricity generator in the CA market at the present time.

Diablo Canyon Nuclear Power Plant NRC license renewal

In November 2009 PG&E applied to the NRC for a 20-year license extension of DCNPP beyond its initial expiration date of 2024-2025. The review was prolonged by post-Fukushima regulatory changes and by specific concerns about the seismic risk of DCNPP, both of which were resolved. Separately, in order to continue operating the plant, PG&E would have to make a significant investment to bring it into compliance with California water cooling regulations. The license renewal process was ultimately interrupted by the 2016 decision to close the plant. PG&E formally withdrew the application in March 2018.

Nearly all nuclear power plants in the US have obtained a 20-year license renewal from the NRC. The NRC staff conducts reviews in less than 22 months, from receipt of an application to a decision on license renewal (longer if there was an adjudicatory hearing) [21]. If resumed, review of the DCNPP license renewal might very well be even shorter because a large fraction of the review was already performed in 2009-2018. We note that if at the expiration of its current license the NRC is still reviewing the application, the plant can continue to operate until the NRC completes its review.

One question about DCNPP's license extension is related to seismic risk. The plant is sited in a generally high-seismic-risk area (most of California is very seismic), and also there is a fault line that runs near the plant. Of course, DCNPP was designed and licensed for this particular site. After the Fukushima accident in 2011 all nuclear power plants in the U.S., including DCNPP, were asked to re-evaluate their seismic and flooding risks. We reviewed the latest NRC documentation on DCNPP's seismic risk, which is summarized in a very recent NRC letter [22]. The letter states that the NRC has concluded that PG&E demonstrated the plant's capacity to withstand seismic hazards re-evaluated after Fukushima. No further actions have been required by the NRC.

In summary, we anticipate that there will be no nuclear regulatory or safety impediments to continuation of DCNPP operation beyond 2024-2025. The impending shutdown of Diablo Canyon, then, is driven mainly by policies regarding once-through cooling for power plants.

The California Water Quality Control Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling [23] is designed to protect marine organisms from power plant intakes. In order to comply with the legislation, power plants must either reduce their cooling water intake by 93% compared to the designed flow rate or implement other operational or structural changes to reduce impingement and entrainment mortality to a comparable level. In 2011, PG&E commissioned a study by Bechtel to investigate options that would bring DCNPP into compliance with this legislation [24]. Bechtel examined a number of options, including forced and passive wet and dry air cooling, which would have reduced the water intake of the plant, and two types of screened intakes, which would not have reduced water flow but would have reduced impingement and entrainment mortality. PG&E chose not to move forward with any of the options examined at the time. If this challenge can be overcome economically, the power plant can continue to produce low-carbon power for years to come. The plant has a significant useful life remaining, and DCNPP may be able to be repurposed to provide immense value for the people of California.

The central question

The central question of this report is this: considering the regulatory, environmental, and economic constraints, could the continued operation of DCNPP provide additional value to the people of California, beyond the grid services already provided? Specifically, could the combined operation of a large-scale desalination plant with the existing nuclear power plant provide fresh water to Californians more economically than other desalination alternatives? If so, where might that fresh water be used?

Aside from seawater desalination, there are a number of other ways that DCNPP could provide additional value, including by generating hydrogen [25]. The scope of this report, though, focuses exclusively on repurposing DCNPP to provide some combination of power and water to the people of California. We understand that decisions regarding which types of power and water resources to invest in are complex, contain myriad value judgments, and involve a large number of stakeholders with a wide variety of interests. The political aspects of building a large-scale desalination plant at Diablo Canyon are outside the scope of this report. Instead, what we detail in this report is, if Californians determine that building large-scale desalination plants is in their interest as a part of a long-term water security strategy, then building a large-scale desalination plant at Diablo Canyon, powered by nuclear power from Diablo Canyon Nuclear Power Plant may have economic advantages over other seawater desalination alternatives in the state. Throughout this report, we compare the costs and benefits of building a desalination plant at Diablo Canyon to any other hypothetical large-scale plant built in California, and also investigate the potential need for desalinated water in areas that fresh water could be transported to. While we have identified several potential water offtakers in this report, none have demonstrated serious interest in building this plant. This report may serve as an initial feasibility study for potential offtakers considering desalination as a part of their water portfolios. A more in-depth analysis of potential offtakers and a description of their water needs can be found in the Clean Air Task Force report on Diablo Canyon [26].

Diablo desalination project as a water source

Core desalination project concept

We begin our analysis by discussing the basics of reverse osmosis, as well as the basic operation of DCNPP. The power plant's electrical and cooling water output bound what is possible in terms of the size and scope of a hypothetical desalination plant co-located with the power plant. A co-located desalination plant will be powered directly by DCNPP, thus reducing charges for electricity transmission and distribution, and allowing for the plants to use a shared seawater intake and outfall. Next, we propose several different configurations for the hypothetical desalination plant, and then go into more depth to determine the requirements of each proposed configuration. The projected costs of building such projects are discussed in later sections.

Basic RO system description

Reverse osmosis is the most commonly used technology for seawater desalination today. At the core of these systems are semi-permeable membranes, which allow water to pass through while rejecting nearly everything else contained in seawater. Feedwater enters RO plants from large seawater intakes, is pretreated with filters or membranes to remove large particles, silt, bacteria, and other constituents, and can be treated with chemicals to adjust the feedwater chemistry. Next, the water is pumped to high hydraulic pressures, which allow water to permeate through the RO membranes against an osmotic pressure difference across the membrane, separating the feedwater into product water and concentrated brine.

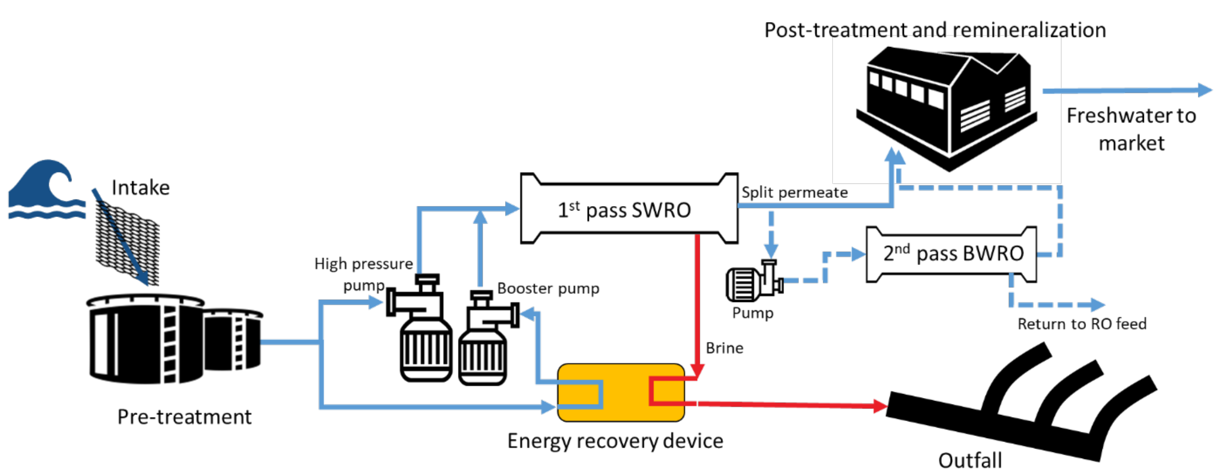

Figure 1. Diagram of a basic two-pass reverse osmosis system.

The fresh water is further treated to ensure that it is disinfected, and minerals are often added back into the fresh water for taste and to ensure that the water does not corrode pipes. The fresh water is then distributed to end-use points. The brine passes through energy recovery devices (ERD's) so that the hydraulic pressure in the waste stream can be recycled within the system, saving energy. The brine is then pumped back to the ocean, where it is discharged. Approximately 65-80% of the total energy used in the desalination plant is consumed by the RO system, with the remainder being used in the intake, outfall, pretreatment, post-treatment, and other facilities [16].

Diablo Canyon Nuclear Power Plant conditions relevant to desalination

The Diablo Canyon Nuclear Power Plant uses a once-through cooling system to condense the steam entering the main condenser of the power plant, as well as to provide cooling to a number of other systems. At full load, the design temperature increase of the cooling water is 10°C above the ambient seawater temperature, and the cooling water flow rate is 110 m^3/s (2.5 billion gpd) [27]. At present, the power plant's open ocean intake is screened with bar racks (9.5 mm bars at 86 mm centers) (3/8-inch bars at 3-3/8-inch centers) and traveling mesh screens (9.5 mm square openings) (3/8-inch square openings) to prevent debris and large biota from entering DCNPP. Sodium hypochlorite is added as needed to help control micro and macro fouling in the intake tunnels, piping, and the condenser tubes [27]. It is assumed that no other pretreatment is performed at present. Historical intake and discharge temperatures from the power plant, as well as cooling water flow rates, are shown in Figure 2 [28]. The salinity of the cooling water is assumed to be between 33 and 34 g/kg (~33,500 ppm) [29]. A summary of DCNPP effluent conditions, and therefore potential desalination plant intake conditions, are shown in Table 4.

Table 4. Summary of DCNPP effluent conditions

	Value	Unit
Temperature	18-27 (65-80)	°C (°F)
Salinity	33.5	g/kg
Flow rate	110 (9.45 million)	m^3/s (m^3/d)
Pretreatment	Screening and chlorination	

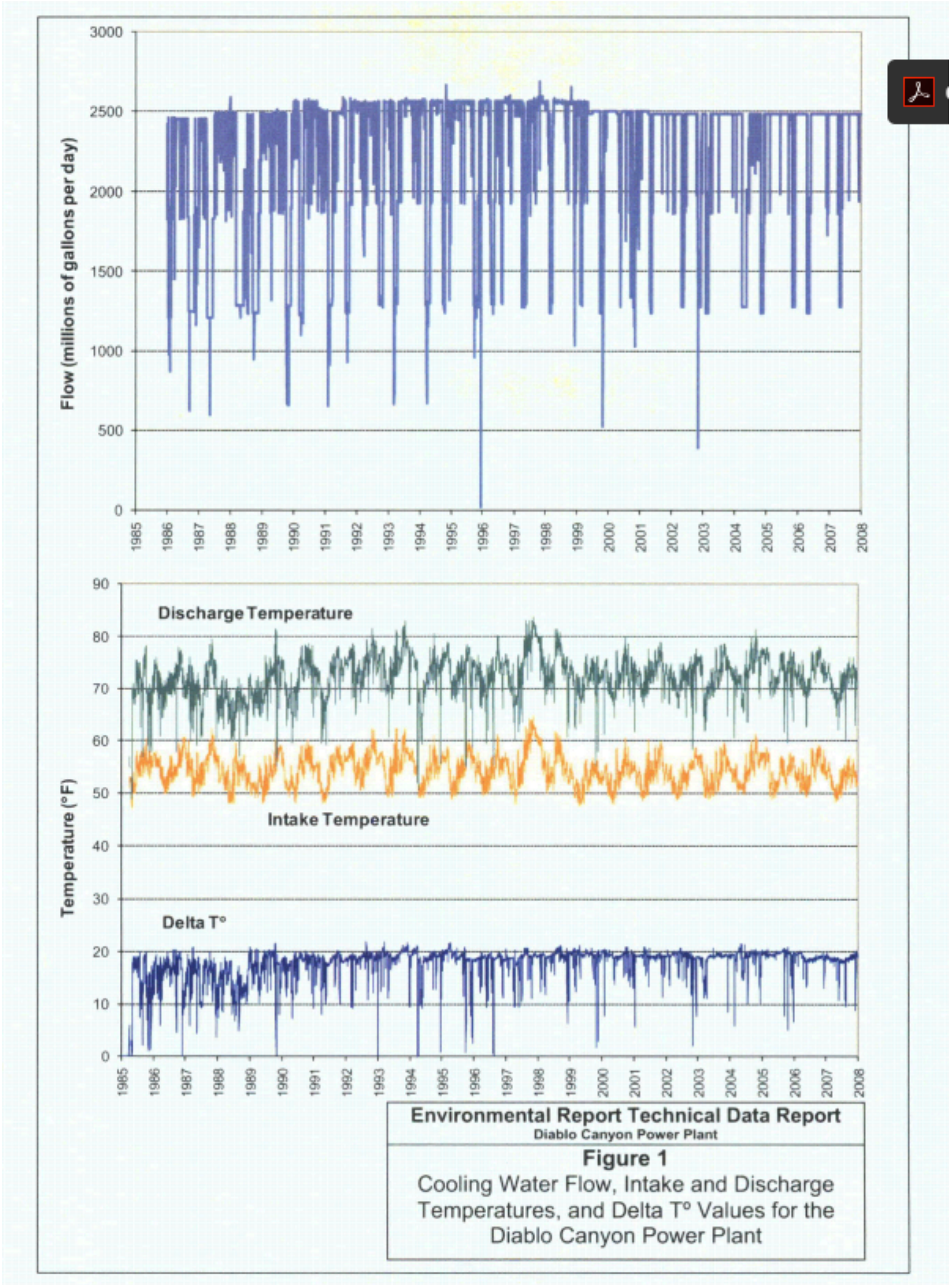

Figure 2. Cooling water flow, intake and discharge temperatures for DCNPP [28].

Plant configuration

A seawater reverse osmosis desalination plant could be configured in many different ways at the Diablo Canyon Nuclear Power Plant. Various arrangements can be implemented to meet different water or electricity needs, to respond to temporally variable water and electricity needs, and to achieve compliance with applicable environmental regulations. Four options are investigated in this report to provide a basic understanding of the wide range of possibilities, and to understand how changing some of the key parameters of the hypothetical desalination plant will change outcomes. These options represent a broad range of possibilities, but they by no means cover the entire space of what is possible at Diablo Canyon. The four options are discussed in order of volume of water output and are illustrated in the accompanying figures. Key values are given in Table 5 and 6.

Table 5. Key boundary values for various desalination plant options.

	No desal	**Option 1: Diablo Desalination Plant**
Outfall temperature	Ocean + 10°C	Ocean + 10°C
Outfall salinity	35,000 ppm	36,700 ppm
Outfall flow rate	110 m^3/s	105 m^3/s
	9,504,000 m^3/d	9,314,730 m^3/d
	2,814,000 ac-ft/y	2,758,155 ac-ft/y
Intake flow rate	110 m^3/s	110 m^3/s
Product flow rate	N/A	2.19 m^3/s
		189,270 m^3/d
		55,845 ac-ft/y
Electricity produced	2240 MW	2240 MW
Electricity to grid	2240 MW	2212 MW

As a high-level, first-order estimate, we assume that all desalination plants will have a specific energy consumption of 3.5 kWh/m^3 (energy consumed per volume of purified product water), and a recovery ratio of 50% (fraction of salty feedwater turned into pure product water). These parameters will fluctuate depending on detailed designs in practice. The current configuration, consisting of only energy production, is shown in Figure 3.

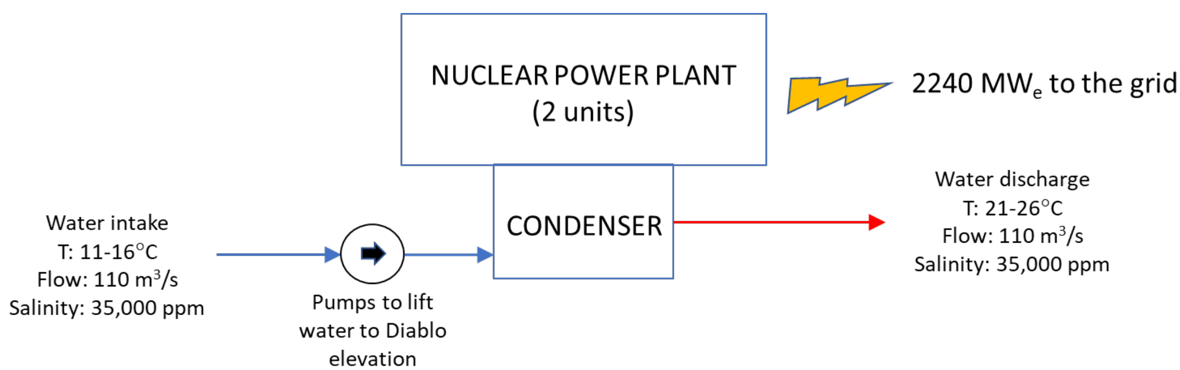

Figure 3. Current conditions at Diablo Canyon Nuclear Power Plant

Option 1: Large-scale desalination plant similar to existing plants

The smallest option we consider in this report is still a large-scale desalination plant, with a capacity of 189,270 m^3/d. This is also the nameplate capacity of the Carlsbad Desalination Plant, and approximately the same size as the proposed plant at Huntington Beach. There are a number of interesting benefits of building at this scale, which will become clearer throughout the report. These include lower salinity brines, after the desalination brine is mixed with the power plant cooling water, which would obviate the need for high-energy diffuser outfalls and allow for the existing outfall infrastructure to remain in place. In this configuration, the electrical requirement of the desalination plant is very small compared to the size of the nuclear power plant.

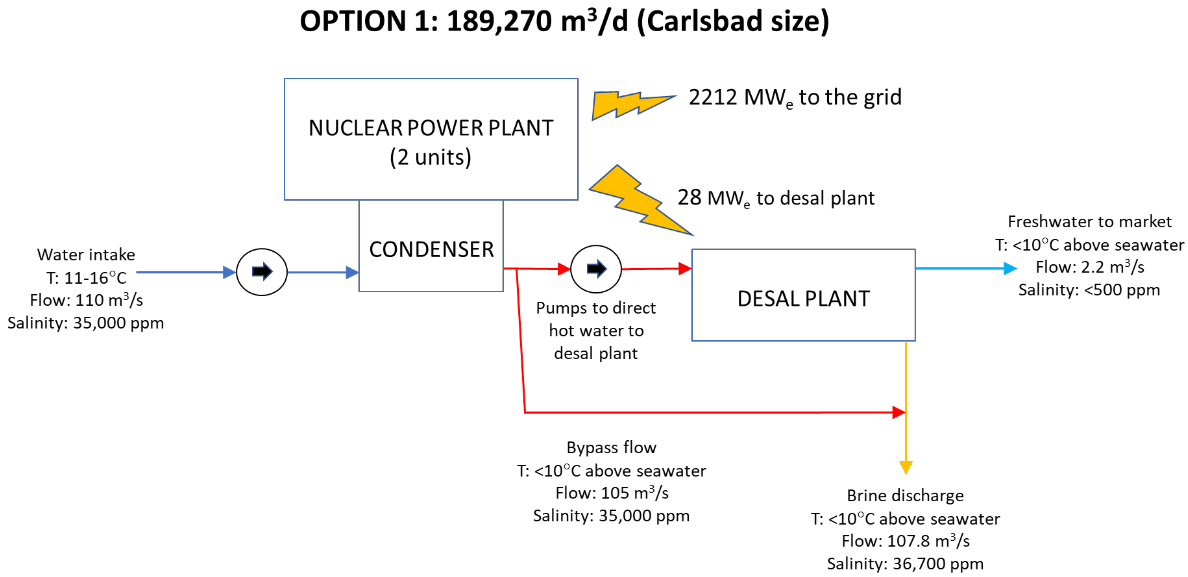

Figure 4. Configuration with a desalination plant with a capacity equal to the Carlsbad Desalination Plant.

Alternative "Mega-size" Configurations

The seawater intake and the electricity production at the Diablo Canyon Nuclear Power Plant could be used to support a much larger desalination plant than the option presented above. Such "mega-sized" plants would be an order of magnitude larger than today's largest desalination plants. Building such large plants poses a significant challenge and would certainly have to be done in stages to accommodate practical limitations (e.g. financing, membrane production capacity). We consider three options to provide a basic understanding of the wide range of possibilities.

Table 6. Alternative mega-sized desalination plants considered as "what-if" scenarios.

	Option 2	**Option 3**	**Option 4**
Outfall temperature	Ocean + 10°C	Ocean + 10°C	Ocean + 3°C
Outfall salinity	46,800 ppm	70,000 ppm	70,000 ppm
Outfall flow rate	82 m^3/s	55 m^3/s	178 m^3/s
	7,084,800 m^3/d	4,752,000 m^3/d	15,379,200 m^3/d
	2,098,000 ac-ft/y	1,407,000 ac-ft/y	4,554,000 ac-ft/y
Intake flow rate	110 m^3/s	110 m^3/s	356 m^3/s
Product flow rate	28 m^3/s	55 m^3/s	178 m^3/s
	2,419,200 m^3/d	4,752,000 m^3/d	15,379,200 m^3/d
	716,000 ac-ft/y	1,407,000 ac-ft/y	4,554,000 ac-ft/y
Electricity produced	2240 MW	2240 MW	2240 MW
Electricity to grid	1887 MW	1547 MW	0 MW

Option 2 – Using half of cooling water from power plant as feedwater

This configuration is a response to the challenging regulatory environment in California. Rather than using the full output of the condenser as feed to the desalination plant, it reduces product water output in favor of an outfall blending scheme that could help to meet environmental regulations without large investments. In this option, DCNPP operates as normal. The desalination plant takes in half of the condenser cooling water, and the other half is used to dilute the brine discharged from the desalination plant (Figure 5). The dilution of the desalination brine would make it easier to comply with the stringent discharge requirements of the California Ocean Plan. A configuration like Option 2 could also be considered if there is not enough water demand to justify building options with larger capacities. Option 2 may also be an intermediate design on the route to building a larger capacity system, which could be built initially, and scaled over time as needed. This configuration also produces excess power that could be sold to the grid, or used for other purposes.

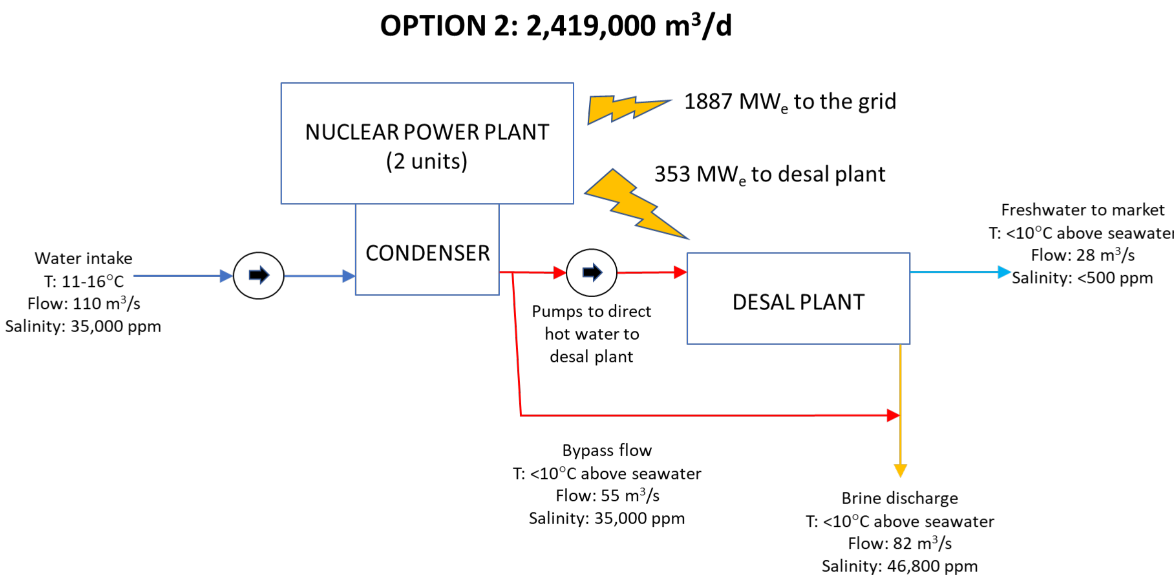

Figure 5. Configuration with half of condenser cooling water being used as desalination feedwater, with the remainder being used to dilute desalination brine.

Option 3 – Use all cooling water from the power plant as desalination feedwater

In this configuration, the power plant would send all its cooling water to be desalinated (Figure 6). In this case, the energy required to desalinate all the cooling water is less than the power produced by the power plant, meaning that there is excess power that can continue to be sold to the grid. This option does not change the amount of water taken in from the ocean. We note that Options 1-3 all would require the same sized ocean intake, in order to provide enough condenser cooling water to DCNPP. This option maximizes the capacity of the desalination plant without increasing the size of the intake infrastructure beyond what would already be required to keep DCNPP operational.

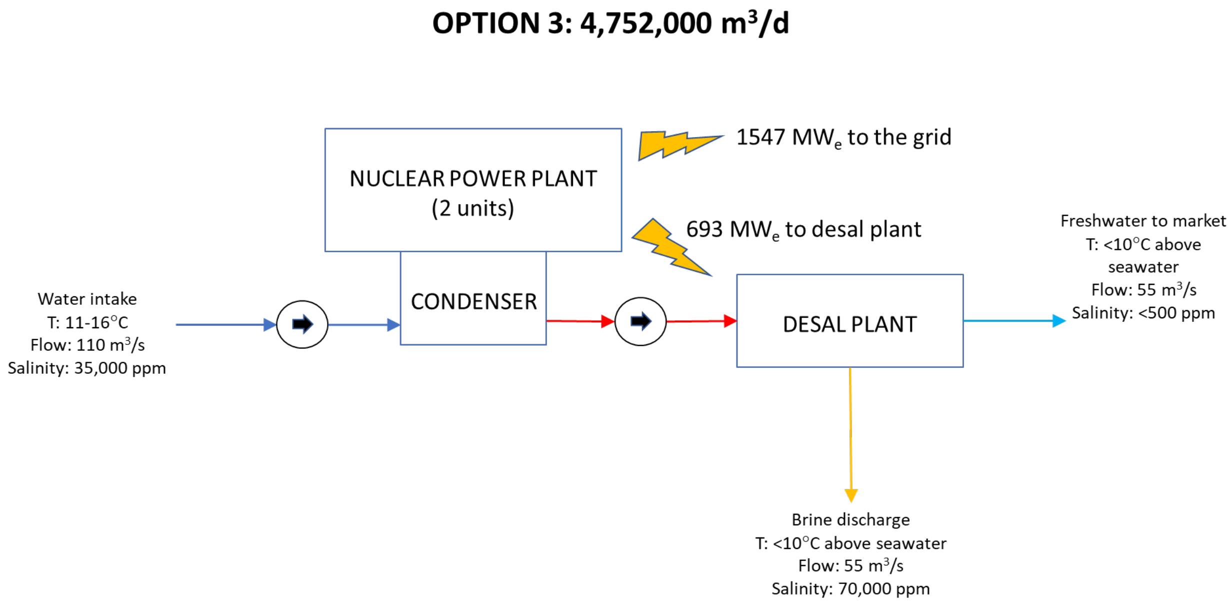

Figure 6. Configuration with all cooling water going to the desalination plant.

Option 4 – Use all electricity from the power plant to produce water

In this configuration, DCNPP is to be completely separated from the California grid. In this case, all of the power, and all of the cooling water is sent to a desalination plant. Because there is excess power beyond what is required to desalinate the cooling water, additional water is drawn from the ocean to be desalinated. This configuration is the largest of the four configurations in terms of water production.

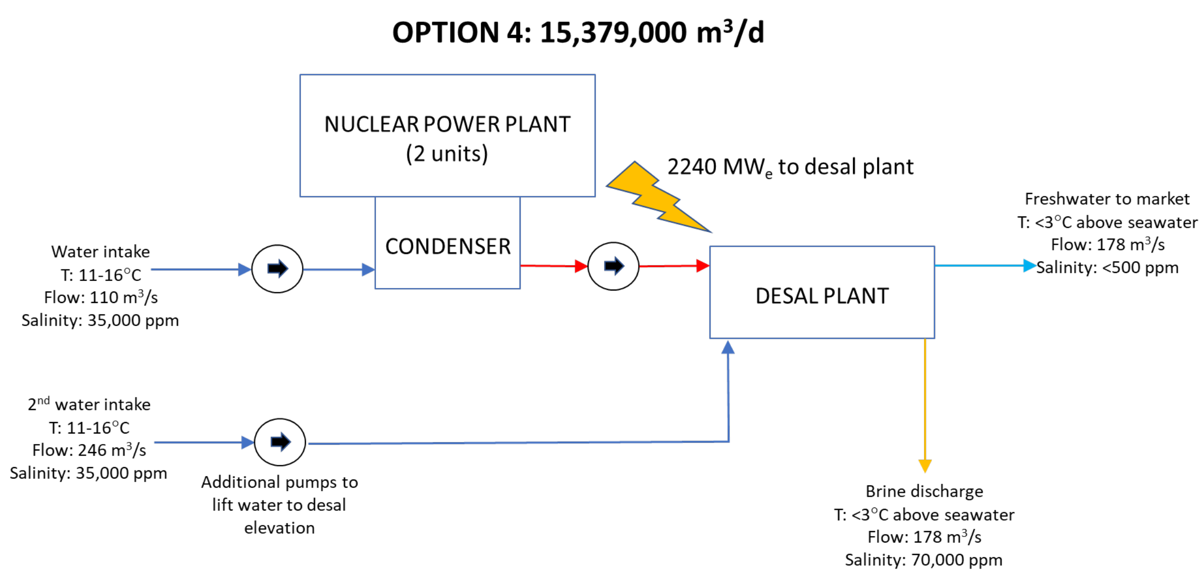

Figure 7. Configuration with all electricity going to the desalination plant, with additional feed water required beyond what is available from existing intake structure.

The enormous capacities of these desalination options are put into perspective in Table 7. We note that Option 3 could produce approximately an order of magnitude more water than the world's largest operating desalination plant. Designing mega-scale plants introduces a number of unique challenges. Such a plant would almost certainly be built in stages, and the first step would be a much smaller desalination plant, one that uses only a small fraction of Diablo Canyon's potential feedwater and power output.

Table 7. Water at a range of scales

	Capacity	Units
Average water consumption of a Californian (2016) [30]	0.32	[m^3/d]
Olympic swimming pool capacity	2500	[m^3]
Aqua Claudia (ancient Roman aqueduct)	184,000	[m^3/d]
Carlsbad desalination plant (largest desal plant in USA) + **Option 1**	**189,270**	**[m^3/d]**
Sorek desalination plant (currently world's largest RO plant) [10]	540,000	[m^3/d]
California Aqueduct Coastal Branch pumping capacity at Las Perillas [31]	1,127,865	[m^3/d]
Diablo Canyon Option 2	**2,419,000**	**[m^3/d]**
Diablo Canyon Option 3	**4,752,000**	**[m^3/d]**
California Aqueduct pumping capacity at Buena Vista [31]	13,223,667	[m^3/d]
Diablo Canyon Option 4	**15,379,000**	**[m^3/d]**
Central Valley Project average annual deliveries to farms	16,800,000	[m^3/d]
California Aqueduct	32,000,000	[m^3/d]
Colorado River at Glen Canyon	47,500,000	[m^3/d]
Average applied water use in California, 1998-2015 [32]	261,000,000	[m^3/d]
Mississippi River	1,550,000,000	[m^3/d]
Amazon River	18,000,000,000	[m^3/d]

Seawater intake

When Bechtel was commissioned to investigate once-through cooling alternatives in 2011 [24], their report noted that the marine waters near DCNPP are significant producers of marine algae, including surface kelp and understory algae, and kelp growth can reach 2 feet per day during the growing season between June and October. The kelp is mowed regularly to avoid problems with the power plant. This area is also subject to tidal fluctuations, waves (normally 5 to 10 feet and reaching 20 to 30 feet during storm events), and wind (typically 10 to 25 mph and sometimes reaching 40 to 50 mph). The water is expected to have a robust fouling community.

If DCNPP is going to continue to operate, and if a desalination plant is co-located with the power plant, the existing power plant seawater intake will need to be modified, retrofitted, or completely rebuilt in order to meet new regulations. As discussed previously, the California Water Quality Control Policy on the Use of Coastal and Estuarine Water for Power Plant Cooling [23] requires that existing power plants using once-through cooling reduce their intake flow rate by 93%. If not feasible, power plants are able to instead put into place measures that reduce the impingement and entrainment of marine life for the facility to a comparable level. If neither of these options are feasible, there are alternative steps that can be taken, on a case-by-case basis, for nuclear power plants to comply with this regulation. These regulations are the primary technical reason for the impending shutdown of the plant.

In addition to the regulations on the power production side, the intake for a co-located power and desalination plant would also have to comply with regulations for desalination plants. In California, desalination intakes are regulated by the California Ocean Plan [33], which is similar, but slightly more rigid than the regulations for existing nuclear power plants with regard to seawater intakes. The California

Ocean Plan also focuses on limiting the impingement and entrainment of marine life. There are two approaches that other desalination projects have taken to meet the key provisions in the California Ocean Plan.

The first is to construct a submerged intake gallery. These intakes are buried below the surface of the ocean floor, and use the sand and sediments on the ocean floor as a natural filter to ensure that marine life does not enter the intake. The benefits of these intakes are that the filtration performed by the ocean floor can reduce the level of pretreatment required by the desalination plant, and there are almost no effects to aquatic life during normal operation. The downside of these intakes are the upfront capital costs, the destruction of large areas of seafloor habitats initially required to build the intakes, the possibility of affecting freshwater aquifers inland of the intake, and the possibility for high maintenance costs and disruption of ocean habitats throughout the life of the plant if the conditions are not favorable. Important factors for the feasibility of submerged intakes are described by the WateReuse Desalination Committee [34]. Submerged intakes are designed similarly to commonly-used slow sand filters. The design surface loading rate of infiltration gallery filter beds is typically between 0.05 to 0.10 gpm/ft^2 (0.034 to 0.068 L/s-m^2). If a surface loading rate of 0.075 gpm/ft^2 (0.05 L/s-m^2) is assumed, an infiltration gallery large enough to draw in all the intake water for the nuclear power plant would be over 500 acres (2.02 km^2) large. For reference, the footprint of the current intake lagoon at Diablo Canyon is approximately 20 acres (0.08 km^2). Due to the complexity of determining the environmental and economic feasibility of a submerged seawater intake, and the complicated regulatory and permitting framework, we direct our focus in this report to the second approach.

The second approach to comply with the California Ocean Plan is to construct submerged screened intakes. California desalination regulations require that new screened intakes have a mesh size of 1 mm or less, and a flow velocity at the screen of no more than 0.5 feet per second. Although these conditions can lead to rapid fouling of the intake screens, screens can be cleaned by a number of methods, such as with an air burst, mechanical cleaning, or by divers. Screened intakes generally cost much less than submerged intake galleries, and their successful operation is less dependent on the local site conditions, such as the wave action, ocean floor composition, and bathymetry of the area. A detailed design study should investigate all options presented here. For the purpose of this analysis, though, Intake Screens, Inc. (ISI) of Sacramento has provided us initial estimates regarding mechanical brush-cleaned wedgewire screens, which will likely be one of the most competitive options. Similar intake systems have been specified for the Huntington Beach desalination plant [35], and are currently being tested at Carlsbad as a potential replacement for the existing intake [36]. We note that there are a number of designs that may be feasible at Diablo Canyon, although we only include one here.

Key to ISI’s design is a submersible electric-drive assembly that rotates wedgewire screen cylinders between nylon brushes. The exterior of the wedgewire is cleaned by a fixed position external brush and the interior of the screen is cleaned by an internal brush that rotates. This brush-cleaning system has proven effective at maintaining a clean screen surface in a number of applications with challenging fouling environments.

Figure 8. ISI mechanical brush-cleaned screen operating in Hudson River (Appendix A – Intake Screens, Inc. Report).

Maintenance of a clean screen surface is critical to providing aquatic organism protection, as fouled screens are prone to developing velocity "hot spots", which increase the potential to either entrain or impinge aquatic organisms and/or result in the inability to convey water through the intake screen. ISI's design includes stainless steel wedgewire mesh with openings of no more than 1 mm, and a through-screen velocity of no more than 0.5 ft/s (15 cm/s). Screen material and internal structures are constructed from 2507 Super Duplex stainless steel with cathodic protection and material isolation to protect against corrosion in the marine environment. The system also has antifouling coatings on other surfaces.

A series of vertically-oriented drum screens would be located at least 300 m (1,000 feet) from shore in relatively deep water (>15 m) (>50 ft) to avoid the more sensitive nearshore marine habitats and potential higher aquatic organism densities located in the nearshore area.

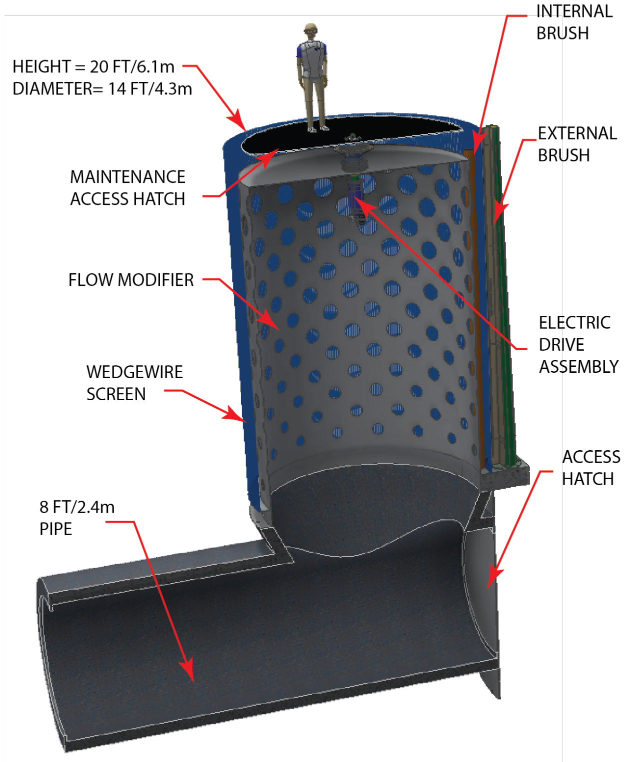

Figure 9. Proposed ISI screen to be used at Diablo Canyon, with a human shown for scale (Appendix A – Intake Screens, Inc. Report).

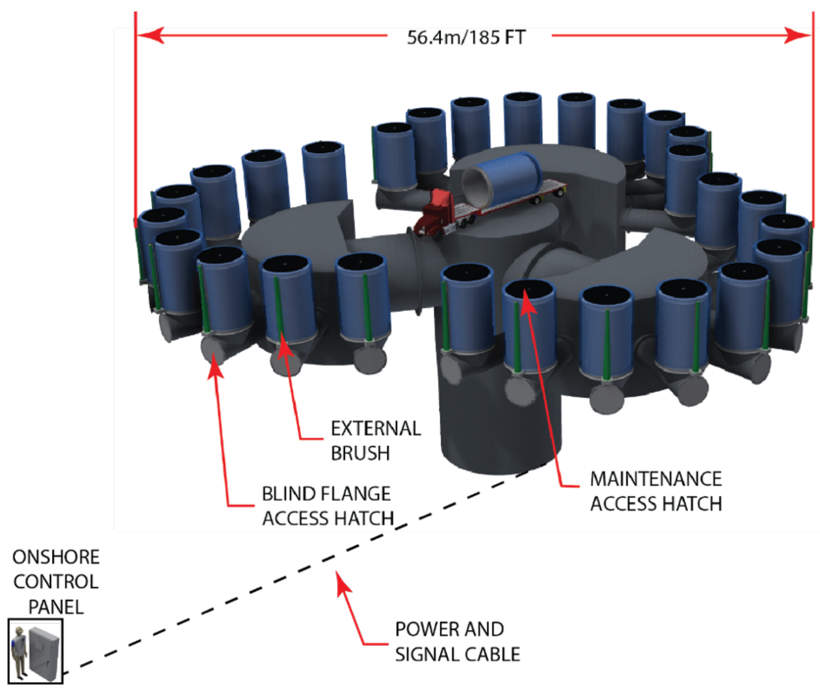

Figure 10. ISI brushed wedgewire screens on concrete manifold array, with flatbed truck shown for scale (Appendix A – Intake Screens, Inc. Report).

The array of screens is designed to achieve equal withdrawal from each wedgewire screen, and the design also allows for inspections and simplified maintenance and repair. Following the approach used in the Bechtel report, the existing shoreline basin would be closed off from the Pacific Ocean by extending the existing breakwater structure. The new section of breakwater would include a stop log structure so the wedgewire screens could be bypassed should the need arise. The shoreline basin would then be connected to each offshore screen array by a drop shaft below the basin that leads to a bored tunnel and terminates at the manifold array.

Figure 11. Aerial view of DCNPP with extended breakwater to isolate lagoon, emergency inlet structure, tunnel extending offshore, and wedgewire screen array for Option 1 (Appendix A – Intake Screens, Inc. Report).

To place the screens in an appropriate offshore, deep water location that minimizes potential impacts to aquatic resources, the tunnel is anticipated to be approximately 335 m (1,100 feet) long. This arrangement allows for the power plant to continue to operate continuously throughout the construction of the new intake, as the existing power plant intake pumps and structure are unchanged. One intake array would be required for Options 1-3, while Option 4, which requires additional feedwater, would require an expanded intake system. Additional information regarding the proposed intake systems can be found in the appendices.

We note that this is just one method of constructing an intake that would meet the needs of the desalination and power plants. The arrangement as shown may need to be modified as additional studies are performed and other requirements are discovered. For example, if the marina inside the breakwater is going to continue to be used for shipping, a different breakwater arrangement may be needed in order to allow the passage of large ships. Possibilities include changing the emergency stoplog structure to something more easily moved, or extending the tunnel to a point closer to the existing intake, and constructing a smaller breakwater or other structure around the outlet, which would allow for the existing breakwater to remain as is. Other options should be investigated, such as Johnson screens with different cleaning mechanisms, and potentially even converting the existing breakwater into a porous dike, which would filter the incoming seawater instead of using a screened intake. For all options, designing around the seismic and environmental concerns will be of utmost importance.

Outfall

The discharge of brine from the desalination presents another challenge. The current power plant outfall consists of surface discharge to Diablo Cove. The hot discharge water is initially carried towards the open ocean by the water's inertia, imparted by the 26 m (85-foot) drop in elevation from the power plant to the shoreline. Beyond Diablo Cove, the buoyancy of the hot discharge causes the thermal plume to spread across the surface, dissipating heat into the atmosphere [28].

For Option 1, the existing power plant outfall could continue to be used, which would allow for significant capital cost savings.

If a mega-scale desalination plant is constructed (Options 2-4), utilizing warm DCNPP cooling water as the feedwater, and discharging brine to the ocean, major changes to the existing outfall scheme will need to be made in order to comply with the new desalination outfall regulations. The California Ocean Plan regulates desalination plant outfalls, and the regulations are designed to limit damage to sensitive coastal ecosystems, especially problems due to high salinity. The California Ocean Plan specifies that brine discharge not exceed two salinity units (parts per thousand) above ambient levels within 100 meters of the discharge point, although this salinity impact zone was extended to 200 meters for other large projects, such as the Carlsbad Desalination Plant. Although Carlsbad's outfall has been shown to have minimal environmental impact [29], it is unlikely that regulators will allow for similar exceptions. Similar to desalination intakes, outfalls are permitted by first completing site-specific feasibility studies for a number of alternatives, after which regulatory committees determine which alternatives are feasible. These detailed feasibility studies are outside the scope of this report.

One of the challenges with desalination brine is that aqueous solutions become denser as they become more saline. The increased density causes undiluted brine to descend to the ocean floor, creating a localized environment that can be detrimental to, or even kill, aquatic life. This phenomenon can be mitigated by ensuring good mixing of brine with ambient waters by using a network of diffusers, or by discharging in locations with strong currents or surface/internal wave action to enhance turbulent mixing and molecular diffusion of salts. In the case of Diablo Canyon, the fact that the brine is also likely to be warmer than ambient temperature helps to reduce the density of the brine, helping the brine to sink less quickly and mix more rapidly.

The density of the brine, which is important for understanding its mixing and dispersion, is shown as a function of temperature and salinity [37,38] for all options in Table 8. It is unlikely that significant cooling of the brine will occur inside the desalination plant itself, given the high mass flow rates of water and limited heat transfer area of the internal piping.

Table 8. Seawater density as a function of temperature and salinity [37,38].

Winter	**Ocean**	**Outfall - No desal**	**Outfall - Option 1**	**Outfall - Option 2**	**Outfall - Options 3&4**
Temperature	11°C	21°C	21°C	21°C	21°C
Salinity	35,000 ppm	35,000 ppm	36,700 ppm	46,800 ppm	70,000 ppm
Density	1026.8 kg/m^3	1024.7 kg/m^3	1026.0 kg/m^3	1033.7.4 kg/m^3	1051.5 kg/m^3
Summer	**Ocean**	**Outfall - No desal**	**Outfall - Option 1**	**Outfall - Option 2**	**Outfall - Options 3 & 4**
Temperature	18°C	28°C	28°C	28°C	28°C
Salinity	35,000 ppm	35,000 ppm	36,700 ppm	46,800 ppm	70,000 ppm
Density	1025.4 kg/m^3	1022.7 kg/m^3	1024.0 kg/m^3	1031.6 kg/m^3	1049.2 kg/m^3

A likely option for waste disposal is a brine diffuser system. Diffusers release high velocity brine through a set of nozzles spread over a wide area, helping to quickly mix the brine with the surrounding seawater. Diffusers represent the most environmentally friendly option for brine disposal, and have been utilized at other plants in sensitive ecological environments such as the Sydney Desalination Plant in Sydney, Australia [39]. Brine diffusers have been shown to have minimal impacts on local fish populations [40]. Diffusers are likely to be required for any new large desalination plant in California due to the strict environmental regulations, with the exception of plants co-located with another source of freshwater being discharged, allowing for the commingling and diluting of brine.

Land requirements and siting

Another challenge with building large desalination plants is finding a proper site for the construction of the plant. A desalination plant of the scale of any of the proposed options will require a large piece of land. At the same time, land costs in California are high, and coastal development for desalination projects faces significant regulatory hurdles and red tape. To estimate the required footprint, we consider other large-scale desalination plants, with a special focus on plants that are site-size constrained, such as plants in the United States and Singapore. Using either published literature when available [10], or a combination of published data and satellite imaging tools, the density of desalination plants are evaluated in terms of capacity per unit area, shown in Table 9.

*Table 9. Approximate density of desalination portion (excluding intake and outfall) of relevant large-scale desalination plants. *Note that Tuaspring includes both a desalination and power plant on the same site, so density is higher than shown.*

Plant	Capacity [m^3/d]	Footprint [acres]	Density [$m^3/d/acre$]
Carlsbad, CA	189,270	5.5	34,413
Tampa Bay, FL	108,831	7.2	15,115
Tuas III, Singapore	136,260	6.2	21,977
Tuaspring*, Singapore	318,500	14.4	22,083
SingSpring, Singapore	136,000	15.6	8,718
Sorek, Israel	540,000	55.0	9,818
Victoria, Australia	444,000	49.0	9,061

Because the proposed desalination plant could share certain facilities with DCNPP (intake, outfall, potential for shared administrative buildings and service roads), and because the large scale should allow for greater effective density (land required for service roads and administrative facilities will not scale linearly with capacity), we believe it is reasonable that a Diablo Canyon mega-plant could reach a density of 40,000 $m^3/d/acre$ while using off-the-shelf technologies and construction methods. For a large-scale plant, the same density as Carlsbad should be possible. Innovations such as multi-story plants, large-diameter membranes, and compact, advanced pretreatment technologies could help to increase the density even further. The resulting footprint ranges of different options are shown in Table 10.

Table 10. Estimated land required for various options.

Option	Land required [acres]
Option 1	5.5
Option 2	60
Option 3	119
Option 4	384

The area inland of DCNPP is mountainous and would likely not be an economical site on which to build a desalination plant. However, along the coast and still near DCNPP are several coastal areas that are relatively flat and may be able to provide a site for the desalination plant.

Topographical maps and satellite imagery were used to estimate the area of viable land near DCNPP. At the scale of Option 1, the land required for a desalination plant could likely be found on or very near the existing plant area, without having to substantially increase the footprint of the combined plant. For larger options, Crowbar Canyon, just to the northwest of DCNPP, may have a usable land area of approximately 100-400 acres. Comparing with Table 10, it becomes apparent that regardless of which option is chosen, the plant will likely have to be very densely constructed. There are a number of other possible locations up and down the Diablo Coast that could support a desalination plant, although the preference would be to limit expansion into new areas for environmental protection purposes. Detailed geographical analysis and examination of appropriate sites is outside the scope of this report.

Figure 12. Land areas projected onto satellite images of the area near Diablo Canyon. We note that the projected areas are not actual proposed plant sites, but are strictly meant to convey the scale of different project footprints.

Figure 13. Aerial view of DCNPP, with Crowbar Canyon in the background.

Figure 14. View of DCNPP from Crowbar Canyon, a potential location for the desalination plant, to the northwest of Diablo Canyon. (Credit NPR)

We note, and Figure 13 and Figure 14 show that the coastline from Point Buchon to Point San Luis (approximately 2 miles to the north and 5 miles to the south of DCNPP) is one of the most pristine coastlines in all of California. The coastline is home to owl limpets, sea palms, and the endangered black abalone, along with a number of other sensitive species. Due to the operation of the nuclear power plant, much of the coastline near Diablo Canyon is currently inaccessible to the public. The lack of human interaction and involvement along this stretch of coast has allowed for plant and animal life to truly flourish, especially in the intertidal zone, which contains an incredible amount of biodiversity. In Diablo Canyon Decommissioning Engagement Panel meetings, environmentalists have shown concern about opening this coastline up to the public after the impending decommissioning of the DCNPP. As areas of the California coast that were once inaccessible to the public become publicly accessible, the diverse inhabitants of the intertidal zone are often trampled by "environmental tourists" who flock to the coasts to enjoy nature. Furthermore, sensitive species, such as abalone, are often poached at an alarming rate [41]. Whatever happens at Diablo Canyon, the valuable natural resource that is the Diablo coast must be protected. If a desalination plant is built in the area, careful planning must be done to ensure that these valuable resources are not affected during construction, operation, and eventual decommissioning of the plant. With careful management, the continued operation of DCNPP and construction of a desalination plant nearby could help to keep the Diablo coast off limits to the public, providing a protected habitat for the endangered and at-risk species that live there.

Another consideration is land ownership, zoning, and permitting. The land DCNPP sits on is zoned as a public facility, while nearby areas that could be used for a desalination plant are zoned as agricultural and rural lands. A desalination plant in the area would likely be located in the coastal zone, which requires additional permits from the California Coastal Commission before construction can begin. Much of the land near DCNPP along the coast is owned by PG&E, or leased by PG&E from Eureka Energy Company [42].

Figure 15. Diablo Canyon lands ownership and land use [42].

If PG&E were to continue to own and operate DCNPP and construct a desalination plant on the adjacent lands they own, no transfer of assets would be required. If PG&E decided to sell DCNPP and the land on which it sits to another entity in order to build a desalination plant, California regulations give first rights of refusal to Native American tribes [43]. The area surrounding DCNPP may also contain Native American cultural sites or burial grounds [44], which could also pose challenges to siting a desalination plant.

To summarize, siting a very large desalination plant (Option 2, 3, or 4) near DCNPP will be very challenging. The area is pristine, ecologically, and ought to be protected as much as possible. The mountainous terrain will pose significant challenges, as will the political landscape surrounding the lands near DCNPP. These challenges may be too much overcome, and may render a mega-scale desalination project at DCNPP infeasible. A more modest plant of Carlsbad scale (Option 1), could easily be contained within the already industrialized zone, making this a much more attraction option from an environmental protection perspective.

Effects of product water quality

In order to determine the desalination plant's requirements, it is important to understand the end user of the product water, as different users will have different requirements for water quality. For instance, if product water is discharged to an aqueduct or canal, blending with other water and with further treatment performed before the water reaches a consumer, the desalination product-water requirements may not be very stringent and would have a lower water cost. In this case, single-pass reverse osmosis membranes may be sufficient to reach the desired product water quality.

An ideal RO membrane would allow only water to pass through, rejecting all other constituents present in the feedwater. In practice, these membranes do a very good job, rejecting over 99.7% of NaCl, the major constituent in seawater. However, some other constituents, particularly boron, are rejected at lower rates. While boron is present in lower quantities in seawater (approximately 4.5 mg/L), it is rejected at only 80-90%. Some fruit trees important to California agriculture can be damaged by leaf burn due to boron concentrations over 1 mg/L, and some very sensitive plants, such as avocados, may be damaged at concentrations as low as 0.5 mg/L. This means that for agricultural use, water that passes through a set of membranes may need to undergo a full or partial second pass, whereby either all the water is passed through membranes a second time, or a portion of the product water passes through a second set of membranes, and is blended back in with the water from the first pass. The second pass results in cleaner permeate water, which is fit for agricultural use or, generally, for irrigation of sensitive crops by municipal water supply. We expect that new desalination projects in California will have to meet these strict boron requirements.

Another concern with water from reverse osmosis plants can be the chemical composition of the water in relation to the pipes that the water flows through. Water from desalination plants is low in minerals, alkalinity, and pH. In this state, water tends to corrode and degrade concrete pipes, and leach metals such as copper and lead into the water. To remedy this issue, product water is commonly remineralized by adding directly or dissolving chemicals that contain calcium or magnesium, such as lime, calcite, or dolomite. With the proper chemistry achieved, the water will tend to deposit minerals onto pipes, forming a protective coating that helps to prevent corrosion and keep water supplies safe and chemically stable [45] .

While issues of product water quality are important, they are quite routine compared to other challenges when considering a desalination plant at Diablo Canyon. Each hypothetical end user's differing requirements will result in slightly different desalination plant designs, and ultimately in a different cost of water. However, we would expect that meeting the product water requirements of different users would incur the same or very similar costs for any new desalination plant anywhere on the California coast. For example, the capital cost to implement a second pass through membranes to reduce the boron concentration at Diablo Canyon is likely to be very similar to the cost (per m^3) at any other location in California. Furthermore, we expect that most offtakers in the areas near Diablo Canyon will have similar product water requirements, both in terms of boron and remineralization. Therefore, it is unlikely that there are major benefits or disadvantages related to product water quality for a desalination plant at Diablo Canyon compared to any other hypothetical desalination plant.

Desalination plant

The design of the desalination plant itself, consisting of everything from pretreatment to remineralization, is likely to be one of the more routine elements of this project. Designs for the plant can be informed by the existing small-scale desalination plant that currently serves DCNPP's needs for drinking water, fire and dust suppression, and power plant makeup water. The existing plant has been operating for over 28 years, and produces 2,450 m^3/d of fresh water (approximately 3 orders of magnitude smaller than the proposed mega-plant). Specifics of the plant design will depend on a number of factors, but one option is presented here.

Table 11. Properties of Pacific Ocean seawater [46].

	Value	Units
Total dissolved solids (TDS)	36,000	mg/L
Temperature	14	Degrees C
pH	8.0	pH
Turbidity	5 (up to 25 during storms)	NTU
Total suspended solids (TSS)	3.6	mg/L
Total organic Carbon (TOC)	3.0	mg/L
Dissolve organic Carbon (DOC)	1.3	mg/L
Chloride	19,000	mg/L
Bromine	70	mg/L
Boron	4.5	mg/L

Using LG Chem's Q+ Projection Software, we have designed a desalination plant to treat incoming feed water from the Pacific Ocean to the standards required for potable drinking water. Typical conditions in the area are given in Table 11. The incoming feed is first pretreated to remove potential foulants which may damage the reverse osmosis membranes. The existing plant at Diablo has a pretreatment design consisting of dual media filters, multimedia filters, UV and cartridge filters. Ferric salts and polymer coagulants are used before the filters, and antiscalant before the SWRO. The pretreatment does not include chlorination [47]. The original membranes lasted 13 years and never required clean-in-place due to both the pretreatment design and the operations [48]. Given their success, any new desalination plant sited at Diablo should use the above pretreatment regime as a starting point. Fouling risk may be greater for a new plant with feed that is warmer than raw ocean water.

The pretreated feed then moves to the first pass of reverse osmosis elements. This first pass is a standard design using seven elements in each pressure vessel and an isobaric energy recovery device to recover pressure from the brine stream. The permeate produced during the first pass has a total dissolved solids (TDS) level that is sufficient for drinking water, but contains an amount of boron that is too high (0.86 mg/L) to meet the standards for agricultural use (≤0.5 mg/L) To remedy this, we utilize a partial second pass, similar to the design used in Carlsbad Desalination Plant. Half of the permeate is diverted to a second pass, where the pH is adjusted from 8 to 10 to increase Boron rejection [49]. At this higher pH level, uncharged boric acid (78-80% removal) disassociates to borate ions (>95% removal). The pH-adjusted feed passes through a train of brackish reverse osmosis membrane elements. The permeate from the second pass is blended together with the permeate from the first pass. This final product stream undergoes remineralization and disinfection before being distributed to offtakers.

Again, if we consider the design and operation of this plant in terms of how it may differ from other new desalination plants in California, a few differences stand out. First of all, using seawater that has been warmed by the power plant has two effects on membrane operation. Increasing the temperature increases the water and salt permeability of the membranes. This means that the plant will be able to operate with either a smaller footprint and higher fluxes, or with the same footprint and reduced energy consumption when compared with a plant with cooler feedwater. However, the increased salt permeability will make the membranes less effective at rejecting salts, meaning that the product water will be saltier, and may lead to the need for more passes through membranes or other additional treatment. The other effect of high temperature is an increased propensity for fouling and scaling in membranes, because certain salts will form hard mineral scales more rapidly at higher temperatures. This can be addressed by changing the pretreatment scheme, adding additional antiscalant chemicals, or cleaning membranes more frequently. Although the temperature in a Diablo Canyon desalination plant will be higher than ambient conditions, and higher than other plans in California, the temperatures are still well within the established operating range for desalination plants worldwide. In fact, many of the world's reverse osmosis plants, operating in the Middle East, operate with even warmer feedwater.

Ultimately, we expect that the elevated temperatures and subsequent effects on plant design will not have a large impact on the overall cost and feasibility of the plant relative to other hypothetical plants in California. As will be shown in later sections, the potential increase in cost due to minor changes in plant design is small relative to the other savings that result from co-locating the plant with DCNPP.

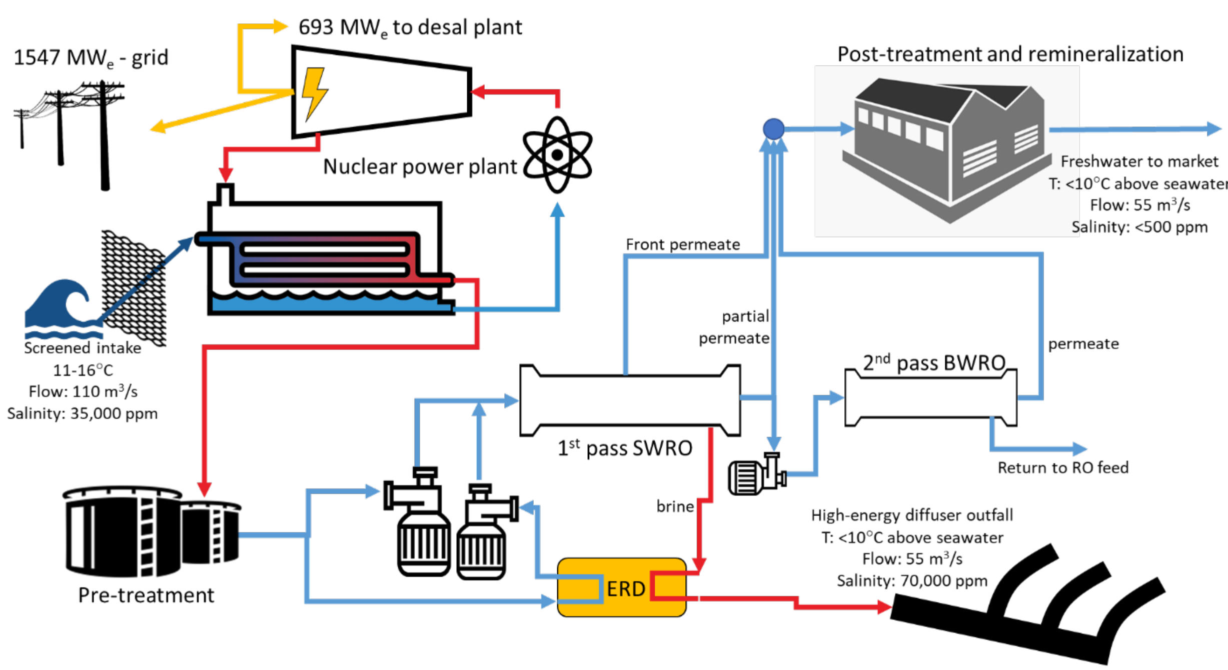

Figure 16. Diagram of a possible layout for a 2-pass RO system integrated with the Diablo Canyon nuclear power plant.

Distribution

We consider two baseline scenarios. In the first scenario, a shallow buried pipeline will convey product water from Diablo Canyon all the way to California's Central Valley, where water demand from farmers is outstripping supply. This pipeline would be about 100 km long, with a net elevation gain of 100 m. In the second scenario, a shallow buried pipeline will convey product water from Diablo Canyon to the Coastal Branch of the CA Aqueduct in San Luis Obispo, from which it is delivered to Lake Cachuma above Santa Barbara (see Figure 17). This pipeline would be about 30 km long, with a more modest elevation gain of 10 m. In both cases the pipeline would be buried.

Figure 17. Map of a portion of the California State Water Project, with Diablo Canyon's location highlighted (Wikipedia).

Our purpose is to estimate the distribution cost per unit water delivered ($\$/m^3$). The total costs scale linearly with flow rate because a lower flow rate implies a proportionally lower pumping power, fewer pipes and fewer pumps. Therefore, here we present the calculations only for one (high) flow rate, i.e., 55 m^3/s.

For such pipelines, we consider very large pipes (3.5 m ID). Such pipes are commercially available in various materials suitable for water distribution, i.e., extruded HDPE [50] and glass reinforced polyester resin [51]. The assumptions made regarding the pipelines are shown in Table 12.

Table 12. Pipeline assumptions

Variable	Value		Units
	Scenario 1	Scenario 2	
Water density, ρ	1000		kg/m^3
Water viscosity, μ	0.0011		Pa-s
Pump isentropic efficiency, η_p	85		%
Flow rate	55		m^3/s
Number of pipes, N	3		-
Pipe length, L	100,000	30,000	m
Elevation gain, h	100	10	m
Pipe inner diameter, D	3.5		m
Surface roughness, ε	0.002		m
Relative roughness, $\lambda = \varepsilon / D$	0.0006		-
Electricity cost[1], Ce	96	54	\$/MWh

The pumping power, pumping cost, and specific pumping cost can be determined using the equations in Table 13. Minor losses are neglected, since the viscous and gravity losses dominate the total pressure drop.

Table 13. Equations for determining pumping energy and costs.

Variable	Equation
Cross sectional area, A	$A = \frac{\pi}{4} D^2$
Velocity, V	$V = Q/(N \cdot A)$
Reynold's number, Re	$Re = \rho V D / \mu$
Friction factor, f	$f = \frac{8}{6.0516} \cdot \frac{1}{\log\left(\frac{\lambda}{3.7} + \left(\frac{7}{Re}\right)^{0.9}\right)^2}$
Pressure drop, ΔP	$\Delta P = \frac{fL}{D} \frac{\rho V^2}{2} + \rho g h$
Pumping work, W_p	$W_{pumping} = Q \frac{dP}{\eta_p}$
Total pumping cost, C_p	$C_p = W_p C_e$
Specific cost of pumping, cp	$cp = \frac{C_p}{Q}$

The results of these equations for the two baseline scenarios considered are shown in Table 14.

[1] We have assumed that the cost of electricity for pumping in Scenario 2 is the cheaper rate at Diablo Canyon. This assumption is correct for pipelines with a single pumping station located at Diablo Canyon. However, for long pipelines with large elevation changes (Scenario 1), multiple pumping stations will be needed; the remote pumping stations will pay the more expensive grid electricity, so the price reported here for Scenario 1 is an average price for two pumping stations.

Table 14. Results from water pipeline pumping equations

Option	Pipeline length [km]	Number of pipes [-]	Pressure drop [bar]	Specific energy [kWh/m^3-km]	Pumping cost [$/m^3]
Scenario 1	100	3	18.8	0.0061	0.059
Scenario 2	30	3	3.7	0.0040	0.006

Based on quotes from two pipe vendors (AGRU and Future Pipe Industries), we estimate a total cost of the pipes of $2.2B for the 100 km pipeline (Scenario 1), and $675M for the 30 km pipeline (Scenario 2). These figures include manufacturing, transportation and installation, and are roughly consistent (on a per unit length and capacity) with other large water distribution pipelines documented by Plappally and Lienhard [15]. Based on quotes from two pump vendors (i.e., Flowserve and Torishima), we estimate the total cost of the pumps for Scenario 1 to be about $57M, and conservatively assume the same for Scenario 2. The efficiency of these pumps is approximately 85%. Assuming the same financing terms as the rest of the desalination plant, the cost of equipment for the pipeline contributes about 0.086 and 0.028 $/m^3 to the cost of delivered water, for Scenarios 1 and 2, respectively. Adding the pumping and equipment costs, the total cost of water distribution is 0.145 $/m^3 and 0.034 $/m^3 for Scenarios 1 and 2, respectively.

Using the same methodology, we have generated a rough estimate of the cost to send water a variety of distances to a number of different offtakers. Cost estimates are shown in Table 15, while distances to other locations can be estimated from Figure 18. The cost of distribution includes the costs of equipment and pumping, and can be added to the levelized cost of water at the desalination plant outlet, which is calculated in Table 18, to produce the estimated cost of water delivered to the offtaker. Distribution costs can vary significantly from these projections depending on the route taken, resulting elevation change, and other factors.

Table 15. Estimate of costs to transport water to different offtakers.

Distance/Net elevation gain	End point (from DCPP)	Pressure drop [bar]	Distribution equipment cost [$/m^3]	Pumping cost [$/m^3]	Total distribution cost [$/m^3]
20 km/ 0 m *	Pismo Beach, San Luis Obispo	1.8	0.019	0.003	0.022
33 km/ 120 m *	Lopez Lake, SWP connection	14.7	0.030	0.026	0.056
50 km/ 200 m **	Paso Robles	24.1	0.044	0.076	0.120
55 km/150 m **	Twitchell reservoir, Lake Nacimiento	19.6	0.049	0.062	0.111
110 km/ 200 m **	Lake Cachuma, Cuyama, King City	29.5	0.095	0.092	0.187
185 km/ 0 m **	Monterey, Salinas	16.6	0.159	0.052	0.211

** one pumping station; ** two pumping stations*

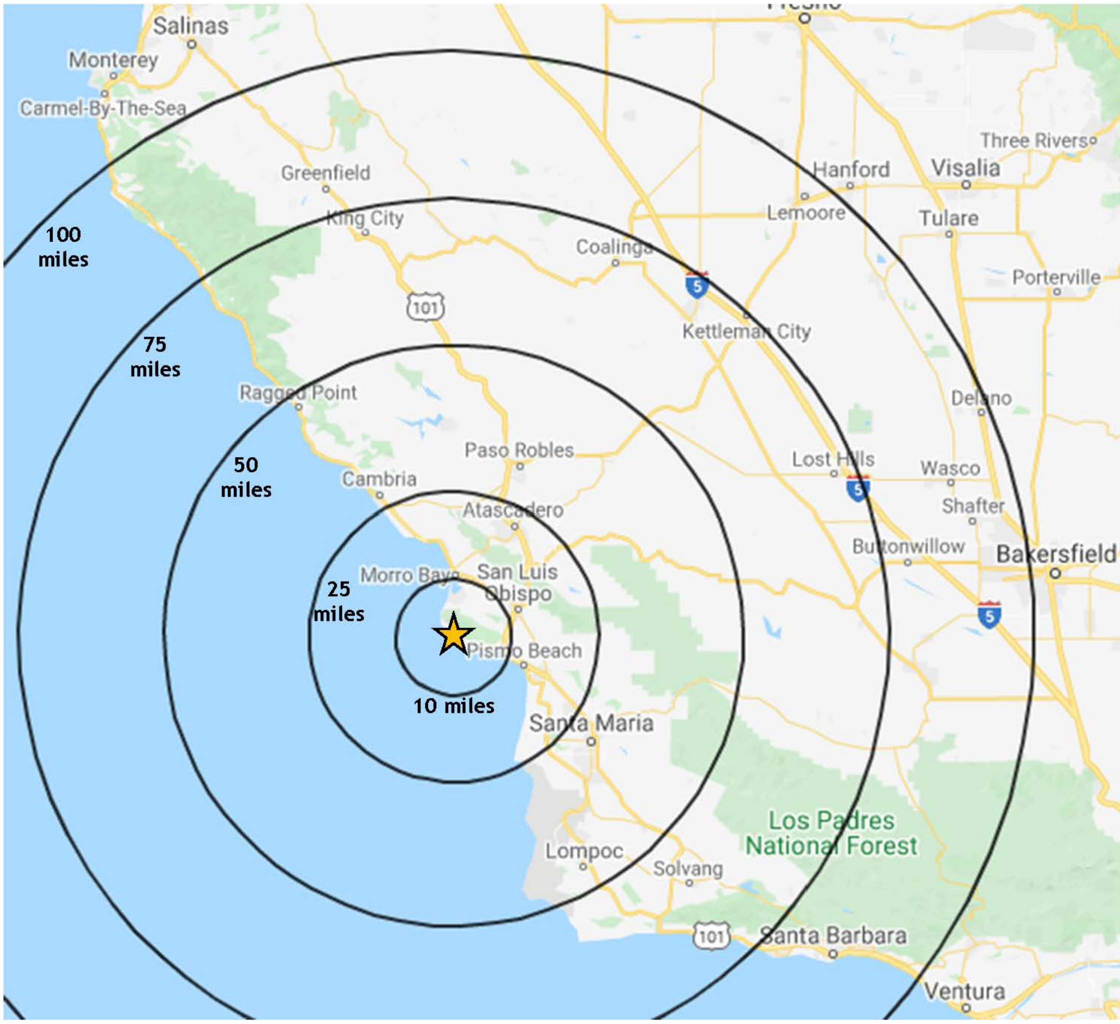

Figure 18. Map showing distances from the Diablo Canyon Nuclear Power Plant.

Construction approach

The construction approach for Option 1 would likely be similar to that of other plants built in California. If larger options are chosen, there will likely be unique issues that arise due to the scale of the project. For example, it is possible that a plant of this size could cause issues with supply chain capacities. Global Water Intelligence projected that a boom in construction of large desalination plants would cause the demand for seawater reverse osmosis membranes to outstrip supply, leading to a supply shortage, increased lead times, and increased membrane prices for the period from 2019-2022 [52]. Construction of a plant as large as Option 3 or 4 may cause enough of a spike in demand to cause its own materials supply shortage.

Questions around supplier capacities, the ability to move such a large volume of construction supplies into the construction site, laydown area, vehicular access, and more are important questions to answer, but are outside the scope of this report. Unique approaches, such as building portions of the plant offsite and shipping them to Diablo Canyon's existing harbor, should be examined to address these issues. This approach has been used before, such as at Cape Preston, which is located north of Perth in Western Australia's Pilbara region. In that case, a 140,000 m^3/d plant was pre-fabricated offsite in sections, and assembled on-site, which helped to reduce both costs and construction time [53].

It is likely that projects as large as Options 2-4 would be constructed in a number of stages or phases, rather than all at once. This approach may have a number of advantages. Although the timeline may be drawn out, and the costs for the plant may increase somewhat, beginning with a smaller plant and building a series of expansions could make zoning, permitting, and construction much easier and cheaper for later stages of the project.

Diablo Canyon Nuclear Power Plant as a power source

There is an excellent match between the power needs of a desalination plant and the power provided by the Diablo Canyon Nuclear Power Plant. Desalination is most economical when the plant operates at a high capacity factor, running 24/7 throughout the year, except for occasional downtime for maintenance. This is exactly the type of power provided economically by DCNPP. As California moves to decarbonize its power grid, the cost advantage of the Diablo Canyon Nuclear Power Plant as a source of zero carbon baseload electricity is likely to grow. Since electricity is a major input to desalination, the availability of economical zero carbon electricity from DCNPP helps keep the cost of water low.

Operational changes to Diablo

Operating a new desalination plant alongside the Diablo Canyon Nuclear Power Plant does not require any major changes to the operation of DCNPP. We would expect minor changes to include the installation of a series of bypass valves and pipes, such that the power plant can operate while the desalination plant is down for maintenance, and vice versa. Both the Power Plant and the desalination plant require a water intake that conforms to California's environmental requirements for the respective plants. However, co-location enables the two plants to share a common intake structure. We assume this investment is made by the power plant and a portion of the cost is passed along to the desalination plant in proportion to the share of electricity generation used by the desalination plant.

As noted earlier, the major requirement for the power plant is the approval of a license extension for another 20 years. License renewals are usually preceded by certain capital investments needed to prepare the plant for additional years of operation. When PG&E was preparing for its original renewal application, it made the major investments for both units of the power plant. The steam generators were replaced in 2008 and 2009, and the reactor pressure vessel heads were replaced in 2009 and 2010. Those are certainly two of the largest capital expenditures relevant to license renewal. We are not aware of other significant expenditures needed that are related to the license renewal, although there may be some.[2] Although the intake will have to be replaced at the cost of hundreds of millions of dollars, the approach proposed in this analysis, implementing screened intakes with an emergency stoplog structure to allow flow into the intake lagoon, is not considered to be safety related, and should not affect the license renewal process. However, based on PG&E's estimates for the original renewal application process, the license renewal process itself could require up to $50 million.

[2] As a part of the original license application renewal process, in June 2011 the NRC issued its Safety Evaluation Report Related to the Diablo Canyon Nuclear Power Plant, Units 1 and 2, Docket Nos. 50-275 and 50-323, Pacific Gas and Electric Company. The report concludes that the requirements of the regulations have been met, and it details a number of License Renewal Commitments.

Power costs

Table 16 shows the historical cost of electricity from Diablo Canyon Nuclear Power Plant for the five years 2016-2020 [17–20]. The average operating cost was $0.03154/kWh. The average capital investment per unit was $0.00864. The average total cost was therefore $0.04018/kWh.

Table 16. Cost breakdown of electricity at Diablo Canyon.

Historical Cost of Electricity from Diablo Canyon Power Plant

			[A] 2016	[B] 2017	[C] 2018	[D] 2019	[E] 2020	[F] 5 yr Avg
[1]	Total Production Expenses	($ milion, nominal)	508.9	497.8	531.6	611.9	522.3	534.5
[2]	Additions to Nuclear Plant	($ milion, nominal)	178.2	198.1	148.5	138.2	63.3	145.2
[3]	BEA Implicit Price Deflator		105.7	107.7	110.3	112.3	113.6	
[4]	Price Index (2020=1.0)		1.0748	1.0549	1.0302	1.0121	1.0000	
[5]	Total Production Expenses	($2020 milion)	547.0	525.1	547.6	619.4	522.3	552.3
[6]	Additions to Nuclear Plant	($2020 milion)	191.6	208.9	153.0	139.9	63.3	151.3
[7]	Net Generation	(TWh)	18.9	17.9	18.3	16.2	16.3	17.5
[8]	Unit Operating Cost	($2020/MWh)	28.93	29.29	29.98	38.31	32.07	31.54
[9]	Unit Capital Investment	($2020/MWh)	10.13	11.66	8.37	8.65	3.88	8.64
[10]	Total Unit Cost	($2020/MWh)	39.06	40.95	38.36	46.97	35.96	40.18

Source:
[1] FERC Form 1, Page 402, Total Production Expenses.
[2] FERC Form 1, Page 120, Total Additions to Electric Plant in Service.
[3] US Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product.
[4] = [3,t]/[3,t=2020].
[5] = [1]*[4].
[6] = [2]*[4].
[7] FERC Form 1, Page 402, Net Generation.
[8] = [5]/[7].
[9] = [6]/[7].
[10] = [8]+[9].

As discussed earlier, continued operation of the power plant would require a new water intake system in order to comply with the California Ocean Plan. The estimated cost, discussed in more detail below, is $500 million.

Levelizing the application cost and intake cost across the plant's generation for a subsequent 20 years of operation at a capacity factor of 90% and a real discount rate of 4.03% adds $0.00230/kWh to the cost of electricity, bringing the total cost of electricity from the Diablo Canyon Nuclear Power Plant to $0.04248.[3]

Our assumption is that the desalination plant can source most, but not all of its electricity needs directly from DCNPP at this cost of generation. While it may be possible to coordinate some of the maintenance outages at the desalination plant with the refueling and maintenance outages at the power plant, it is unlikely that all of them can be coordinated. Therefore, the desalination plant will need standby power service from the grid. We assume the desalination plant purchases 90% of its needs directly from DCNPP and 10% of its needs from the grid. Based on PG&E's current tariffs, we estimate the average cost of standby service as possibly as high as $0.1595/kWh. Therefore, the blended cost of electricity to the desalination plant is $0.05418/kWh. This is approximately 40% of the $0.1388/kWh average cost of

[3] The Energy Information Administration's Annual Energy Outlook 2021, Electricity Market Module, February 2021, p. 9 reports a nominal discount rate of 5.9%. Assuming an annual inflation rate of 1.8%, this translates to a real discount rate of 4.03%.

electricity to California's industrial sector throughout 2019, and a significant savings on the cost of electricity to the desalination plant.[4]

Project economics and economic benefits to California economy

Baseline cost of water estimate

One of the main factors determining whether or not a desalination plant is feasible is the levelized cost of water. While estimating the cost of a desalination plant an order of magnitude larger than any plant in existence is not a trivial task, we believe valuable insights may be drawn by estimating these costs. We begin by using projection tools from DesalData [54], a product of Global Water Intelligence, that uses data from a large number of existing plants to estimate the costs of new desalination plants based on a range of inputs. We use these tools as the basis to estimate desalination plant costs.

Certain direct variable costs (replacement parts, chemicals, electricity) will scale linearly with plant size, while many indirect and labor costs do not. As a baseline, the values shown in Table 17 were used as inputs to DesalData cost projection tools, and the output costs were modified using data from additional research in order to make projections.

Table 17. Capex inputs for baseline case in DesalData Cost Estimator.

Salinity (mg/L)	35000
Min temp (C)	20
Max temp (C)	26
Pretreatment	Standard
Second pass (%)	50
Remineralization	yes
Intake/outfall	Onerous
Permitting	Onerous
Country	USA

We assumed economies of scale exist for direct capital expenditures up to a capacity of 400,000 m^3/d. Beyond this point, all capital and direct operating costs, except for labor, are assumed to scale linearly with size. This is because economies of scale for direct capital expenditure costs are only projected to exist to a certain point, beyond which additional capacity generally leads to added complexity of flow distribution, treatment and operations. It is assumed that building beyond this scale will lead to multiple identical parallel plants with some shared facilities, such as intake and outfall [55]. We assume that some of the indirect capital costs, such as the cost of legal and professional work, design, and management costs will not scale linearly with capacity, and these line items are one of the primary benefits of building plants at large scales. We assume that civil costs and installation costs will scale directly with system capacity, even though we know that in reality there will be some per-unit cost reductions with large scales. This is an intentional overestimate of these costs, which serves to keep our cost estimates conservative.

[4] The 2012 Water Purchase Agreement for the Carlsbad desalination plant established a formula price based off of the SDG&E tariff. In 2012 that formula gave a price just over $0.092/kWh. The price increases with the SDG&E tariff. In 2012, the average price of electricity paid by industrial companies in California was $0.1072/kWh.

In addition to these various engineering, procurement, and construction (EPC) costs, there will be expenditures on various indirect costs. These include pre-construction costs, various owner's costs, as well as transaction fees and closing costs, reserves and contingencies, and interest during construction. For the desalination plant in Carlsbad these items were very large, amounting to 59% of the EPC costs. To maintain consistency with that most recent experience in California, we added an indirect cost item equal to 59% of the total EPC costs itemized above (36% of the total capital cost).

We note that these costs, and the resulting levelized cost of water, shown in Table 18, are a first-order estimate, and significant deviations are possible. Using cost trends from plants smaller than 250,000 m^3/day to predict the costs of plants an order of magnitude larger will lead to errors. Detailed design studies would be necessary to produce a more precise cost estimate. However, the purpose of this report is not to produce water costs accurate to within a few cents per m^3, but to determine if a desalination project at Diablo Canyon is feasible. Some of these line items, such as intake and outfall costs, civil costs, and the financing package numbers can change in ways that will significantly affect the total cost of water as detailed design studies are performed. Factors that can drastically change the price of water are considered in the following subsections.

Differentiating Factors

While the methods in the previous section provide a first-order estimate of the cost of the desalination plant, there are a number of factors that could cause the cost of a desalination plant to deviate from predicted values very significantly, which deserve additional attention. Some of these factors are already well known within the desalination community, and are laid out in Global Water Intelligence's Market Forecast [11]. These factors are responsible for the fact that plants of similar size that have been built in the last few decades can have very different costs. We discuss these factors in detail here, with a specific focus on whether they will be important in differentiating a hypothetical Diablo Canyon mega-plant from other plants in California.

Electricity source and electricity costs

High power costs may drive up the overall cost of desalination considerably. As the impetus for this analysis is a large-scale power plant readily available with low-cost power, costs for construction of electrical infrastructure will be very low. The low cost of available power from DCNPP is one of the major advantages that a desalination plant at Diablo Canyon would have over a plant at any other location in California. Low cost, reliable power from DCNPP can be available for approximately $0.054/kWh, a major reduction in the cost of power compared to grid-sourced power. This factor is one of the main advantages for a Diablo Canyon plant relative to other plants in California.

Coordinated operation of the desalination and power plants may allow for additional cost benefits. For example, certain desalination plant designs allow the plant to enter a "hot shutdown" mode, quickly entering a low-power mode while maintaining flow through the membranes [56]. Coordinated operation with the power plant could allow for the desalination plant to opportunistically shut down so that additional power could be sold into the grid in times when rates increase or during emergency shortages.

Seawater and product water quality

Seawater on the California coast is much less saline than more challenging feedwaters, such as those in the Arabian Gulf. While the question of product water quality is highly dependent on the end user of the water, we do not expect challenges that would significantly increase the price of water due to product water quality (i.e., ultrapure product water required for semiconductor manufacturing). We also do not expect the costs to achieve a given product water quality to be significantly different for different desalination plants in California (i.e., the cost of a second pass at Diablo Canyon would be approximately the same as the cost of a second pass at any other California desalination plant). As discussed previously, we do not believe that there will be significant cost increases due to product water requirements that would significantly escalate the capital or operating costs compared to other desalination plants in California.

Red tides and algal blooms

These seasonal phenomena can interrupt plant operation, and if continuous operation is required, additional pretreatment steps may be necessary, such as dissolved air flotation. The Diablo Canyon site is known to have annual acidification events as a result of domoic acid [57]. This harmful algal bloom (HAB) event is caused by the diatom *pseudo-nitzschia* and makes a neurotoxin which can accumulate in the food chain. Some years are worse than others; when severe, the seawater pH drops 1 unit and microscopic algae multiply. These HAB events also occur at other locations along the California coast and are increasing in frequency, intensity and duration [58].

Another seasonal threat that may have an effect on plant operation is the presence of jellyfish. Jellyfish can clog intakes and cause entire plant shutdowns. This has happened at Diablo Canyon several times, including in 2008 [59] and 2012 [60]. It is unclear how newer intakes will be affected by the problems of algal blooms, red tides, and jellyfish. However, we have not seen evidence that would lead us to expect significant differences between Diablo Canyon and other California desalination plants with respect to these operational challenges.

Contractor experience and labor costs

In regions of the world with many large desalination plants, such as the Middle East, the wealth of historical operating data and the familiarity with the local environmental conditions, laws, regulations, and contract structures allow contractors and engineers to design and build plants with smaller margins for risk, resulting in lower costs. Additionally, labor costs for plant design, construction, and operation in other parts of the world are lower than in the United States. Higher labor costs are factored into the water price, but we do not expect large variations from one part of California to another.

There may be significant advantages for a Diablo Canyon desalination plant in terms of labor costs, due to the scale of the project. Long-term operating labor costs for desalination plants stay relatively constant even with increasing plant capacity, providing a cost advantage for Diablo Canyon over smaller plants. With regard to labor and indirect costs associated with plant construction, as mentioned previously, there would be significant cost savings for a large-scale plant. In summary, we do not expect significant labor cost benefits relative to other California desalination plants at the same scale. Any benefits that are realized would likely be due to the choice of larger-scale plants.

Additional pumping requirements, storage, and conveyance

Cost estimates for pumping water to consumers were discussed earlier in this analysis. It is assumed that pumping the intake water from the existing nuclear power plant to the desalination plant does not include significant elevation changes (although this may become a factor depending on the proposed site of the desalination plant). It is assumed the power plant pays to pump seawater through the intake and up 85 feet to the nuclear power plant. Additional pumping costs are relatively straightforward to estimate once a location for the plant and the location of the customer are determined. If additional storage infrastructure is required, such as additional tanks or reservoirs, the capital expenditure could increase significantly. Depending on who the final offtakers are, this may be an area where Diablo Canyon could have a significant disadvantage. If there are no offtakers nearby, the costs of constructing long pipelines could outweigh the unique benefits of a Diablo canyon project, making smaller, decentralized desalination plants located closer to the offtakers more feasible. The investigation of potential offtakers, and the determination of the cost to bring water from Diablo Canyon to those customers, should be a primary focus of further detailed investigations.

Financing and length of water purchase agreement

Financing terms can also have a large impact on the total cost of water. An increased debt/equity ratio, and lower interest rates and equity yield allow for greatly reduced water costs. It is estimated the cost of financing amounted to about 1/3 of the total cost of water at Carlsbad, which had a total water cost of $1.61, while Sorek 2, a new plant being built in Israel with a total water cost of $0.405, is expected to have financing costs that are less than 20% of the total water price. The debt/equity split for Carlsbad was 79.5/20.5, versus 85/15 for the new Sorek 2. The interest rate and return on equity for Carlsbad are 5% and 10%, respectively, while for Sorek 2 they are around 2.5% and 8%. The way that water purchase agreements are structured, and investor perception of the project will have a major impact on the feasibility and final cost of water of the project.

We have not been able to find evidence that larger projects receive substantially better financing terms than smaller desalination plants, so we assume for now that financing terms will be similar to those of other desalination plants in California, with a 30-year term and a 4.5% weighted average cost of capital (WACC). We do not assume any differences in financing between plants at Diablo Canyon and other plants in California, although in practice there will be. The way that the project is structured from an ownership and operational may also have a substantial impact on how the project would be realized as well. In this paper, we have assumed that PG&E owns and operates the power and desalination plants.

Permitting and political opposition

As an example of the challenging permitting situation in California, the ongoing project proposed for Monterey, CA has been going through permitting issues in some capacity for approximately 30 years [61]. Building anything on the coast in California is difficult to do, and a mega-scale desalination plant is potentially a tough sell from a political perspective. The costs, both in terms of time and money, that could be associated with drawn out lawsuits and permitting battles could be a deal breaker for this project. Local support for desalination can be a major factor in determining whether new projects have a path forward.

Intake and outfall

The entire Carlsbad desalination plant project is estimated to have cost $650 million. If regulators require the use of subsurface intakes, the additional cost to retrofit the plant could be up to $800 million [35]. The type of intake and outfall required at Diablo Canyon will greatly influence the total cost of water. While we do not attempt to estimate the cost of subsurface intakes at Diablo Canyon, we can estimate the cost of screened intakes, like those being permitted at Huntington Beach, using existing studies. Bechtel estimated the cost of the undersea pipeline from the intake lagoon, intake screens, and the structure to seal the intake lagoon at approximately $400 million. ISI estimated the cost of rotating intake screens for Options 1-3 at $70-$100 million. While the cost of a seawater intake utilizing the structures of

Bechtel attached to the screens of ISI would almost certainly be less than the combined estimated costs of the two projects, as the costs of the screens in the Bechtel report would be avoided, we conservatively estimate the cost of the overall intake at $500 million.

One factor that would need to be addressed is how the intake costs are shared between the desalination plant and power plant. We assume that, for Options 1-3, the cost of the intake is borne by the nuclear power plant, and then passed along to customers, including the desalination plant, through the price paid for power. This is because the same large intake needs to be built for the power plant, regardless of which desalination plant option is chosen. For Option 4, the intake is larger than would be required by the power plant itself, so the incremental intake costs are assumed to be completely borne by the desalination plant.

The outfall is more difficult to estimate in terms of financial expenditure, although there are existing projects that can help by providing some precedent. As discussed earlier, the Sydney Desalination Plant uses a diffuser-style outfall to mix undiluted brine with seawater, and is located in a sensitive ecological area with strict environmental regulations, providing an example for Diablo Canyon to follow [62]. The outfall system at that plant is estimated to have cost 20-30% of the total capital expenditure of the plant [63]. The plant has a capacity of 250,000 m^3/d.

At a larger scale, we can consider the Deer Island Wastewater Treatment Plant in Boston, MA. This plant is connected to the largest outfall tunnel in the world, with a capacity that almost exactly matches our proposed Option 3. The tunnel has a peak capacity of 4,921,000 m^3/d. The outfall tunnels down 420 feet below Deer Island, then through a 24-foot diameter tunnel, 9.5 miles out into Massachusetts Bay, where 50 risers bring wastewater to diffusers. This outfall cost $390 million [64].

Finally, we can also consider the costs that have been estimated to implement screened intakes at the Carlsbad Desalination Plant [65]. We utilize these costs, in addition with what we know about the way costs will likely scale with system size, in order to come up with cost estimates. It is assumed that the cost of the outfall system will not rise linearly with the capacity of the outfall, providing additional cost benefits to larger projects.

Environmental expenditure

The costs of land acquisition and the costs of mandated environmental remediation projects are not included in our estimate. As a part of the permitting process, regulators can require additional environmental action to offset any potential environmental damages. For example, the permits for the proposed desalination plant in Huntington Beach would require the plant operator to assume responsibility for the preservation, enhancement and restoration of the Bolsa Chica wetlands [66]. The Carlsbad desalination plant also has a number of preservation and restoration agreements to offset any damage caused by its operation [67]. Land acquisition and environmental remediation projects are likely small costs relative to the scale of the project though. The land lease at Carlsbad is approximately $1.3 million per year, escalating with inflation [68]. The estimated costs of environmental remediation and greenhouse gas credits are on the order of $10 million at Carlsbad, plus several million annually, compared to a total project cost of approximately $1 billion [69]. These expenditures are determined on a case-by-case basis and are outside the scope of this report. However, we do note that there may be advantages for a Diablo Canyon project in this respect, as the desalination plant would be powered with carbon-free electricity, obviating the need for carbon offsets.

Table 18. Projected costs for all options, along with projected costs of building another Carlsbad-sized desalination plant (not co-located with a power plant) somewhere else in California.

	Option 1	Option 2	Option 3	Option 4	Carlsbad
Nameplate capacity (m^3/d)	**189,270**	**2,419,000**	**4,752,000**	**15,379,000**	**189,270**
Utilization rate (%)			80		
Energy consumption (kWh/m^3)			3.5		
Electricity price ($/kWh)	$0.054	$0.054	$0.054	$0.054	$0.139
Discount rate (%, real)			4.5		
Amortization period (years)			30		
Capital costs (millions of dollars)					
Pretreatment	60	683	1,343	4,345	60
Pumps	23	252	495	1,602	23
Equipment and materials	59	674	1,324	4,285	59
Membranes	14	158	310	1,002	14
Pressure vessels	4	45	88	286	4
Piping, high-grade alloy	31	348	685	2,215	31
Energy recovery devices	3	34	66	214	3
Civil costs	52	595	1,168	3,781	52
Design costs	85	250	300	350	85
Legal and professional	21	100	125	150	21
Installation services	25	279	548	1,772	25
Intake structure total costs	500	500	500	1,545	75
Intake costs paid by desal plant	0	0	0	1,045	75
Outfall	0	647	826	1,456	325
Intake and outfall total	0	647	826	2,500	400
Indirect costs (dev, finance)	222	2,398	4,294	13,277	458
Total capex	**599**	**6,463**	**11,571**	**35,780**	**1,235**
Operating costs (annual, millions of dollars)					
Parts	2	25	49	160	2
Chemicals	5	59	115	373	5
Labor	4	7	7	9	4
Membranes	2	25	49	160	2
Electrical energy	13	168	329	1,065	34
Total annual opex	**25**	**283**	**551**	**1,767**	**46**
Water price breakdown ($/m³)					
Total capital cost and amortization	$0.53	$0.45	$0.41	$0.39	$1.10
Parts, chemicals, and membranes	$0.15	$0.15	$0.15	$0.15	$0.15
Energy costs	$0.19	$0.19	$0.19	$0.19	$0.49
Labor	$0.07	$0.01	$0.01	$0.01	$0.07
Overheads	$0.03	$0.03	$0.03	$0.03	$0.03
Water price ($/m³)	**$0.98**	**$0.84**	**$0.79**	**$0.77**	**$1.84**
Water price ($/AF)	**$1,207**	**$1,032**	**$978**	**$952**	**$2,269**

Levelized cost of water

With all the factors above considered, we come to an estimate of the levelized cost of water, shown in Table 18. The cost of water shown in this table is the cost at the outlet of the desalination plant. The costs of transmission pipelines and pumping energy, shown in Table 15, can be added separately to find the total cost of water for each offtaker.

We emphasize again that the purpose of performing this cost estimate exercise is not to accurately project what the total cost of water would be, but to try to make a relative comparison between desalination plants at Diablo Canyon and plants at other locations in California, in order to assess the feasibility of such a plant. As Table 18 shows, the cost of water for any Diablo Canyon project is significantly lower than what we would expect for other desalination plants in California, leading us to believe that such a project would be financially feasible. The low cost is due to three main factors: shared infrastructure, lower energy costs, and benefits of scale.

For the smallest plant we examined, the Carlsbad-sized plant, the ability to use the nuclear power plant's condenser water as feed obviates the need to construct a new intake. Additionally, the ability to mix brine with the existing discharge from the power plant while staying within the salinity discharge limits obviates the need to construct expensive outfall infrastructure. These savings, as well as the energy savings, lead to significant price reductions on some of the most expensive line items for a new desalination plant. At much larger scales, the benefits of shared outfall infrastructure are eventually reduced or eliminated due to elevated discharge salinities and increased feedwater requirements. However, the immense scale allows for additional cost reductions, such as reduced design and labor costs.

For all Diablo Canyon plants investigated, there are significant cost reductions relative to other potential desalination projects in the state. Even with reduced costs, these costs are not competitive with many traditional water resources when considering only the current monetary cost [70]. However, as traditional sources are further exploited, the cost of incremental additional water supply increases, both in terms of financial costs and environmental costs, making alternatives, such as carbon-free desalination, much more attractive.

Conclusion

California is facing intertwined challenges at the nexus of energy, water, and environment. In this report, we set out to determine whether co-locating a desalination plant with DCNPP would be technically feasible and might produce water more cheaply than other large-scale desalination alternatives. We considered what potential large-scale and mega-scale desalination alternatives might look like, and we considered the plant design, siting, intake, outfall, distribution, power sources, and integration with DCNPP. We have shown that, as configured, a desalination plant at DCNPP is very likely to be economically attractive when compared to other seawater desalination alternatives. The final costs of water, including distribution, are between \$0.79 and \$1.19 per m^3 within a distribution radius of 100 miles from DCNPP. This water production would be powered with a carbon-free source, and it would be free from the risks of drought and shifting weather patterns. Such a plant represents a significant reduction in the cost of desalinated water when compared to large-scale desalination alternatives at other sites, which we estimate to cost at least \$1.84 per m^3.

This estimate is preliminary, and significant site-specific development would be required to produce a more precise cost of water. Significant challenges will accompany siting the plant, developing an intake and outfall plan that will receive approval from all regulators, and developing a construction plan that deals with the remote and environmentally sensitive nature of the area. The current timeline of DCNPP's closure, structuring water purchase agreements, and a host of political issues may also pose challenges to such a project. However, we believe we have shown in this report that, with DCNPP's continued operation, building a large-scale desalination plant on-site is feasible and economically attractive. Further, this plant would help to secure California's water and energy supplies in a carbon-free manner.

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Appendices

Appendix A – Intake Screens, Inc. Report

DIABLO CANYON POWER PLANT
CONCEPTUAL DESIGN AND BUDGETARY ESTIMATE FOR FINE-SLOT MECHANICAL BRUSH-CLEANED WEDGEWIRE SCREENS

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DIABLO CANYON POWER PLANT
CONCEPTUAL DESIGN AND BUDGETARY ESTIMATE FOR FINE-SLOT MECHANICAL BRUSH-CLEANED WEDGEWIRE SCREENS

Intake Screens, Inc. (ISI) is pleased to provide this conceptual design and budgetary estimate for installation of a fine-slot mechanical brush-cleaned wedgewire screen system at the Diablo Canyon Power Plant (DCPP). The sections that follow provide an overview of ISI and our wedgewire screen systems, a basis of design, conceptual design, and budgetary estimate.

OVERVIEW - INTAKE SCREENS, INC.

ISI uses patented technologies and award-winning designs to fabricate self-cleaning wedgewire screen systems that address site-specific conditions and provide the highest level of aquatic organism protection available today. ISI has been delivering intake screen systems for 25 years and has completed more than 300 custom screen design and fabrication projects across freshwater, estuarine, and marine environments. Each project includes careful consideration of site conditions and regulatory requirements to develop a customized screen system optimized for the site. Key ISI design innovations and features considered during each project's design phase include:

- Selection of wedgewire screen material (0.5 - 9.0 mm) with low approach (0.2 - 0.4 fps) and through-screen velocities (0.3 - 0.8 fps) to meet aquatic organism protection regulatory criteria
- Use of mechanical brush-cleaning systems to ensure reliable sourcing of water and conformance with aquatic organism protection velocity criteria
- Careful selection of conical, cylindrical, and other screen shapes to best suit site conditions
- Use of retrieval systems to facilitate inspection and maintenance of screen systems
- Use of anti-fouling coatings and unique brush configurations to maximize cleaning effectiveness
- Material selection, cathodic protection, and isolation of dissimilar metals to minimize corrosion
- Use of drive types that are best suited to site conditions including selection of hydraulic, electric, turbine and solar powered systems
- Minimization of head loss through design of low-velocity systems
- Incorporation of air bubbler systems to reduce surface ice, water jets to move debris, and sediment resuspension systems to maintain site elevations.

ISI's project delivery expertise includes large-scale, design-build projects where we provide complete design, build, installation, commissioning, and training services. This experience allows us to optimize designs to reduce total project cost, facility downtime, and minimize regulatory hurdles across all our projects.

ISI Mechanical Brush-cleaned Wedgewire Screens

What differentiates ISI screens is our patented brush-cleaning system. This system involves a submersible drive assembly that rotates wedgewire screen cylinders between nylon brushes. The exterior of the wedgewire is cleaned by a fixed position external brush and the interior of the screen is cleaned by an internal brush that

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SACRAMENTO, CA 95832

rotates on a bearing bar. This brush-cleaning system has proven effective at maintaining a clean screen surface in the most challenging fouling community and debris loading environments. Maintenance of a clean screen surface is critical to providing aquatic organism protection where a screen that becomes fouled by organism growth or debris accumulations is prone to developing velocity "hot spots" which increase the potential to either entrain or impinge aquatic organisms including fish eggs, larvae, juveniles, and adults and/or result in the inability to convey water through the intake screen. Uniformity of approach and through-screen velocity is maintained over the entire screen surface through incorporation a graduated porosity flow modifier inside the screen. The arrangement of a typical mechanical brush-cleaned wedgewire screen is shown in Figure 1.

Figure 1. Intake Screens, Inc. Typical Mechanical Brush-cleaned Screen

The ISI screen cleaning system is operated from a Programmable Logic Controller (PLC) with touchscreen Human-machine Interface (HMI) located at the shoreline or in a control room (Figure 2). A typical screen cleaning cycle will include one minute of forward rotation and one minute of backward rotation of the screen cylinder. Typical screen cleaning frequency is two to five cleaning cycles per day. Screen cleaning cycle can be manual, programmed by the operator, and/or triggered based on a pressure differential or other threshold signals built into the system. All ISI screen cleaning systems are design to be able to run continuously. Figure 3 shows the effectiveness of the ISI brush-cleaning system at keeping a screen surface clean in the extreme fouling community found in the estuarine Hudson River.

Figure 2. Intake Screens, Inc. Typical Programmable Logic Controller (PLC), Control Panels and Touch Screen Human Machine Interface (HMI)

Figure 3. Intake Screens, Inc. Mechanical Brush-cleaned Screen Operating in Estuarine Hudson River

BASIS OF DESIGN - DIABLO CANYON POWER PLANT WEDGEWIRE SCREEN SYSTEM

The following sections provide the key principles, assumptions, rational and criteria used to develop this conceptual design and budgetary estimate. Critical information to allow the sizing of the screen system is design flow rate, screen slot opening size, and approach or through-screen velocity. After sizing of the screens, the location, orientation, and other features are determined based on site-specific conditions.

DCPP Design Flow Rate

While there are several electrical generation and desalination capacities being considered for DCPP, we understand there are just two design flow scenarios to be considered for conceptual design purposes:

Flow Scenario 1: 110 m^3/s (3,885 cfs)
Flow Scenario 2: 356 m^3/s (12,572 cfs).

Anticipated Slot Size and Velocity Requirements

The California State Water Resources Control Board issued a *Water Quality Control Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling* in 2010 which provides guidelines related to once-through cooled power plant environmental protections and electric reliability within the state. The policy has been amended several times since original publication, with the current version having an effective date of November 30, 2020 (CWB 2020). In terms of environmental protections, the policy sets a "Track 1" technology-based standard of reductions in cooling water flows by at least 93 percent (derived from what is expected to be achievable with installation of closed-cycle wet cooling towers) to reduce both entrainment (withdrawal of small organisms through the cooling water system) and impingement (entrapment of larger organisms on the traveling water screens at the entrance to the cooling water system). These facilities must also achieve a through-screen velocity of 0.5 fps or less for the remaining cooling water withdrawal.

For facilities that successfully demonstrate to the State Water Resources Control Board that meeting Track 1 is not feasible, facilities may reduce entrainment and impingement through use of operational or structural controls, or both. These facilities have an opportunity to use "control technologies" to address impingement by reducing through-screen velocity to 0.5 fps or less and address entrainment by demonstrating that they reduce entrainment by 90 percent of what would be achievable under Track 1 (i.e., reduce entrainment by at least 84 percent). This compliance approach also includes monitoring requirements which should be considered as a part of compliance costs and risks.

Overall, the 2010 policy has resulted in the decommissioning or planned decommissioning of once-through cooled power plants in the state due to high retrofit costs, parasitic loads/reduced plant efficiency, permitting challenges associated with retrofits, and other factors. While operation of once-through cooling in the state has been declining, permitting of desalination facilities withdrawing from marine waters has increased. The intake requirements for these desalination projects are relevant to determining what might be appropriate for DCPP.

The Claude "Bud" Lewis Carlsbad Desalination Plant is in operation today and withdraws water from the Agua Hedionda Lagoon's outer pond. The facility's 2019 National Pollutant Discharge Elimination System (NPDES) permit allows the facility up to five years to install a new source water intake structure. The permit indicates that, after review of tens of alternative intake structure technologies and designs, the San Diego Water Board permitted the facility to withdraw seawater through a wedgewire screen with a slot size no larger than 1.0-mm (to reduce entrainment) and at a through-slot velocity of not more than 0.5 fps (to reduce impingement). The placement of the screens is to be in an area that avoids the rocky shoreline habitat, and the intake laterals may be covered with natural sediments to restore habitat impacts after installation. The permit allows for pilot testing of fine-slot wedgewire screens within the five-year installation period.

The Huntington Beach Desalination Facility is a proposed project with a draft NPDES permit. The draft permit requires that the intake be comprised of 1.0-mm or smaller slot size rotating brush-cleaned wedgewire screens composed of stainless steel. Stainless steel was specified in this case rather than copper-nickel or other alloys over copper leaching concerns. The screens are to be operated such that the through-screen velocity does not exceed 0.5 fps at any time. Chemical and heat treatment of the offshore intake is prohibited.

With consideration of the 2014 policy applicable to once-through cooled power plants and the recent NPDES permitting requirements placed on desalination facilities, it is reasonable to assume that the DCPP screens would need to be constructed from 1.0-mm slot size stainless steel wedgewire material and have a through-screen velocity of no more than 0.5 fps. A mechanical-brush cleaning system will be required to maintain a clean screen surface and reduce the potential for exceedance of the through-screen velocity criteria. Antifouling coatings would be required rather than chemical or heat treatment. Finally, the placement of the screens will need to minimize potential environmental impacts (e.g., entrainment, impingement, habitat impacts).

Installation Environment

This marine waters near DCPP are high salinity (~35 ppt) and are expected to contain a robust fouling community. According to Bechtel (2014), the marine waters near DCPP is an area of significant production of marine algae, including surface kelp and understory algae and where kelp growth can reach 2 feet per day during the growing season between June and October. This area is also subject to tidal fluctuations (typical elevations are 0 to +6 feet above mean lower-low water), waves (normally 5 to 10 feet and reaching 20 to 30 feet during storm events), and wind (typically 10 to 25 mph and sometimes reaching 40 to 50 mph) (Bechtel 2014).

CONCEPTUAL DESIGN

The above basis of design indicates that the DCPP wedgewire screen system *must* include the following design specifications:

- 1.0-mm slot size wedgewire screen with a through-screen velocity of no more than 0.5 fps
- Mechanical brush-cleaning system on each screen
- Stainless steel screen construction
- Screens are to be located in an area that minimizes potential for environmental impacts
- Two flow scenarios are to be evaluated: 110 and 356 m^3/s.

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With consideration of site conditions, ISI *recommends* these additional design specifications:

- Wedgewire screen material and internal structures should be constructed from 2507 Super Duplex Stainless Steel with cathodic protection and material isolation to protect against corrosion in the marine environment
- Antifouling coatings should be applied to the wedgewire screen flow modifier to maintain uniformity of flow over the wedgewire screen surface
- The screen system should be located approximately 1,000 feet from shore in relatively deep water (>50 ft) to avoid the more sensitive nearshore marine habitats and potential higher aquatic organism densities located in the nearshore area
- Due to the distance from shore an electric drive system is recommended to power the brush-cleaning system. This electric drive assembly is to be contained within 2507 Super Duplex Stainless Steel isolation chamber filled with freshwater or oil and equipped with an air bladder to allow for thermal expansion and contraction
- The manifold array that supports the screens and connects to the central header pipe must be engineered to achieve equal withdrawal from each wedgewire screen[1]
- The wedgewire screens should be vertically oriented drum screens to enable boat/barge inspections and simplified maintenance and repair where brushes, drive assemblies, and screens can be unbolted and raised vertically to the water surface and reinstalled similarly
- Access hatches should be included on the top of the screens to allow for easy access to the internal brush and drive assembly
- Access hatches should be included in the manifold array to allow for intake pipe, manifold array, and screen inspection as well as potential pigging of the pipe.

To accommodate the required flow rates, a D168-240EC-F screen is proposed for the DCPP project (Figure 4). This is a drum screen ("D") with a cylinder measuring 168 inches in diameter and 240 inches long. The screen has an electric drive assembly ("E"), is made of 2507 Super Duplex Stainless Steel ("C") and is flange mounted ("F"). Each screen would have 1.0-mm slot openings and 1.75-mm wire width resulting in a 36.36 percent open area. At a 0.5 fps through-screen velocity, each screen would have a design flow rate of 4.53 m^3/s (159.9 cfs) and an approach velocity of 0.18 fps. The screens will be installed on a concrete manifold to ensure uniform withdrawal from each screen (Figure 5)

[1] When screens are installed in series on a straight pipe, the most downstream screens (relative to the withdrawal stream) will tend to take more flow than the upstream screens. This can result in more debris loading on the downstream screens and violation of velocity criteria in a worst-case scenario. ISI has found that manifold arrays are generally preferable to flow baffling or other modifications that would be required to achieve equal flow distribution for a linear pipe array.

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8 4 1 7 R I V E R R O A D
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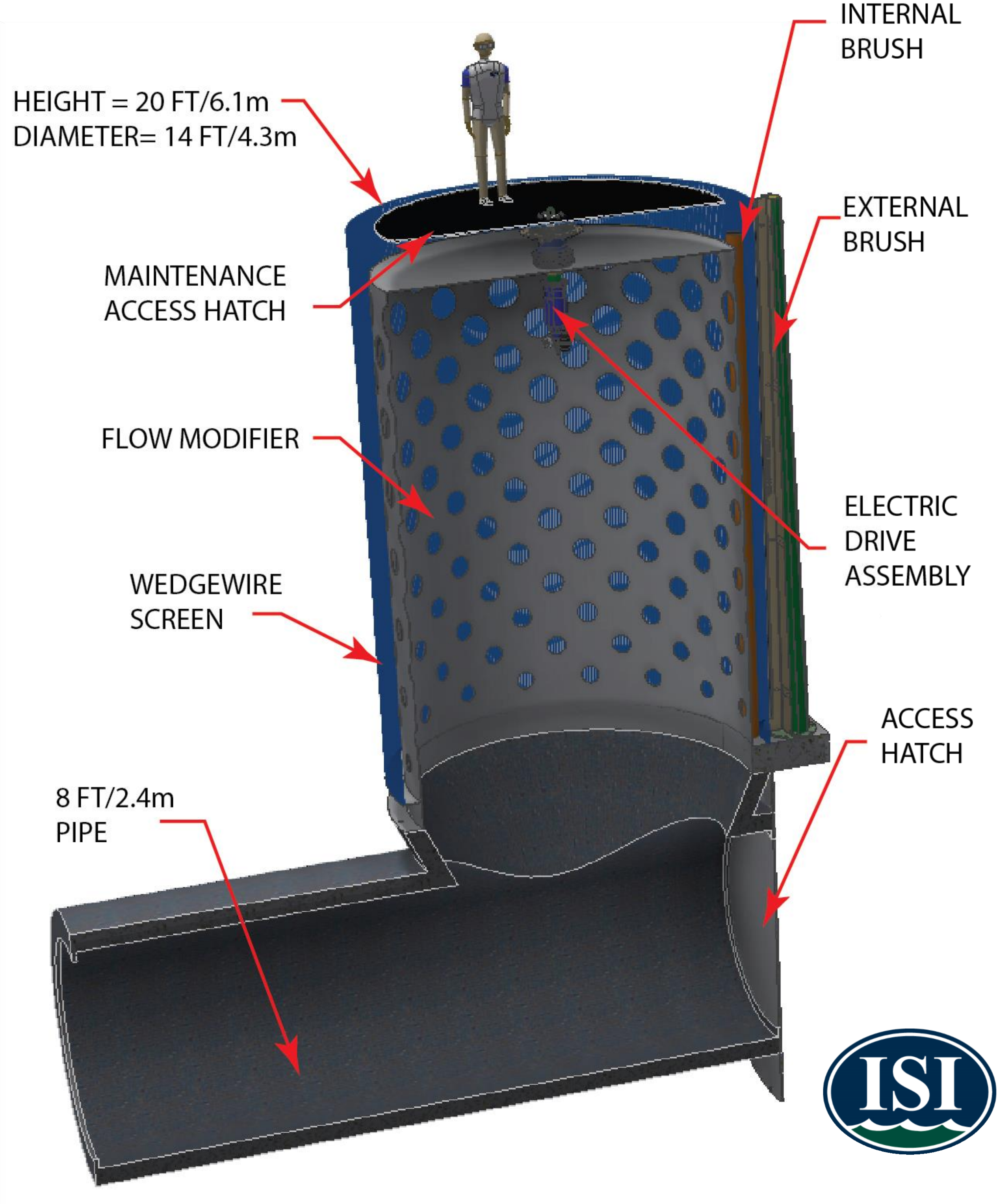

Figure 4. Intake Screens, Inc. D168-240EC-F Wedgewire Screen Proposed for Diablo Canton Power Plant (Note: human shown for scale)

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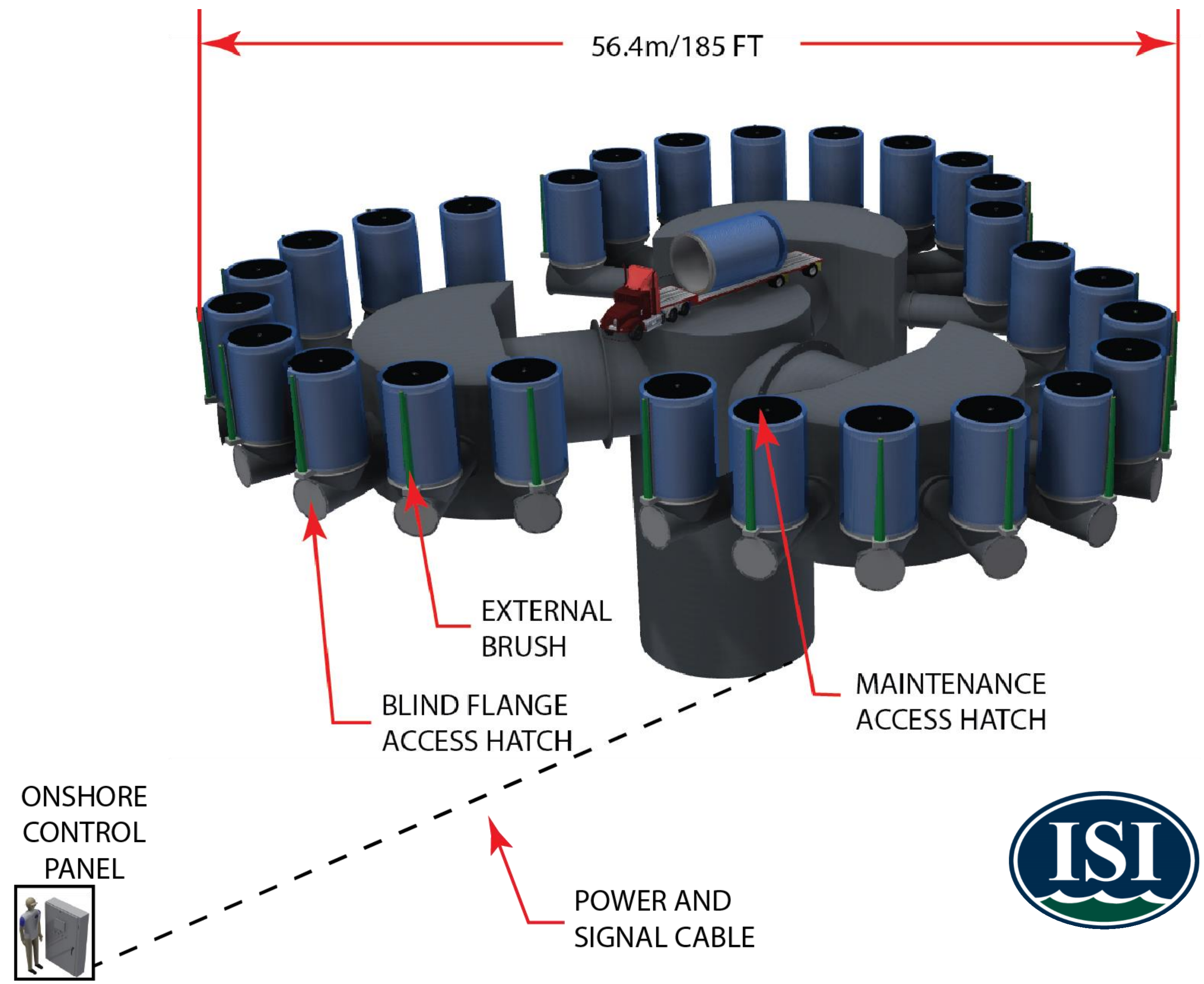

Figure 5. Intake Screens, Inc. D168-240EC-F Wedgewire Screen on Concrete Manifold Array (Note: screen on flatbed shown for scale)

Table 1 provides the recommended number of screens, manifold arrays, and other key design parameters for the two flow scenarios being considered. The screen surface area is overbuilt by 11 and 3 percent in these scenarios to allow some debris occlusion before the through-screen velocity criteria would be exceeded. A typical screen overbuild target is around 10 percent.

Table 1. Diablo Canyon Power Plant D168-240EC-F Screen System Details

Flow Scenario	No. of Screen	Number of Screens Per Manifold Array/Number of Manifold Arrays	Total Capacity	Screen Surface Area Overbuild (percent)	Full Flow Through-Screen Velocity (fps)	Full Flow Approach Velocity (fps)
Flow Scenario 1: 110 m^3/s; 3,885 cfs	27	27/1	4,318 cfs	11	0.45	0.16
Flow Scenario 2: 356 m^3/s; 12,572 cfs	81	27/3	12,955 cfs	3	0.49	0.18

Following the approach used in Bechtel (2014), the existing shoreline basin would be closed off from the Pacific Ocean by extending the existing breakwater structure. The new section of breakwater would include a section of reinforced concrete walls and stop log structure so the wedgewire screens could be bypassed should the need arise (Figure 6). The shoreline basin would then be connected to each offshore screen array by a drop shaft below the basin that leads to a bored tunnel and terminates at the manifold array (See Figures 6 and 7 for Flow Scenario 1 and Figure 8 for Flow Scenario 2). To place the screens in an appropriate offshore, deep water location that minimizes potential impacts to aquatic resources, the tunnel is anticipated to be approximately 1,000 feet long. Lining of the tunnel may be required depending on the rock and fault conditions encountered during boring.

The wedgewire screens would be controlled by a PLC with touchscreen HMI located in the DCPP control room. Power and signal cable would be routed within protective conduit from the control room to each screen either within the intake pipe or along the seafloor. Power cable would be used to power the drive assemblies while signal cable would provide operational status and overtemperature and moisture feedbacks.

Appendix A provides PowerPoint slides from a presentation made to the Electric Power Research Institute (EPRI) in November 2020 detailing an ISI once-through cooling water intake system screen retrofit project at a power plant in New York State. This project includes many elements that are like those proposed for DCPP.

BUDGETARY ESTIMATE

Budgetary estimates were developed for each design flow scenario. The estimates include the complete wedgewire screens, antifouling coatings, controls, power and signal cable, concrete manifold array, engineering submittals, equipment delivery to the site, installation support, operator training, and 2-year warranty. The budgetary estimate for the 110 m^3/s design flow system is \$70-\$100M. The budgetary estimate for the 356

m^3/s design flow system is $200-250M. These budgetary estimates include the equipment shown in Figure 5 (where the 356 m^3/s design flow system would have a total of three (3) screen arrays) and does not include construction or installation of the screen systems.

REFERENCES

Bechtel Power Corporation. 2014. Alternative Cooling Technologies or Modifications to the Existing Once-through Cooling System for the Diablo Canyon Power Plant. Report No. 25762-000-30H-G01G-00001.

California Water Board (CWB). 2020. Water Quality Control Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling. State Water Resources Control Board. Amended on November 30, 2020.

Figure 6. Aerial View of Diablo Nuclear Power Plant with Breakwater Extended to Isolate Lagoon, Emergency Inlet Structure, Tunnel Extending Offshore and Wedgewire Screen Array for 110 m^3/s Option

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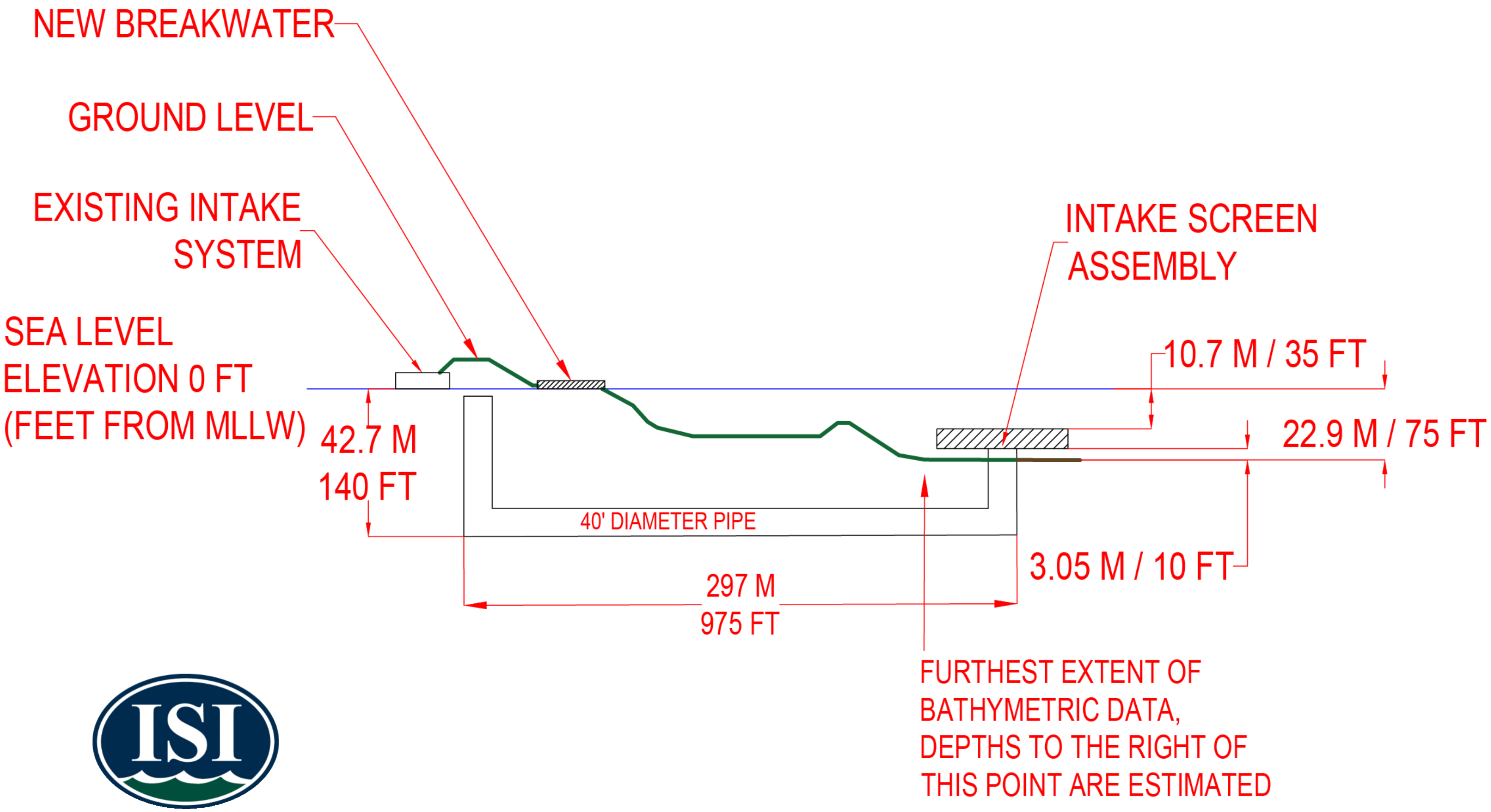

Figure 7. Section View of Diablo Nuclear Power Plant Tunnel Extending Offshore and Wedgewire Screen Array for 110 m^3/s Option

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Figure 8. Aerial View of Diablo Nuclear Power Plant with Breakwater Extended to Isolate Lagoon, Emergency Inlet Structure, Tunnels Extending Offshore and Wedgewire Screen Arrays for 356 m^3/s Option

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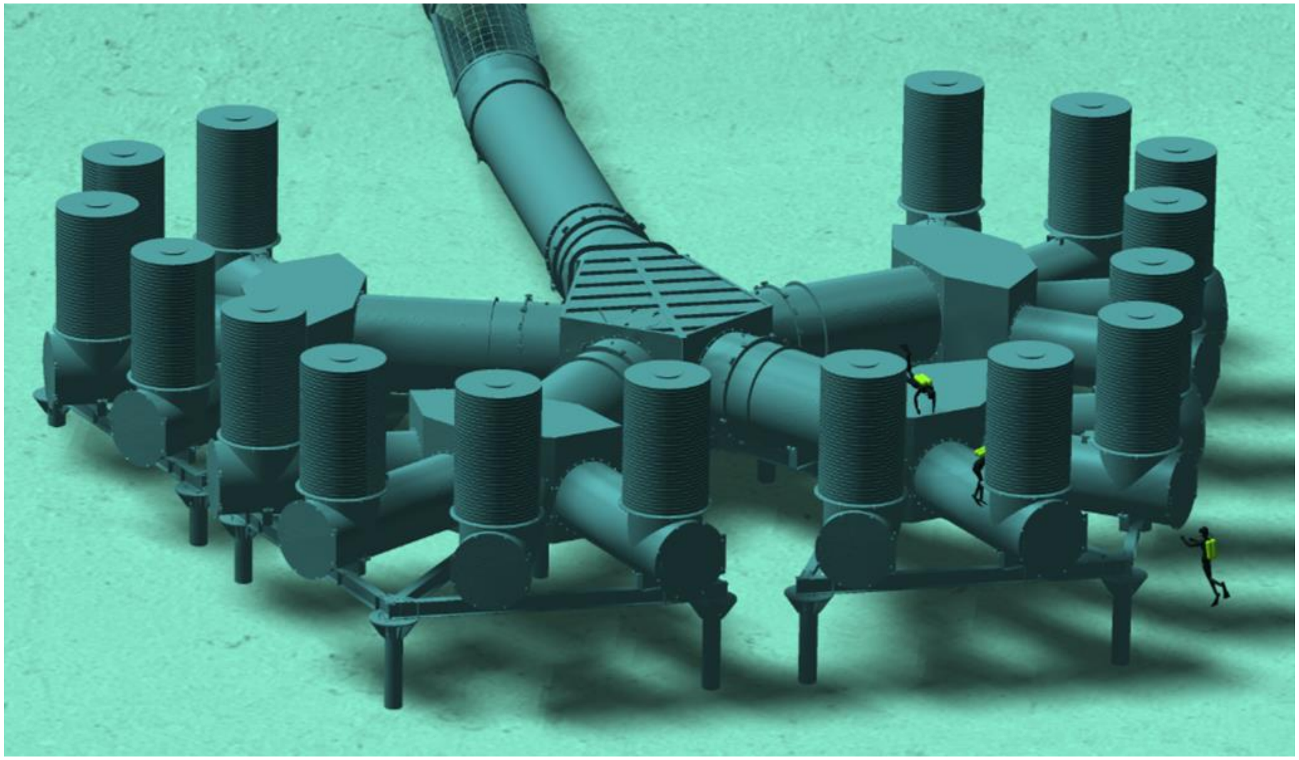
APPENDIX A

DESIGN, CONSTRUCTION, AND OPERATIONAL HISTORY OF A 0.75-MM SLOT SIZE BRUSH-CLEANED WEDGEWIRE SCREEN RETROFIT AT A ONCE-THROUGH COOLED POWER PLANT




Design, Construction, and Operational History of a 0.75-mm Slot Size Brush-cleaned Wedgewire Screen Retrofit at a Once-through Cooled Power Plant
EPRI
November 2020
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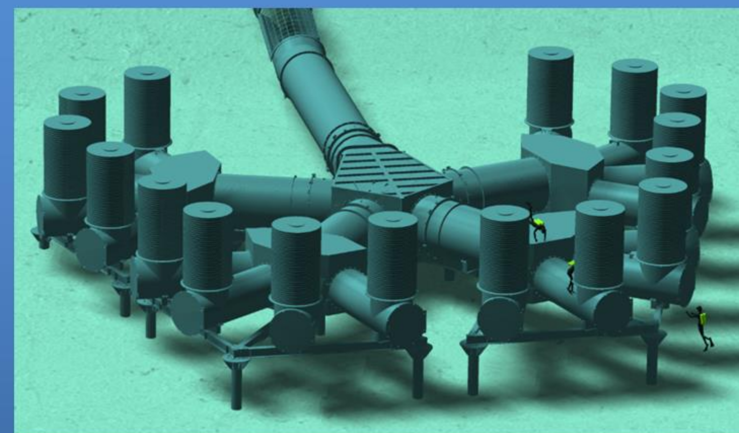
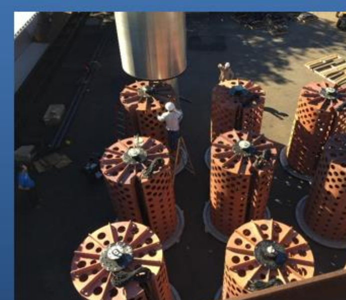
AGENDA

- Background
- Design and Construction
- 2020 Dive Inspection
- Q&A





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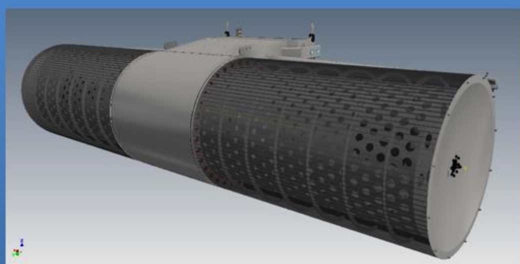
INTAKE SCREENS, INC.

Brush-Cleaned Wedgewire Systems ● Fish Protection ● Founded 1996



Design, Fabrication, and Installation Capabilities

Cone-Shaped Wedgewire Screens

Fixed and Retrievable Wedgewire Screens

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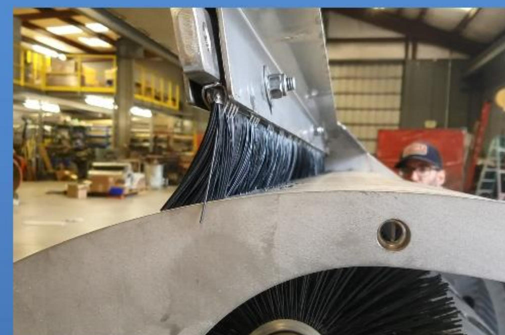
INTAKE SCREENS, INC.

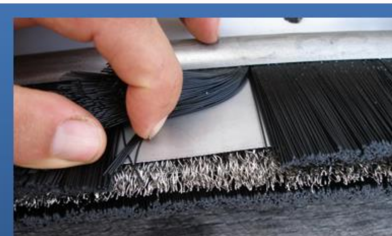
ISI Screen Advantages

- No fish or debris collection and conveyance
- Large screen surface area in small footprint
- Exceptional debris and biofouling control
- Designs tailored to address site-specific challenges
- Small slot size and low approach and through-screen velocities meet the most stringent fish protection requirements



External and Internal Brush

Valley Power Plant, Milwaukee, WI



Fine-slot Brush Design

0.75mm Slot, 30% Open Area

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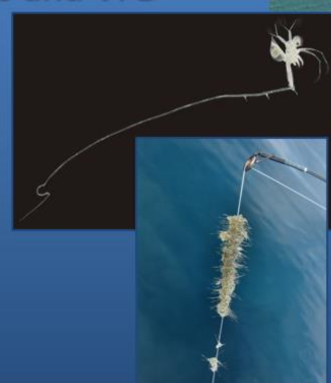
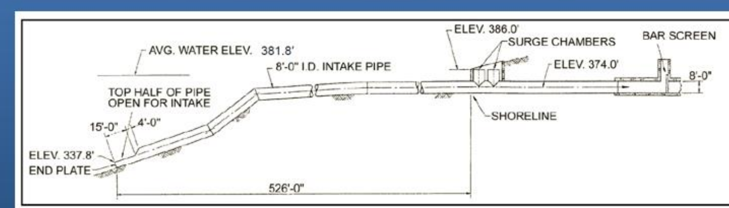
CAYUGA POWER PLANT - BACKGROUND

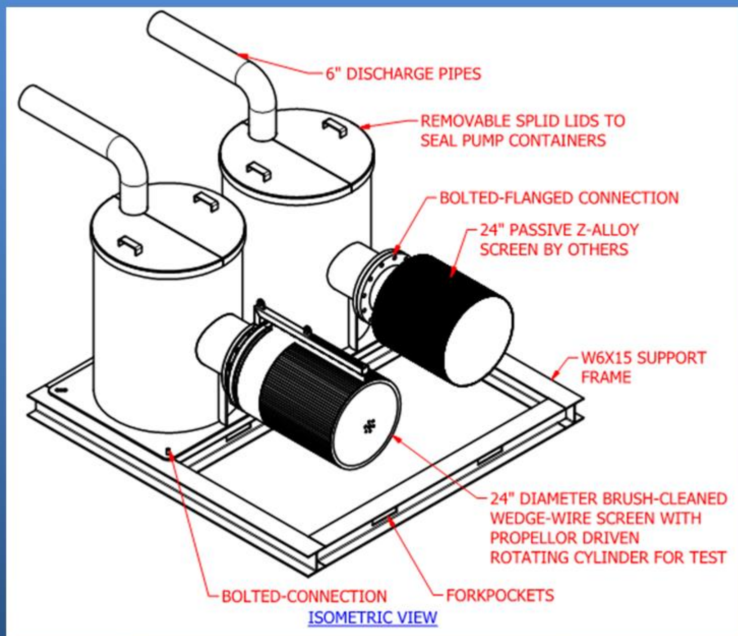
- 306 MW coal-fired power plant
- 245 MGD offshore, deep water intake with 1 ft^2 coarse grating; condenser backwashed to remove fish and debris
- 2015 BTA Determination
  - 0.5-1.0-mm wedgewire screens and VFD
  - 0.5-mm pilot study required
- Debris Concerns
  - Zebra and quagga mussel
  - Fishhook waterflea
  - Algae
  - Uprooted SAV





CAYUGA POWER PLANT - BACKGROUND

ISI constructed 0.75-mm mechanical brush-cleaned and 0.75-mm Cu-Ni passive screen pilot testing



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CAYUGA POWER PLANT - BACKGROUND

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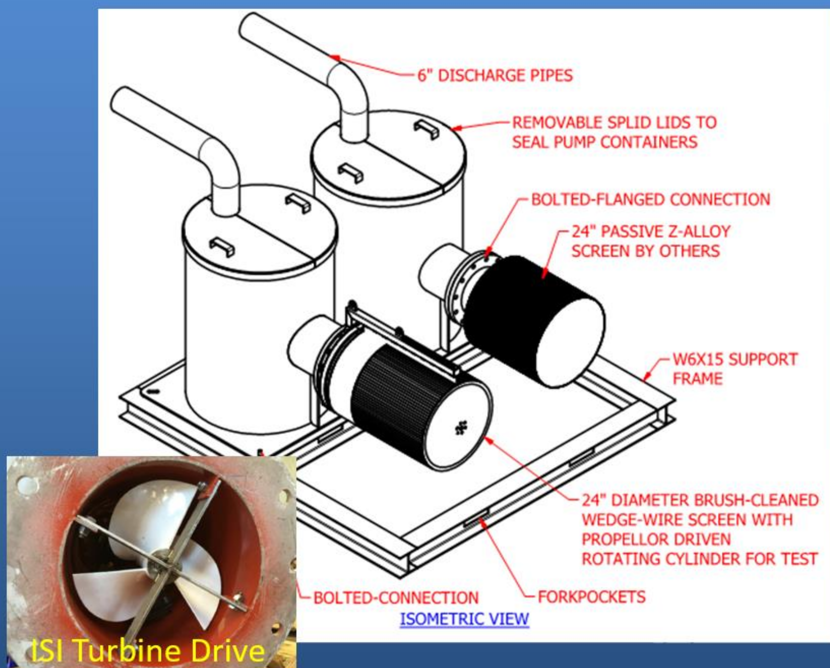

- Both screens 24-in diameter and 24-in long
- 1.4 MGD flow rate = 0.56 fps TSV
- Turbine drive on ISI screen
- Pump amperage measured as surrogate for blockage (although data never reported on)
- Screen coupons (4 x 4-in samples) included Cu-Ni, 316L SS, Juton Sealion Resilient, Juton Sealion Repulse
- 4-month study (mid July- mid November) with 2x per month diver inspections

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CAYUGA POWER PLANT - BACKGROUND

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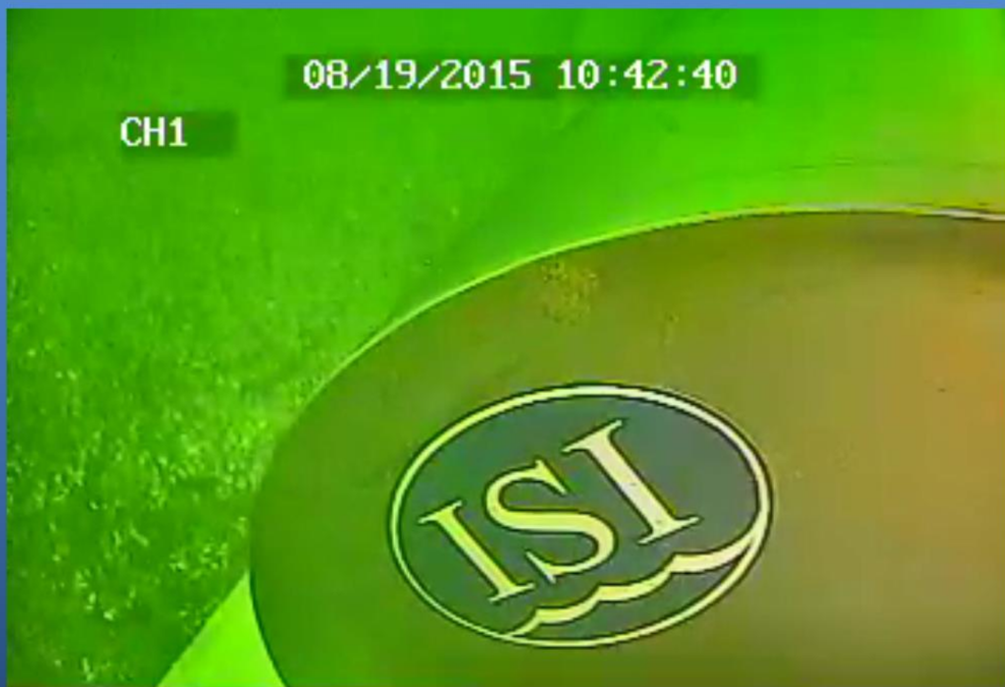

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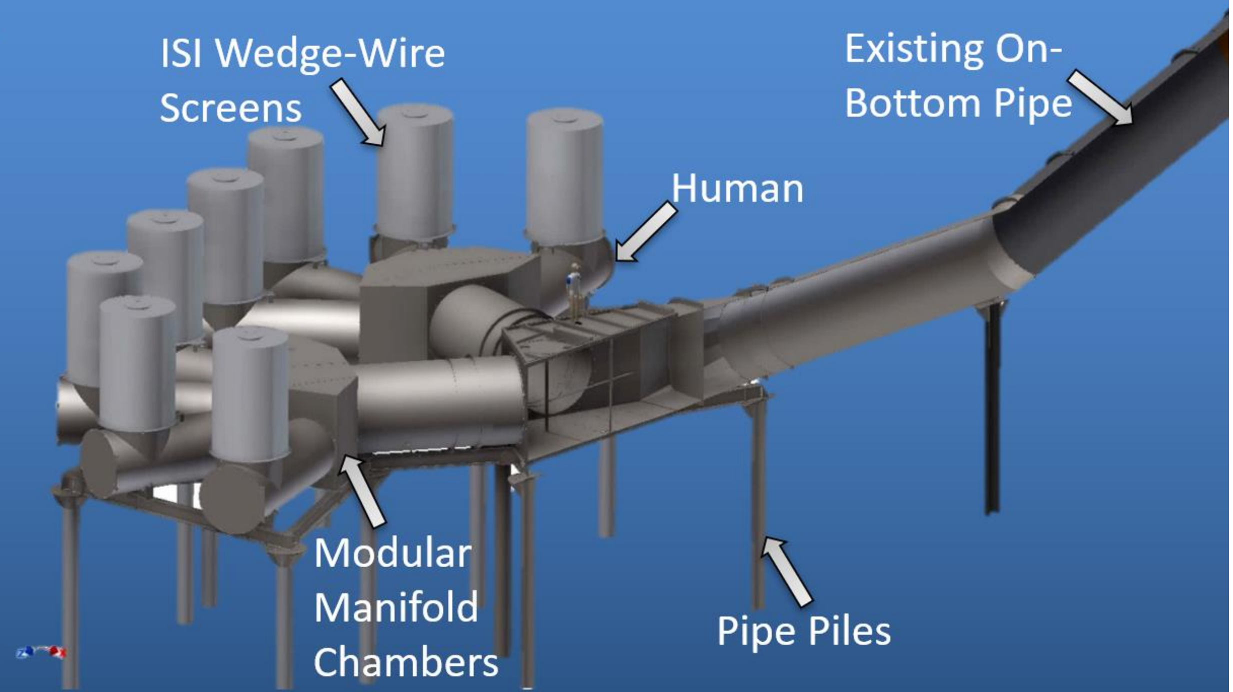
CASE STUDY: CAYUGA LAKE INTAKE RETROFIT

- ISI Wedge-Wire Screens
  - 16ea. 83” x 120”
  - 0.4 fps through-screen velocity
  - 0.75mm slot width
- Manifold:
  - 4 “radial” branches
  - ~150 tons steel
- Submarine Cables:
  - ~22,000 ft installed



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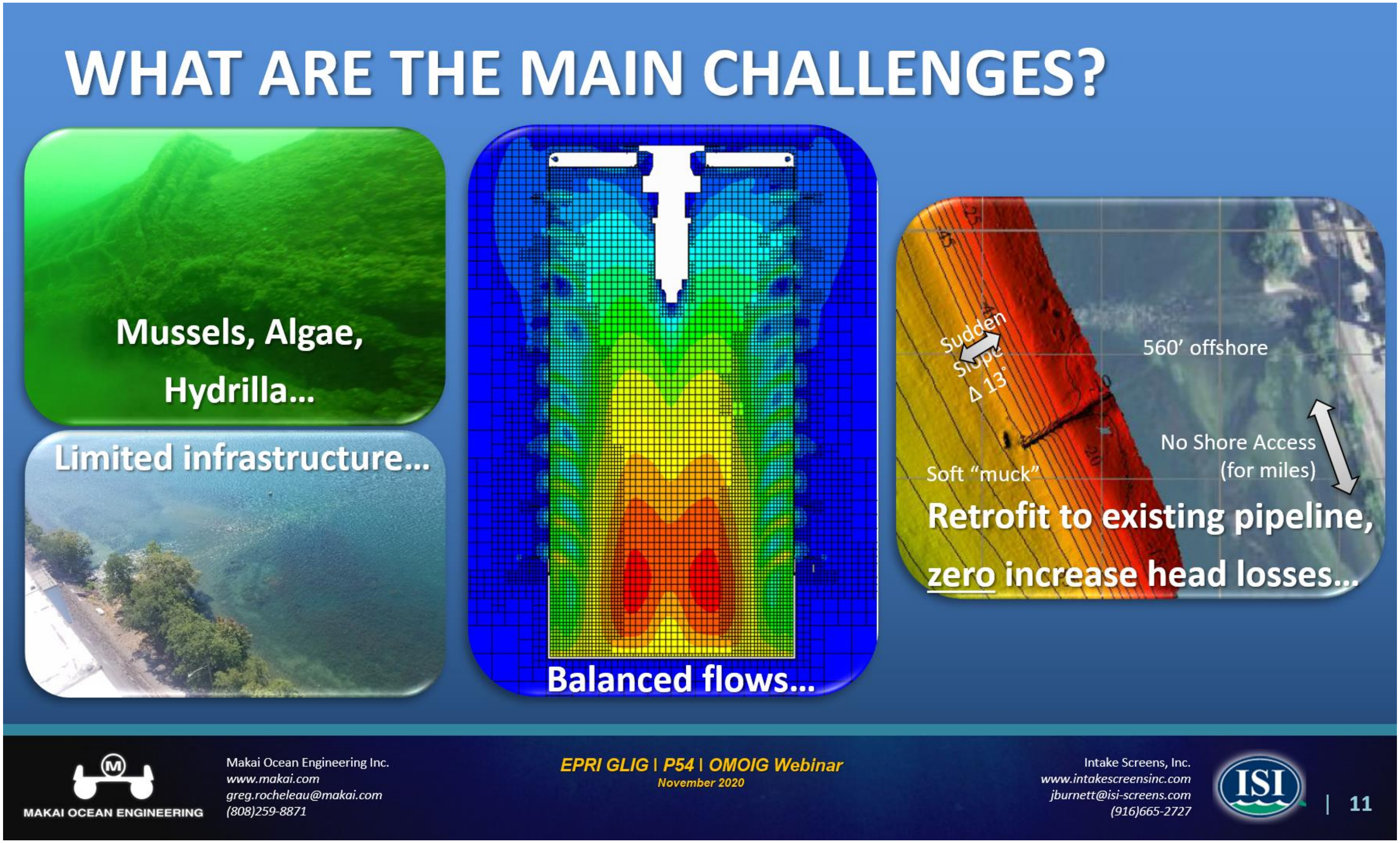
WHAT ARE THE MAIN CHALLENGES?
Mussels, Algae, Hydrilla…
Limited infrastructure…
Balanced flows…
Sudden Slope Δ 13°
560' offshore
No Shore Access (for miles)
Soft "muck"
Retrofit to existing pipeline, zero increase head losses…
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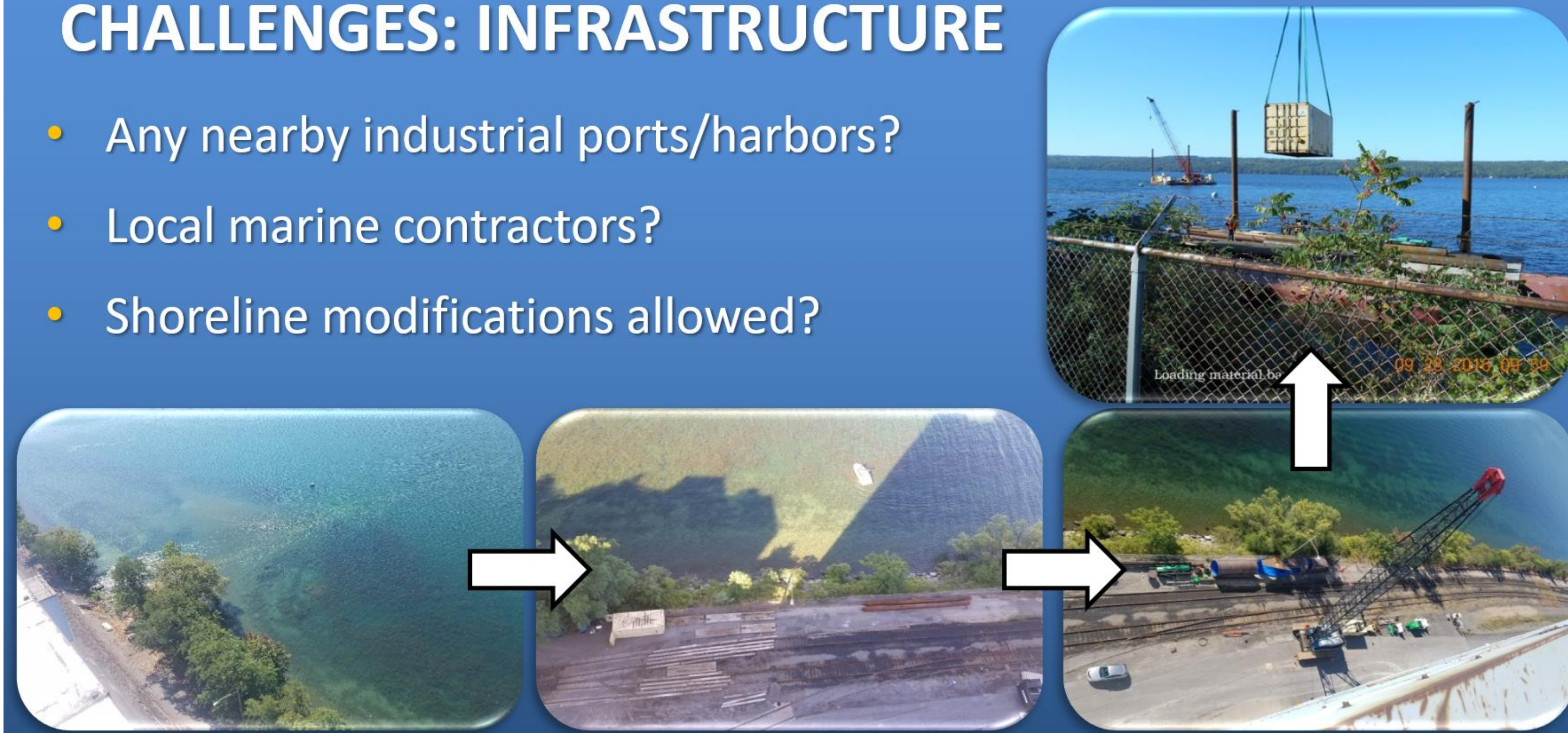
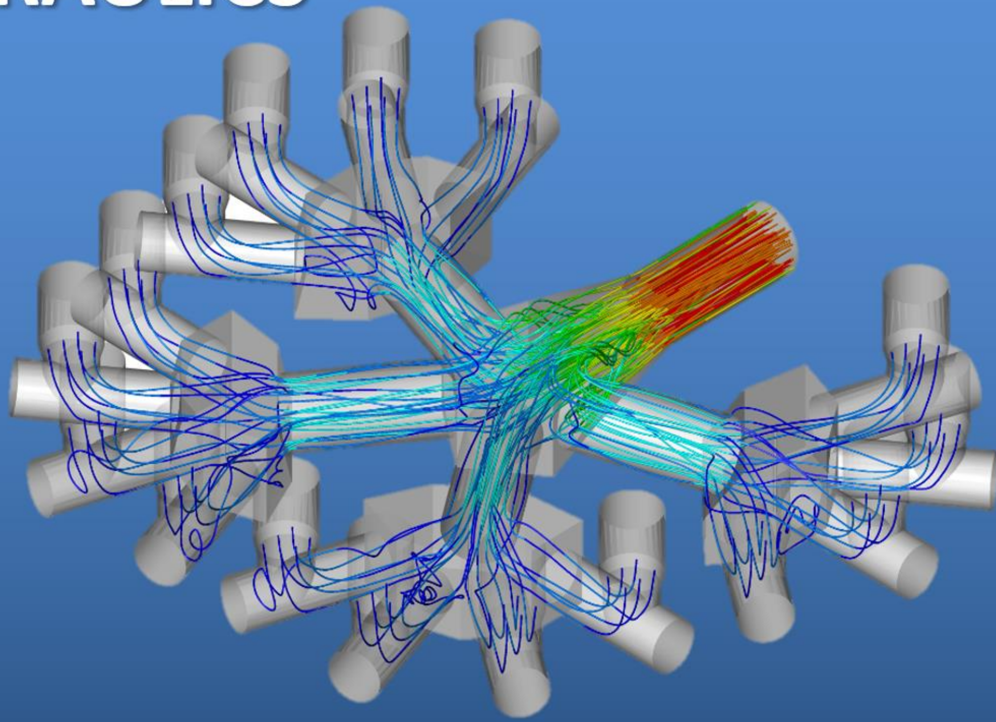
CHALLENGES: INFRASTRUCTURE

- Any nearby industrial ports/harbors?
- Local marine contractors?
- Shoreline modifications allowed?



CHALLENGES: HYDRAULICS

- Existing pump station
- Flow balance
- Zebra mussel fouling
- Distance offshore



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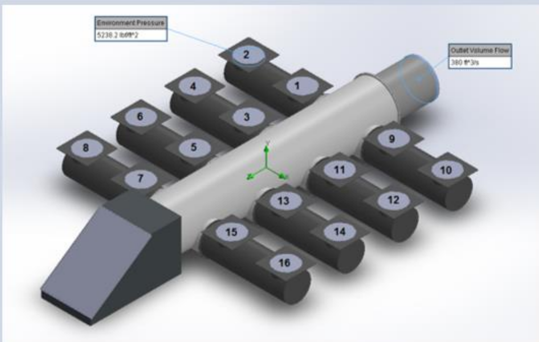
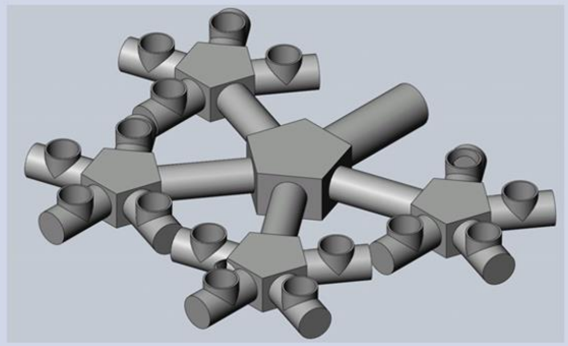
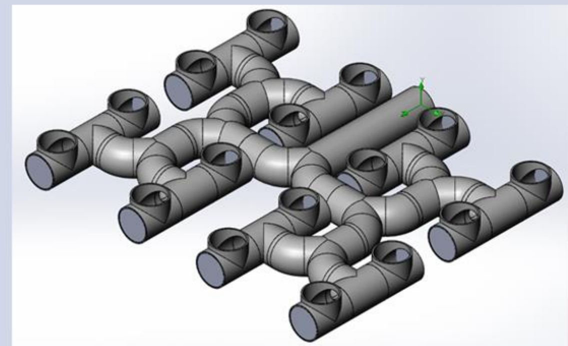
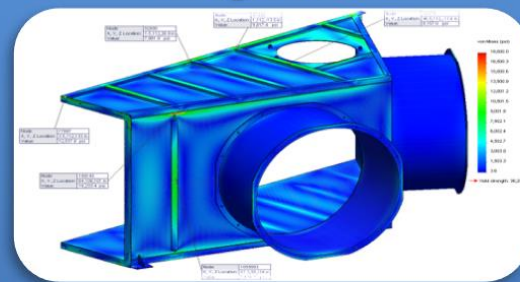
HEAD LOSS & UNIFORM FLOW

Linear	Radial	Symmetric
		
Unbalanced, highest flow losses. Most compact, simplest.	Balanced flow. Modular construction and easy diver access.	Balanced flow. Poorer diver access for maintenance.

INTEGRATED DESIGN

Diver & subsea friendly

Design Loads

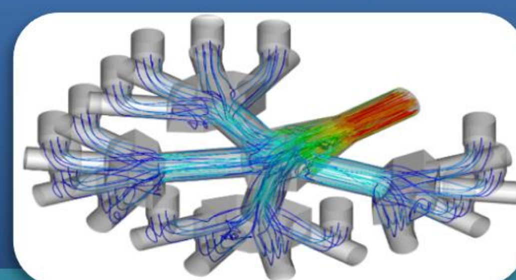


MAKAI INTEGRATED DESIGN

- Construct-ability
- Geotech
- Structure & FEA
- Flow & CFD

Foundations

Balanced flow



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CONSTRUCTION…
Fabrication at ISI in California
Screens, manifold, and dry land fit ups
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CONSTRUCTION…

- Shipped via truck, chambers assembled on offshore barge
  - No onsite fit up required

CONSTRUCTION…

- Installed in modular components
- Pieces located relative – no absolute positions required

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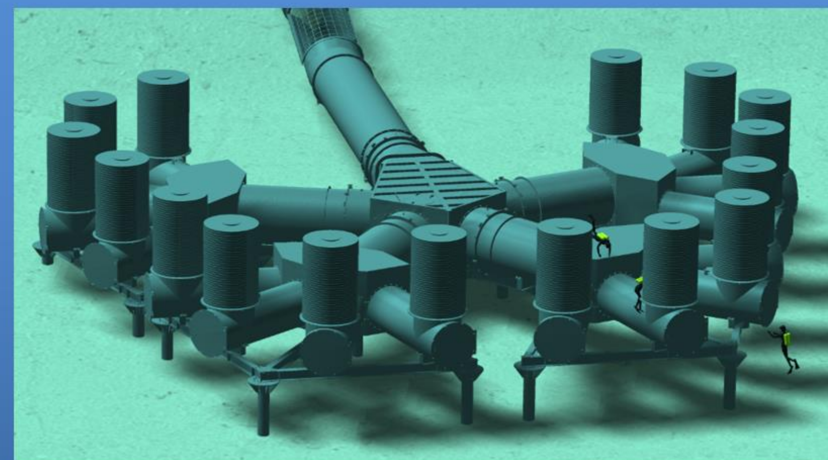
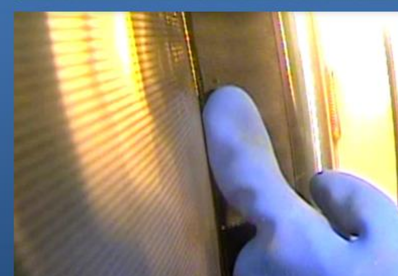
CONSTRUCTION…

- Cables to shore routed through intake pipeline

KEY FINDINGS

- Construction of large offshore screen installations is feasible
- Symmetrical screen layouts recommended for balanced flow
- Brush cleaned screens provide cleaning of mussels and debris
- Design process needs to integrate constructability based on real world offshore experience
- The modular approach reduces offshore construction risks





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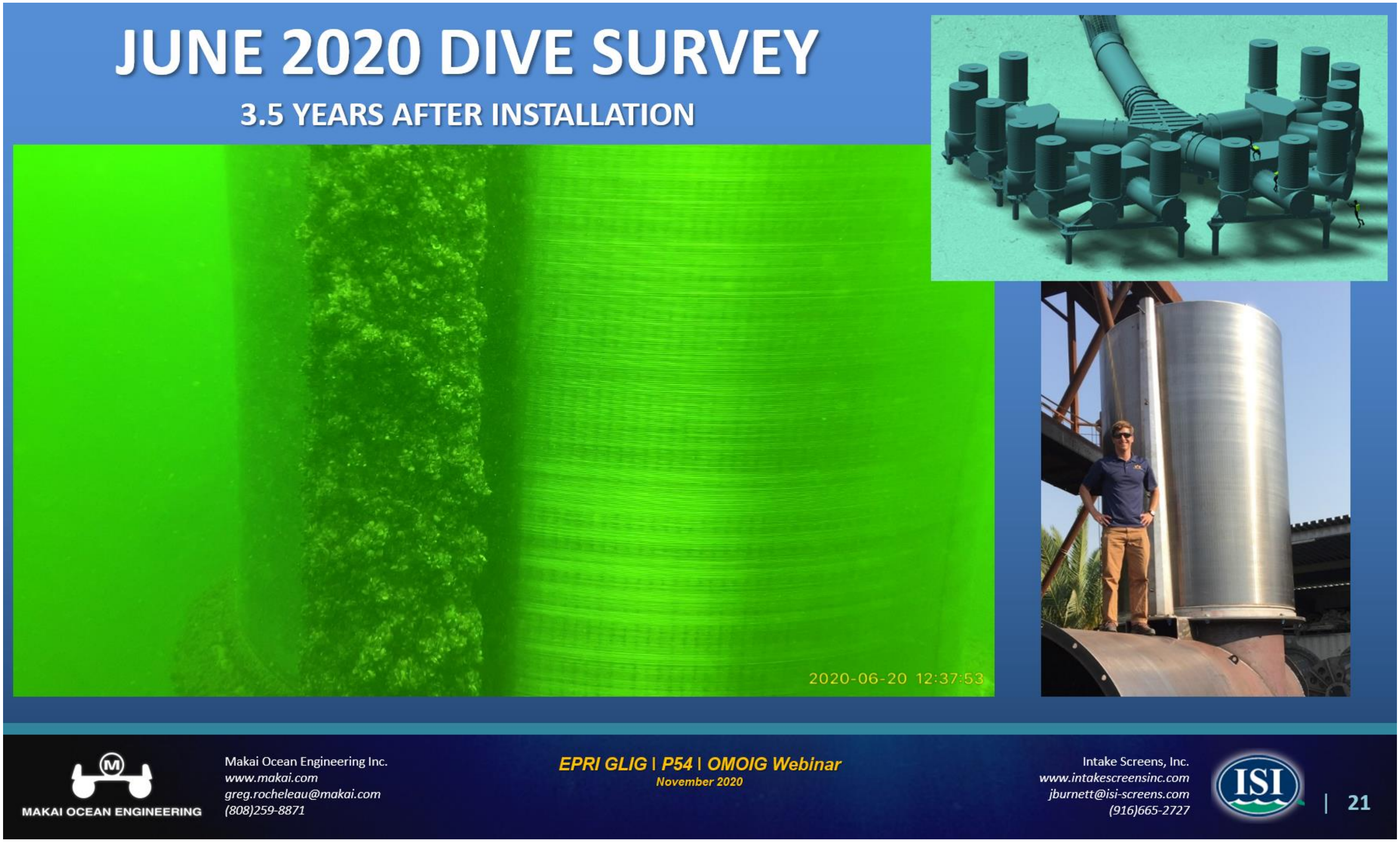
JUNE 2020 DIVE SURVEY
3.5 YEARS AFTER INSTALLATION
2020-06-20 12:37:53
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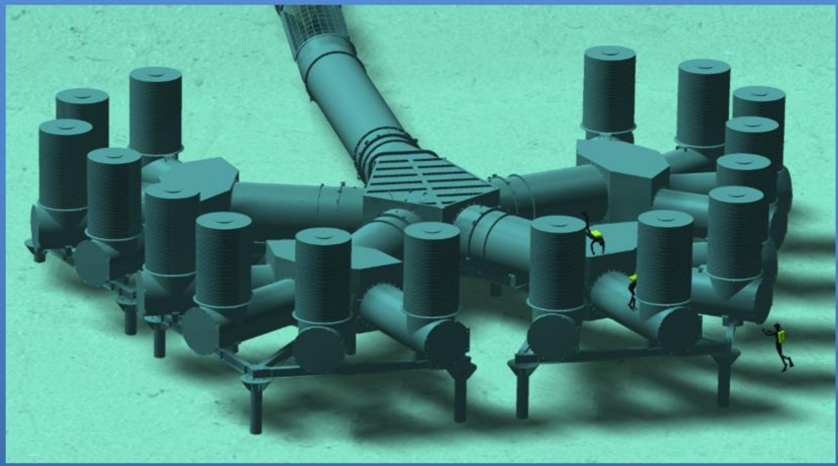
CAYUGA OPERATOR COMMENTS FROM 11/9/2020

- "The screens have worked great"
- "Never had an issue" involving screen malfunction
- No maintenance performed
- Lower heat rate with installation of screens
- No more diver cleaning of intake to remove mussel shells
- Exceeded NYSDEC I&E reduction requirements



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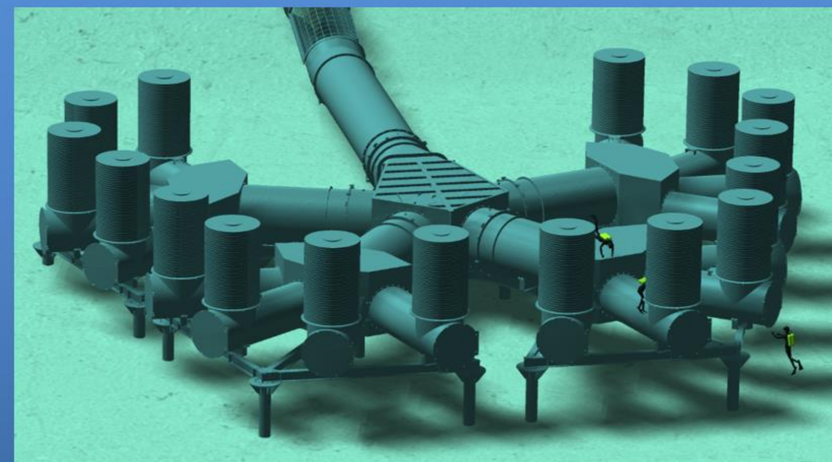
CAYUGA OPERATOR COMMENTS FROM 11/9/2020

- Generation and circulating water pumps stopped operation last August
- 400-acre site anticipated to convert to solar farm with data center(s)
- They will maintain permit and operate one screen going forward
- 15 screens are available for repurposing at another facility
- Contact ISI for information or a facility contact



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