California ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

# FINAL PROJECT REPORT

# Design and Build of Low-Rate Initial Production Line for Energy-Efficient Wastewater Processing

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# PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency; renewable energy and advanced clean generation; energy-related environmental protection; transportation; and energy transmission and distribution.

In 2011, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned electric utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company, and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

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- Providing societal benefits.
- Reducing greenhouse gas emissions in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs, first with energy efficiency and demand response, next with renewable energy (distributed generation and utility-scale projects), and finally with a clean electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Design and Build of Low-Rate Initial Production Line for Energy-Efficient Wastewater Processing is the final report for EPC-21-019 conducted by Porifera, Inc. The information from this project contributes to the CEC Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

# ABSTRACT

Water is a critical resource in drought-prone California. Treating industrial streams (such as wastewater and food and beverage water processing) has historically been a hurdle because traditional methods such as thermal evaporation or high-pressure systems consume massive amounts of energy, carry high operating costs, and require large footprints. Porifera's proprietary forward osmosis technology addresses this gap. Instead of relying on heat or pressure, Porifera's systems harness the power of osmosis, a natural process that gently extracts clean water across a specialized, semi-permeable membrane. To process these challenging streams at a commercial scale, Porifera packages several membrane packets together to form a series of compact membrane modules, which are then assembled into full water treatment systems. Although several pilot tests of these systems were successful, widespread commercial adoption of this technology was previously hindered by large footprints and prohibitive costs associated with small membrane modules.

This project scaled up Porifera's manufacturing capabilities by designing and building an automated low-rate initial production line for its large-format membrane modules. These larger modules provided identical processing capabilities as previous models but in a smaller footprint, while also reducing membrane module costs. The project successfully met its goals and objectives in building an automated manufacturing line capable of producing reliable membrane packets daily. By optimizing supply chains, obtaining quality-controlled injection-molds, and customizing the robotic equipment assembly line, the team achieved high manufacturing yields under strict quality control standards.

The expedited production and deployment of this technology will directly benefit California investor-owned utility ratepayers by decreasing peak electricity demands associated with water reuse, while simultaneously reducing greenhouse gas emissions across the industrial sector.

**Keywords:** forward osmosis, membrane, manufacturing, concentration, water reuse.

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# EXECUTIVE SUMMARY

## Background

California's ongoing drought challenges place immense pressure on industrial sectors to limit freshwater extraction and find sustainable ways to reuse water. However, recycling water to a high-purity standard is difficult. Traditional treatment methods such as reverse osmosis consume massive amounts of energy, are cost-prohibitive, or require large footprints that make them incompatible with many existing industrial facilities.

Porifera developed a proprietary forward osmosis (FO) membrane technology that addresses these challenges. Forward osmosis moves water across a semi-permeable membrane using a natural osmotic pressure gradient instead of relying on the extreme pressures required in reverse osmosis. This comparatively "gentle" process both reduces energy equipment usage and lowers fouling rates. It further enables treatment of more challenging feed streams, including those with higher levels of chemical oxygen demand that conventional membranes struggle to handle, such as industrial wastewater and beverage processors (for example, beer, wine, fruit juices). As a result, FO is well suited for producing high-purity water and supports near zero liquid discharge in industrial applications with lower energy consumption than existing treatment methods.

Porifera's proprietary FO membrane technology is the building block of its fluid treatment systems. Individual membrane packets are glued together with supportive components to form elements. These elements are stacked together to form modules and, depending on the requirements of the feed stream being treated, are then arranged in various configurations to form a fully assembled system.

While this technology has proven to be highly efficient in numerous commercial pilot tests, widespread adoption faced barriers: the processing footprint and cost. To make the system viable for a broad spectrum of industrial facilities, the technology needed to scale up. To improve manufacturability and commercial adoption of the system, Porifera transitioned from the PFO-100 model to its larger PFO-200 model. With the PFO-200 model, the overall equipment footprint and costs were reduced since it allowed significantly more volume to be processed per module. This meant that fewer modules and less supporting hardware were needed to achieve the same processing capacity. This project was initiated to close the manufacturing gap and establish a low-rate initial production line for large-format membrane modules.

## Project Purpose and Approach

The primary purpose of this project was to establish the manufacturing infrastructure required to produce PFO-200 membrane modules at scale, targeting industrial sectors facing pressure

to reduce freshwater consumption and reuse wastewater. To both ensure commercial viability and demonstrate success, the project established specific goals to:

- Design and build a low-rate initial production manufacturing line capable of producing 56 units per day of membrane packets.
- Achieve a low-rate initial production line failure rate between 1 percent and 5 percent of membrane packets.
- Achieve 50-percent cost savings compared with state-of-the-art technology.
- Demonstrate the ability to reduce total system footprints.

To achieve these goals, the team employed a phased approach. Phase 1 established the core semi-automated line, scaling capacity from 14 to 72 membrane packets per day. Phase 2 focused on continuous process optimization and advanced automation, including precision laser cutting and automated adhesive dispensing that ensured commercial-scale reliability.

## Key Results and Conclusions

The project successfully developed and commissioned the semi-automated manufacturing line, exceeding its production targets. During Phase 1, the line achieved a production rate of up to 72 membrane packets per day, surpassing the original 56-packet goal. Furthermore, the team maintained exceptional quality control, achieving an average failure rate of 4.6 percent across different membrane rolls, successfully meeting the 5-percent failure rate target. The project also validated commercial savings and system footprint reductions. Techno-economic analysis demonstrated that using PFO-200 elements to concentrate products prior to export cut costs by nearly 50 percent, yielding over $36.7 million in annual savings for a 10,000 kilograms per hour juice processing system. Furthermore, the system's modular design successfully maintained the same throughput while reducing the required facility footprint when compared with baseline configurations.

Scaling up from the legacy PFO-100 to the PFO-200 modules yielded dramatic performance improvements. By increasing the port size from 0.5 inches to 1.87 inches and arranging up to 360 spacer plates (or 10 elements) in parallel, the new design supported an increase in flow rate. This achieved a 75-percent reduction in feed impedance and a 95-percent reduction in draw impedance compared with the legacy model.

The project team successfully identified and resolved several complex technical barriers during the scale-up (including thermal mold warping and internal adhesive inconsistencies) by redesigning custom gaskets and implementing strict quality controls. These changes ensured that all elements passed rigorous testing prior to commercial use.

## Knowledge Transfer and Next Steps

To foster adoption, Porifera executed a targeted outreach strategy focused on the food and beverage sector. The team successfully demonstrated the technology's capabilities by generating high-concentration samples of fruit juices exceeding 65° Brix, and coffee extracts up to 60° Brix. Degrees Brix (symbol °Bx) is a measure of the dissolved solids in a liquid,

based on its specific gravity, and is commonly used to measure dissolved sugar content of a solution. For sugar, 1° Bx = 1 g of sucrose/100 g of solution. These demonstrations, paired with customized techno-economic business cases generated from project data, were shared directly with stakeholders. To reach a broader audience, the team updated its online resources and engaged industry contacts by exhibiting or presenting at 20 major conferences between 2023 and 2026, including the 2024 Membrane Technology Forum. Moving beyond the project's grant term, Porifera will leverage this operational data and manufacturing success to transition directly into full-scale commercial deployment across food and beverage markets. Porifera also developed a project case study detailing the PFO-200's performance advancements, which was shared with food processing professionals and equipment providers at the 2024 Membrane Technology Forum.

Porifera also developed a project case study detailing the PFO-200's performance advancements, which was shared with food processing professionals and equipment providers at the 2024 Membrane Technology Forum.

## Benefits to California Ratepayers

The successful scaling of this manufacturing line directly supports California's energy and climate goals through increased electricity reliability, lower costs, and increased safety. When implemented in place of competing traditional technologies, systems using the large-format modules are estimated to yield annual electricity savings of 72,000 megawatt-hours by 2030, scaling to 1,467,000 megawatt-hours by 2040. Furthermore, these systems feature peak electrical demands that are nearly 30-percent lower for water reuse applications and 70-percent lower in total power demand when compared with seawater desalination. The technology also drives substantial environmental benefits, specifically greenhouse gas emission reductions of 30 percent for industrial water reuse, 85 percent for near zero liquid discharge projects, and 70 percent relative to seawater desalination projects. The broad implementation of efficient water technologies could reduce the need for energy intensive zero liquid discharge and water reclamation via desalination. Beyond immediate energy savings, expediting the manufacturing of this technology will allow industrial facilities to capture and reuse more nutrients from waste streams while significantly reducing logistics, shipping, and storage costs.

# CHAPTER 1: Introduction

California's frequent droughts and growing water demand require aggressive water conservation and recycling within the state's agricultural and industrial sectors. However, achieving high-purity water for reuse is historically limited by the energy it requires. Conventional treatment systems (such as thermal evaporators or high-pressure desalination) consume immense amounts of power, driving up operating costs and requiring massive footprints. To solve this issue, Porifera developed its proprietary forward osmosis (FO) technology. By utilizing osmosis to draw clean water across a membrane, the system eliminates the need for either high heat or pressure. This low-energy method effectively treats complex industrial streams and wastewaters, enabling near zero liquid discharge (ZLD).

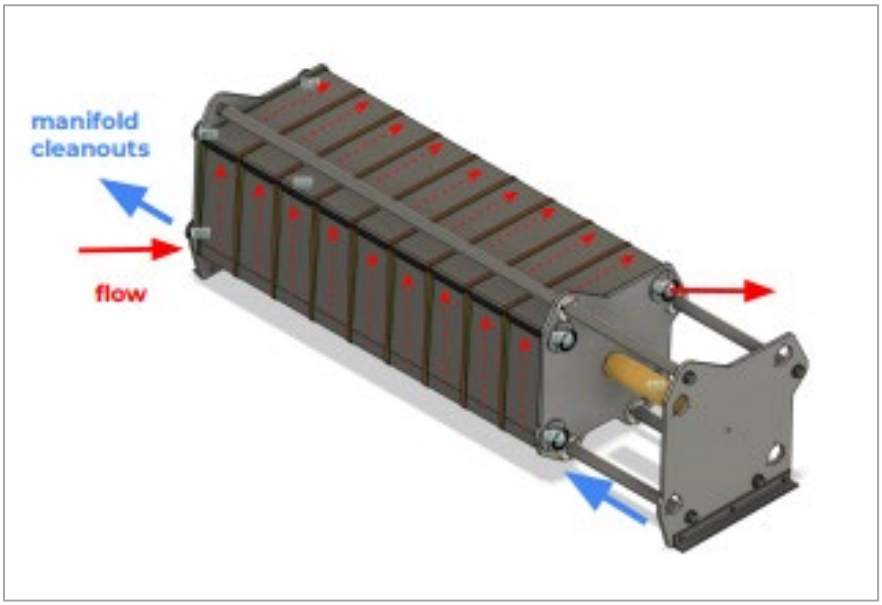
Prior to this project, Porifera successfully demonstrated its FO technology in numerous commercial pilot tests using its legacy PFO-100 membrane module. Despite its excellent performance, widespread commercial adoption was hindered by physical and economic limitations. Customers consistently indicated that the equipment footprint was too large and the capital costs too high for standard industrial implementation. Additionally, the older PFO-100 design faced flow distribution and channeling issues. Its small 0.5-inch port sizes created significant fluid impedance, which limited overall pressure and flow rates and made clean-in-place maintenance difficult. To achieve widespread market adoption, the technology needed to be scaled up to a larger format — the PFO-200 membrane module.

## Project Purpose and Goals

The primary purpose of this project was to overcome these scaling hurdles by designing and building a low-rate initial production (LRIP) manufacturing line for the new, large-format PFO-200 membrane modules. The PFO-200 operates on the same core principles as the PFO-100 but features larger ports (1.87 inches) and up to 360 plates arranged in parallel to support a greater-than-tenfold increase in flow rate (Figure 1). The project's overall goals were to:

- Design and build a semi-automated manufacturing line to mass produce these large-format packets.
- Validate a reliable supply chain for manufacturing components.
- Demonstrate the PFO-200's ability to process the same amount of water as the PFO-100, but in a footprint smaller than the earlier version.

**Figure 1: PFO-200 Module and Flow Path**




**The scaled-up PFO-200 element features larger port sizes and parallel plate arrangements, drastically reducing impedance and allowing higher flow rates.**

Source: Porifera Inc.

To gauge the project's success, the following metrics were established to:

- Achieve a production target of 56 membrane packets per day using the new automated line.
- Maintain exceptional manufacturing quality, with the LRIP line's packet failure rate strictly held to between 1 percent and 5 percent.
- Achieve a greater-than-50-percent cost savings compared with state-of-the-art competing technologies.
- Reduce the physical footprint of the fluid treatment system built from the modules while maintaining water throughput.

## Target Audience and Market

The primary audiences for this technology are the industrial and agricultural sectors seeking to reduce freshwater intake and manage difficult wastewater streams. Specific market applications include food and beverage producers (for product concentration and wastewater reuse).

## Benefits to California's Clean Energy Goals and Ratepayers

This project directly supports California's clean energy goals by decarbonizing industrial water treatment. Expediting the manufacturing of the PFO-200 will benefit California utility ratepayers by improving grid reliability and lowering costs through significant energy demand reductions. When deployed, systems using PFO-200 technology consume nearly 30 percent

less peak electricity for water reuse applications, and 70 percent less total power than seawater desalination. This is projected to result in annual electricity savings of 72,000 megawatt-hours (MWh) by 2030, and 1,467,000 MWh by 2040. Furthermore, it provides corresponding greenhouse gas emission reductions of up to 85-percent for near-ZLD projects, playing an additional vital role in California's climate change strategy.

# CHAPTER 2:
# Project Approach

## Project Objectives and Participants

To achieve the goal of scaling up from the legacy PFO-100 format to the larger PFO-200 format, the team established a structured methodology driven by the following core objectives to:

- Design and build a semi-automated pilot manufacturing line with an initial production rate of 14 membrane packets per day.
- Upgrade the semi-automated pilot manufacturing line to be more fully automated to produce 56 membrane packets per day.
- Design and build equipment for product quality control (QC) testing.
- Validate proof of manufacturing quality by producing membrane packets that pass vacuum testing (which the team later adapted into highly accurate osmotic permeability and delamination testing).
- Establish and validate a supply chain for production parts.
- Demonstrate the production of the product using the LRIP pilot line while maintaining consistent product quality.
- The project was executed by key personnel, including engineers and manufacturing technicians. To accomplish specialized manufacturing tasks, Porifera partnered with Simplexity, an engineering design firm, to design the intricate molds required for the spacer, head, and foot plates. Porifera also teamed up with Kennerley-Spratling, an injection molding company, to manufacture products from those molds and execute the high-volume production of the plates.

The project scope of work was divided into major milestones driven by a phased build-out.

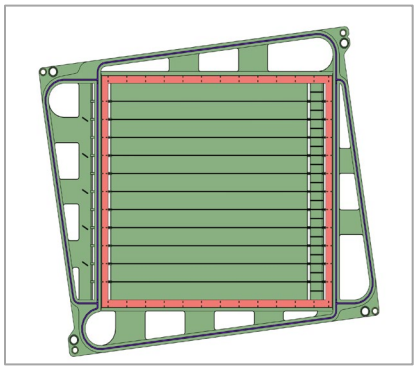
## Phase 1: Manufacturing Design, Build, and Automation

Phase 1 encompassed the design and build of a semi-automated LRIP line that successfully achieved a production rate of up to 72 membrane packets per day, surpassing the project's 56-packet target. It involved creating detailed bill of materials for frames, motors, machined plates, and electrical components, alongside comprehensive computer aided design (CAD) models to visualize the workflow. The team partnered with the vendor Simplexity to design the initial injection molds for the spacer plates and successfully assembled the core line equipment. This core equipment included the plate-to-plate machine, a specialized glue dispenser, curing racks, and a dedicated curing oven.

The technical components designed and assembled during Phase 1 included:

- **Spacer Plate Molds:** Porifera collaborated with Simplexity and Kennerley-Spratling to design and manufacture the stainless-steel injection mold for the spacer plate. Enhancements included larger ports to reduce head loss, streamlined flow geometry for cleanability, and improved glue line features. Figure 2 shows the CAD drawing and final mold.

**Figure 2: Spacer Plate CAD Drawing and Mold**

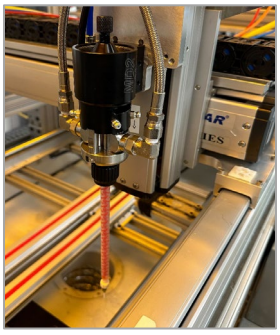


**The custom-designed spacer plate mold allowed for larger ports and streamlined flow geometry to reduce energy consumption and increase flow.**

Source: Porifera

- **Glue Dispenser and Plate-to-Plate Machine:** The team assembled customized gluing equipment to apply the 2-part adhesive system to the plates and constructed a plate-to-plate machine to seamlessly assemble the layered element structure. Figure 3 displays the plate-to-plate assembly setup. The machine is equipped with an aluminum frame and plate, along with a motor that drives all the pulley components below the surface. The machine stacks each PFO-200 component (membrane packet, spacer plate, head and foot plates) together to form an element.

**Figure 3: Plate-to-Plate Machine Components and Glue Machine**



**The semi-automated plate-to-plate machine used for assembling the PFO-200 element spacer plates together**

Source: Porifera

- **Curing Racks:** The team designed and built dedicated curing racks to securely hold, organize, and store the plates during the manufacturing process (Figure 4). The racks also allow the glue to dry (cure).

**Figure 4: Curing Racks for Plate Storage**

**Custom aluminum curing racks are designed to safely store and organize the plates to dry both before and during assembly.**

Source: Porifera

- **Curing Oven and Curing Carts:** Once glued and assembled, the modules required heat treatment within a specified temperature range to ensure optimal glue strength. To achieve this, the team designed and procured an insulated curing oven equipped with a timer, auto shut-off, and dedicated curing carts to safely transport the modules into the oven (Figure 5).

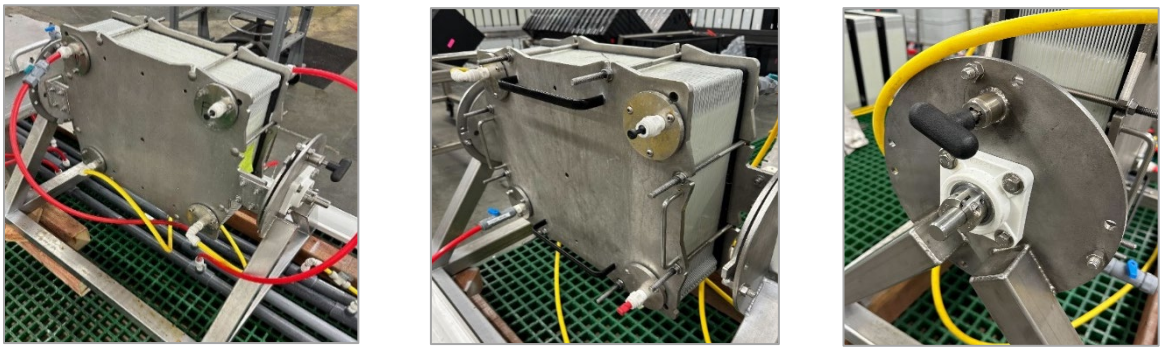
**Figure 5: Curing Oven and Curing**

**The insulated curing oven ensured consistent heat distribution for the assembled modules, utilizing rolling curing carts for safe material handling.**

Source: Porifera

- **Osmotic Permeability (OSP) Test Station:** To establish rigorous quality control, the team designed the OSP test station to actively "wet test" assembled elements and identify any leaks prior to commercial deployment (Figure 6). These tests were integral to validating their performance and efficiency. The stations were equipped with a robust stainless-steel frame that provided structural integrity and support. A strong back plate was incorporated to enhance stability and hold the ports during the test. Plumbing, fittings, hoses, adapters, and hardware components were designed to ensure seamless flow and accurate testing results.

**Figure 6: OSP Test Station**



**The OSP test station was designed to be a dedicated wet-testing unit to identify leaks in assembled elements.**

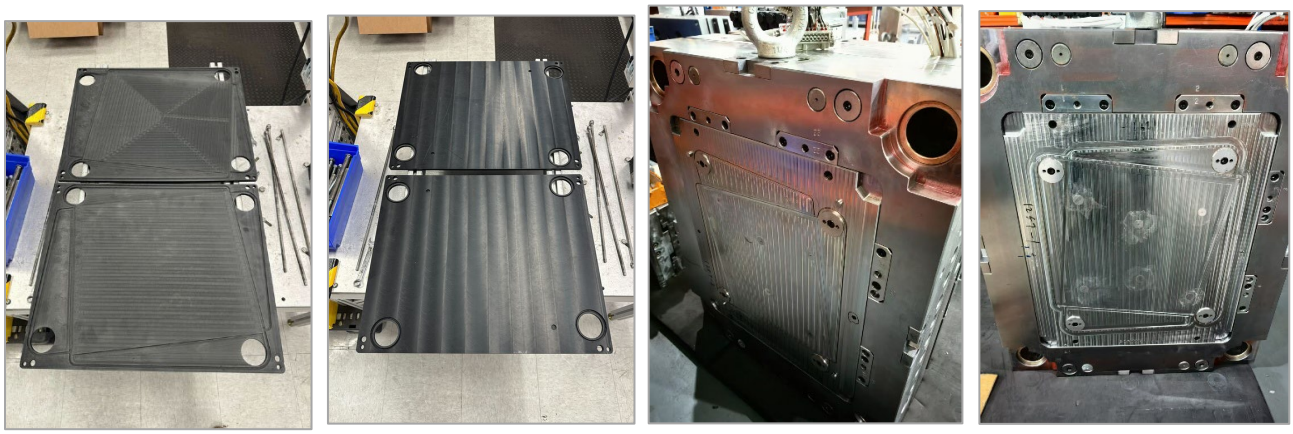
Source: Porifera

## Phase 2: Advanced Equipment Design and Optimization

With the core semi-automated line exceeding production targets, Phase 2 focused on process optimization, advanced quality assurance and quality control (QA/QC) capabilities, and resolving edge-case manufacturing challenges for the elements. The methodology in this phase shifted toward finalizing the heavy-duty molds, refining the robotic assembly, and introducing specialized secondary equipment to support durability testing and handling. The technical upgrades developed and integrated during Phase 2 included:

- **Head and Foot Plate Molds:** Instead of using machined head and foot plates from Phase 1, the team designed injection molded head and foot plates with support from Simplexity (Figure 7). The custom molds were built and sent to Kennerley-Spratling for manufacturing. The enhancements to the mold included larger ports — which minimized head loss, boosted flow rates, and reduced energy use — alongside an improved internal geometry for better cleaning of the element.

**Figure 7: Injection Molded Head and Foot Plates**



**The redesigned head and foot plates incorporated improved glue line features and parallel flow paths.**

Source: Porifera

- **Lift Cart:** To safely transport the heavy, fully constructed PFO elements to and from the curing oven, the team integrated hydraulic lift carts, which minimized manual handling, reducing the risk of product damage (Figure 8).

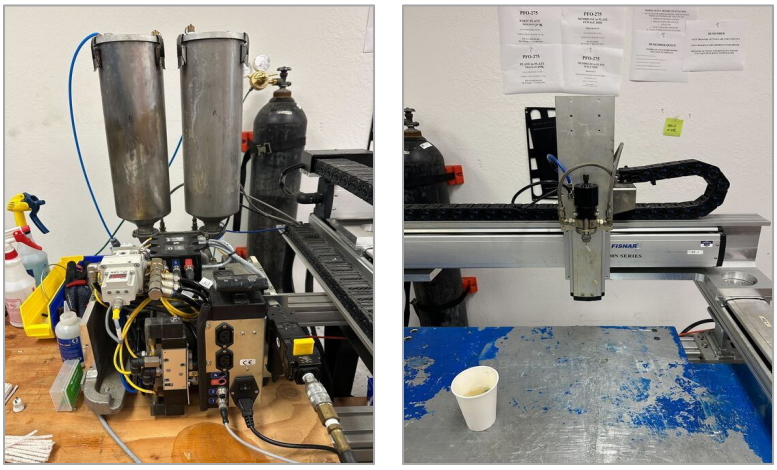
**Figure 8: Lift Cart**

**Lift carts were introduced to ensure the safe and consistent transport of heavy completed elements.**

Source: Porifera

- **Retrofitted Glue Robot:** The existing glue robot was modified to support PFO-100 as well as PFO-200 elements (Figure 9). The glue robot was used to dispense adhesive onto spacer plates and head and foot plates with controlled volume and placement. Automated dispensing improved repeatability, reduced variability associated with manual application, and supported consistent glue bonding quality across all manufactured elements.

**Figure 9: Retrofitted Glue Robot**



**The upgraded glue robotic system was designed to ensure consistent adhesive application.**

Source: Porifera

- **Chiller and Temperature Control:** A dedicated chiller was installed to precisely control the temperature of process lines and jacketed tanks during QA testing and product trials (Figure 10). This was critical for maintaining draw temperature and supporting repeatable process conditions and feed product quality.

**Figure 10: Chiller**

**The dedicated chiller unit was used for strict temperature control during QA testing.**

Source: Porifera

- **Draw Prep System:** The Draw Preparation Skid is an automated system that prepares solutions for QA/QC testing and element pickling (Figure 11). The Draw Preparation Skin ensured consistent solution composition and quality, reducing operator variability and supporting repeatable PFO-200 element performance.

**Figure 11: Draw Prep System**

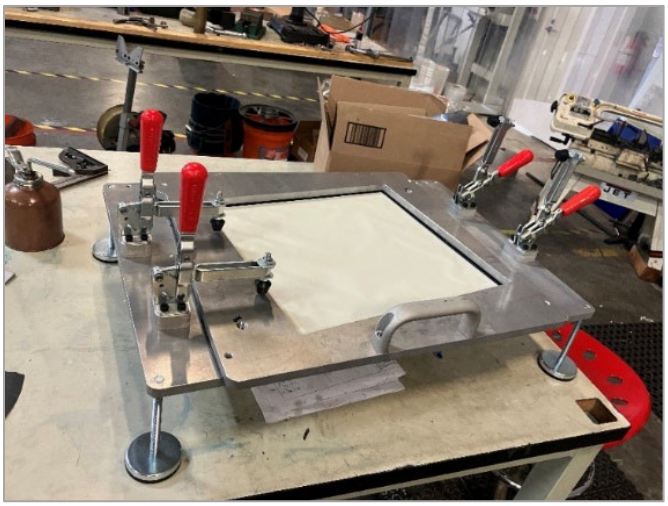
**The draw preparation system supported automated solution handling during manufacturing QA/QC.**

Source: Porifera

- **Single Plate Tester:** To evaluate glue bonding performance prior to full element assembly, the team implemented a single plate tester to test the different components

of the element (Figure 12). This enabled early-stage durability testing to strengthen quality control.

**Figure 12: Single Plate Tester**

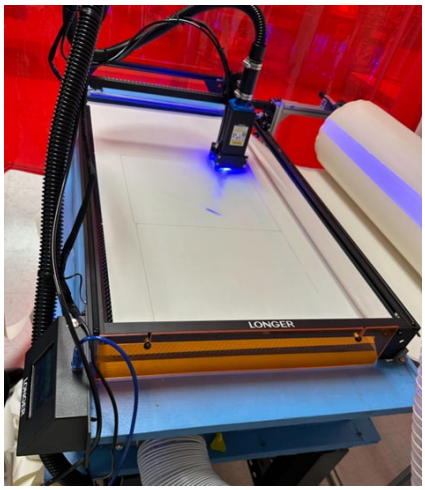


**Quality assurance equipment was developed to test single spacer plate endurance and evaluate glue bond performance before full assembly.**

Source: Porifera

- **Precision Laser Cutter:** To further optimize material handling and production efficiency during Phase 2, the team procured and integrated a precision laser cutter for the thin-film composite (TFC) membranes (Figure 13). Transitioning to an automated laser system allowed the team to cut the membrane rolls far more precisely and accurately than previous methods. This critical upgrade directly increased the usable membrane yield, significantly reduced expensive material waste, and boosted the overall speed and efficiency of the element assembly process.

**Figure 13: Precision Laser Cutter in Action**




**The precision laser cutter integrated in Phase 2 allowed highly accurate cutting of membrane rolls, significantly reducing material waste and increasing overall manufacturing efficiency.**

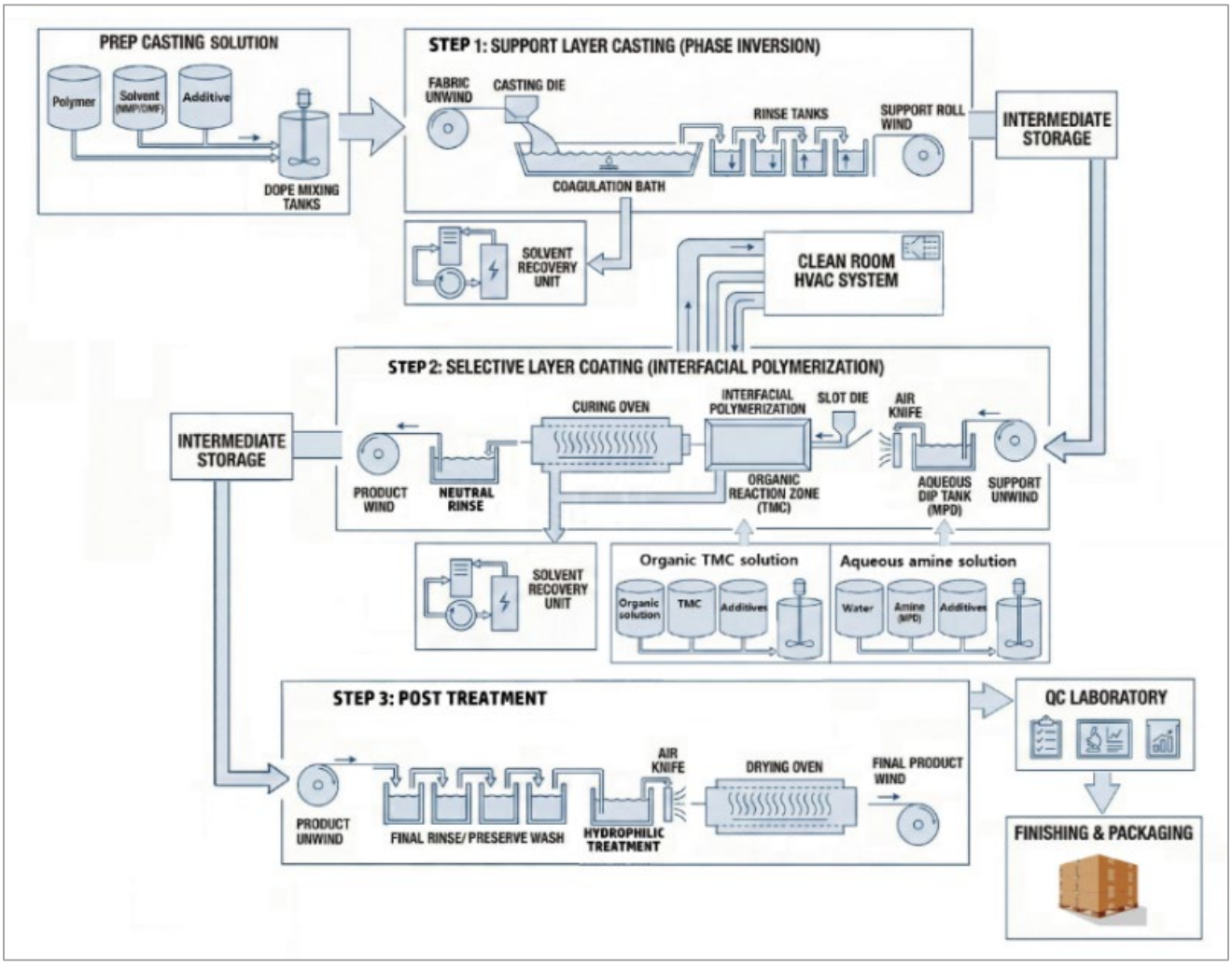
Source: Porifera

## Supply Chain Validation Methodology

Simultaneous to the physical equipment build, the team evaluated supply chain stability across three critical component categories to both ensure long-term manufacturability and maintain a component failure rate of less than 5 percent.

- **Injection-Molded Plates:** The team evaluated partners for both design and high-volume production, ultimately choosing Simplexity for the design of the stainless-steel molds and Kennerley-Spratling for the high-volume manufacturing of the spacer, head, and foot plates.
- **Manufacturing Line Equipment:** The team validated procurement pipelines for the custom manufacturing equipment, vetting suppliers for foundational components (frames, motors) as well as the advanced automation hardware required for the test stations and curing ovens.
- **Membranes:** The team evaluated two distinct methodologies for producing the TFC membranes. "Supply Chain A" used a continuous, single-step high-speed production line, which was prone to errors. "Supply Chain B" used a step-by-step modular process, which allowed for granular quality control and error isolation. Figure 14 shows the three major stages required for membrane manufacturing.

**Figure 14: Schematic Diagram of TFC Membrane Manufacturing**




**The TFC membrane manufacturing process involved three primary stages evaluated during supply chain validation: support layer casting (phase inversion), selective layer coating (interfacial polymerization), and post treatment (washing, hydrophilization, and drying).**

Source: Porifera

## Risks, Barriers, and Mitigation Strategies

During the development and scaling of the manufacturing line, the team encountered several technical and operational barriers. The structured testing approach allowed it to systematically address and resolve each issue.

- **Physical Alignment and Squareness:** Early in Phase 1, inconsistent clamping heights led to non-uniform glue lines and misalignment between head, foot, and spacer plates, causing stack-up errors. This resulted in element-to-element seal leaks. The team mitigated this risk by physically engineering hard stops and squareness guides directly into the glue fixture plates, successfully maintaining alignment throughout the curing process.

- **Thermal Heat Distribution:** The initial design of the curing oven experienced significant heat transfer to the cold facility floor, creating uneven heat distribution and threatening the glue curing process. To solve this, the team introduced an insulated blanket underneath the curing carts, establishing a stable, uniform temperature.
- **High-Temperature Component Warping:** Rigorous endurance testing revealed that operating temperatures between 113°F (45°C) and 131°F (55°C), combined with backpressure, caused the molded head and foot plates to warp. This warping caused the external ribs to slide and deform into one another by approximately 0.8 millimeters, partially opening the element feed channels and compromising seals. The team addressed this severe barrier by prioritizing mold design revisions and re-casting the molds to improve rib alignment and thermal stability.
- **Adhesive Failures:** The team observed internal glue line failures that compromised the structural integrity of the elements. Through systematic testing, the issue was traced to crystallized and expired adhesive materials, as well as uneven mixing from the dispenser. The team eliminated this barrier by establishing strict material expiration protocols, improving glue tank maintenance schedules, and retrofitting the glue dispensing robot.
- **Membrane Supply Chain Yields:** The continuous membrane manufacturing process (see Supply Chain A) proved highly sensitive; a single deviation cascaded through the line, resulting in massive material waste and downtimes. By strategically pivoting to the step-by-step modular process (see Supply Chain B), the team validated parameters at each specific stage, isolating failures and preventing full-scale losses.

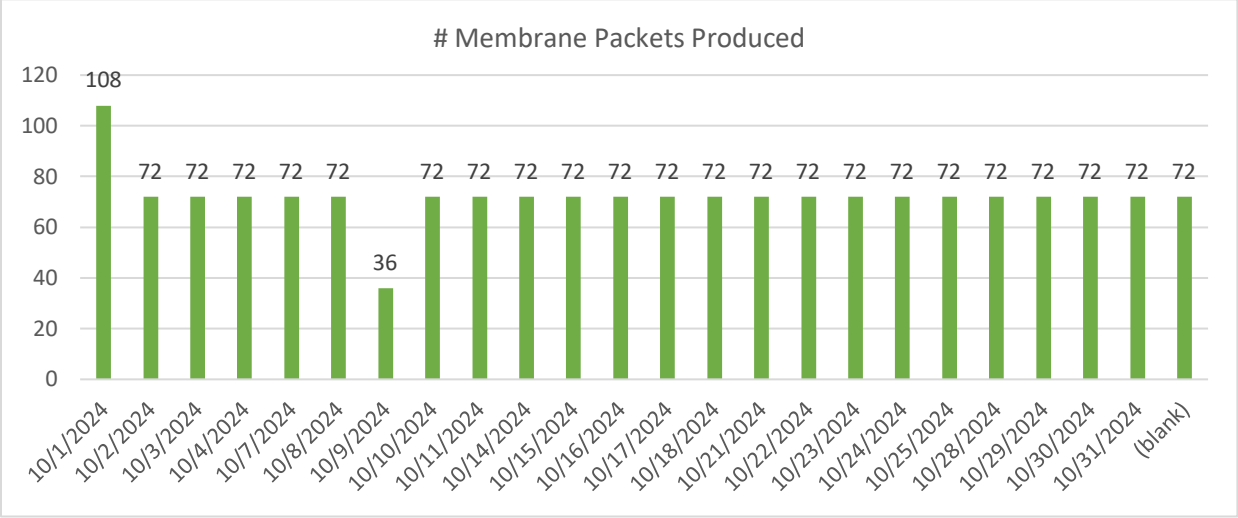
# CHAPTER 3:
# Results

## Achievement of Primary Project Goals

**Goal 1:** Design and build an LRIP manufacturing line capable of producing 56 units per day of PFO-200 membrane packets.

- **Result - Exceeded:** The semi-automated manufacturing line developed in Phase 1 was efficient. The system achieved a peak production rate of up to 72 membrane packets per day, exceeding the project's 56-packet target. See Figure 15.

**Figure 15: Membrane Packets Produced Per Run Period**




**Production tracking demonstrated that the manufacturing line exceeded the 56-packet target to reach up to 72 packets per day.**

Source: Porifera

**Goal 2**: Design the manufacturing line to produce quality membrane packets with a failure rate of between 1 percent and 5 percent.

- **Result - Achieved:** Rigorous quality control measures ensured that larger quantities did not compromise product integrity. Across a large-scale manufacturing run of 3,888 total membrane packets, the team observed only 180 failed packets, resulting in an average failure rate of 4.6 percent. Table 1 shows the failure rates recorded across different membrane production rolls. The failures in Roll 0923#6 were due to thermal warping of the molded head and foot plates. The failures in roll 1122#3 were due to defective (expired) glue. See the "Technical Barriers and Impact on Results" section for more details.

**Table 1: Membrane Packet Production and Failure Rates**

| Membrane Roll | Total Membrane Packets Produced | Failed Membrane Packets | Failure Rate |
|---|---|---|---|
| 0923#6 | 1728 | 108 | 6.3% |
| 1121#1 | 36 | 0 | 0.0% |
| 1122#1 | 1224 | 0 | 0.0% |
| 1122#2 | 72 | 0 | 0.0% |
| 1122#3 | 828 | 72 | 8.7% |
| **Total** | **3888** | **180** | **4.6%** |

Source: Porifera

**Goal 3:** Achieve more than 50-percent savings compared with state-of-the-art technologies.

- **Result - Achieved:** The team successfully demonstrated that replacing state-of-the-art thermal evaporators and traditional shipping methods with the PFO-200 system yielded massive operational and logistical savings for food and beverage processors. To quantify these savings, Porifera conducted a technoeconomic analysis in collaboration with an industrial client that exports orange juice from Brazil, one of the world's largest suppliers to the global orange juice market. Historically, exporting not-from-concentrate orange juice required shipping millions of gallons of water across the globe, which was both very expensive and carbon intensive. By utilizing the PFO-200 system to concentrate the orange juice to 66° Brix prior to export, the client avoided high operating expenses and drastically reduced shipping volumes.

  The joint analysis evaluated the cost of exporting to markets in China and the Middle East. As shown in Table 2, shipping not-from-concentrate in drums costs approximately $6.38 per kg, whereas shipping the 66° Brix concentrate in drums drops the cost to just $3.33 per kg. This represents direct savings of $3.05 per kg (a nearly 50 percent reduction in shipping costs, prior to calculating other operating expense savings). On a commercial scale, this implementation translates to a financial opportunity of over $36.7 million in savings per year for a single system with a 10,000 kilograms per hour (kg/h) juice processing capacity.

**Table 2: Analysis of Export Savings for a Single System with a 10,000 kg/h Juice Processing Capacity**

| Orange Juice | Unit | Cost or Value |
|---|---|---|
| Concentrate in Drums (at 66 °Brix) | $/kg | $3.33 |
| Not From Concentrate in Drums | $/kg | $6.38 |
| The Difference | $/kg | $3.05 |
| Total Opportunity | per year | $36,734,913 |

Source: Porifera

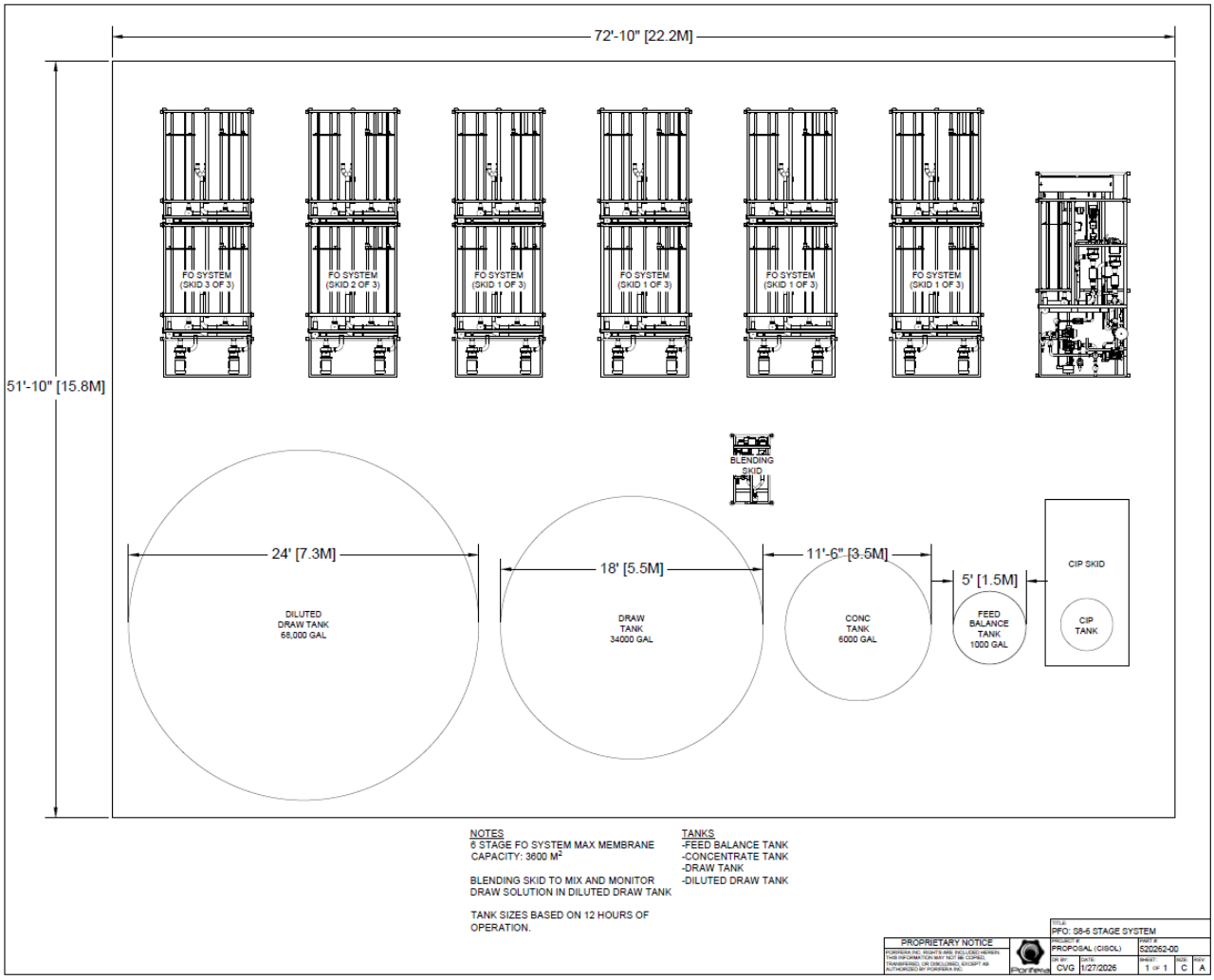
**Goal 4:** Demonstrate the PFO-200's ability to reduce total system footprint while maintaining water processing throughput.

- **Result – Achieved**: Scaling up from the legacy PFO-100 design to the PFO-200 design enabled large footprint reductions at both the element and system levels. At the element level, increasing the port sizes from 0.5 inches to 1.87 inches and engineering the modules to hold up to 360 plates arranged in parallel (instead of a series configuration) reduced feed impedance by 75 percent and draw impedance by 95 percent. These internal improvements enabled a greater flow rate per element.

  At the commercial system scale, this translates into highly dense continuous processing skid configurations. Based on system footprint modeling, achieving a commercial scale processing capacity of 10,000 kg/h (concentrating juice to 65 °Brix) using a baseline multi-skid expansion design of PFO-100s would require an estimated facility footprint of 4,000 square feet.

  By contrast, utilizing Porifera's high-capacity system architecture (see Figure 16) powered by the PFO-200 elements, the total system footprint drops to just 1,825 square feet (73 ft by 25 ft). This achieved the same 10,000 kg/h water processing throughput while reducing the total system footprint. Furthermore, the system designs are modular and expandable (from 3 to 6 stages); stages can be added or filled with additional membrane area at a later time, maximizing processing capacity without requiring new floor space.

**Figure 16: High-Capacity System Architecture Layout Powered By PFO-200**




**High-capacity PFO-200 system layout design for processing 10,000 kg/h of juice**

Source: Porifera

## Achievement of Project Objectives

Beyond the primary goals, the project team successfully executed the specific technical objectives required to validate both the manufacturing process and the resulting product.

**Objective 1 -** Develop a semi-automated pilot line, initially producing 14 membrane packets per day.

- **Result - Completed:** As described under Goal 1, the team successfully developed and assembled the foundational equipment for the semi-automated line during Phase 1, achieving up to 72 packets per day.

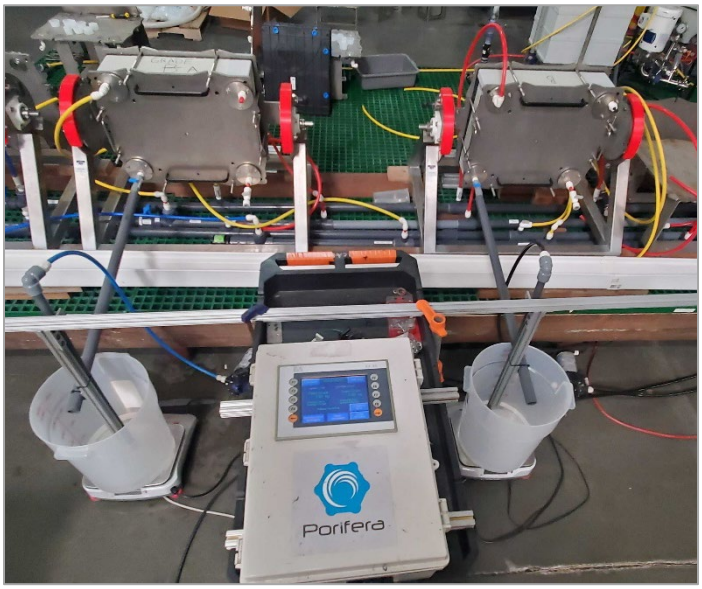
**Objective 2 -** Upgrade to a fully automated line to achieve 56 packets per day.

- **Result - Achieved:** The team successfully achieved and exceeded this objective. The upgraded line ultimately supported a production rate of up to 72 packets per day (described in Goal 1).

**Objective 3 -** Design and implement QC testing equipment.

- **Result - Completed:** To ensure rigorous quality control, the team designed and built the OSP wet testing equipment (Figure 17). This custom test station actively evaluates assembled elements to detect micro-leaks and structural defects before commercial deployment.

**Figure 17: OSP Equipment in Action**




**The custom OSP test station actively "wet tests" assembled elements prior to commercial deployment to identify leaks.**

Source: Porifera

**Objective 4:** Demonstrate consistent product quality in the LRIP**.**

- **Result - Achieved:** Consistent product quality was successfully maintained throughout the manufacturing scale-up. This was demonstrated by the 4.6 percent failure rate achieved across thousands of packets (Goal 2). Furthermore, the team demonstrated consistent quality by conducting extensive cleaning studies on elements fouled by high-pulp orange juice and coffee (Figure 18). Testing a pulsed-flow cleaning mode across 18 different flow path configurations demonstrated significant, repeatable improvements in element cleanability and flux recovery.

**Figure 18: Internal View of Autopsied Element Following a Juice Trial**

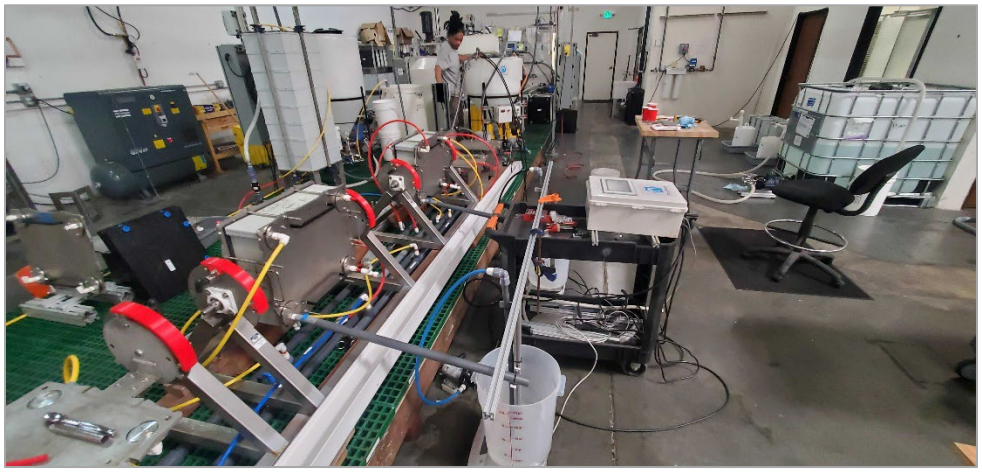
**Cross-section view of an autopsied element after an orange juice product trial showed little to no fouling caused by pulp.**

Source: Porifera

**Objective 5:** Validate manufacturing quality through vacuum testing.

- **Result - Modified and Achieved:** During the course of the project, this objective was strategically modified to replace vacuum testing with highly accurate delamination testing and OSP testing.
    - **Delamination Testing:** A new test was developed as a direct response to early glue line issues. During delamination testing, water is pushed at approximately 3 pounds per square inch (psi) through the draw side of the membrane; any leakage through to the feed side immediately indicates a seal failure (Figure 19).

**Figure 19: Delamination Test in Action**



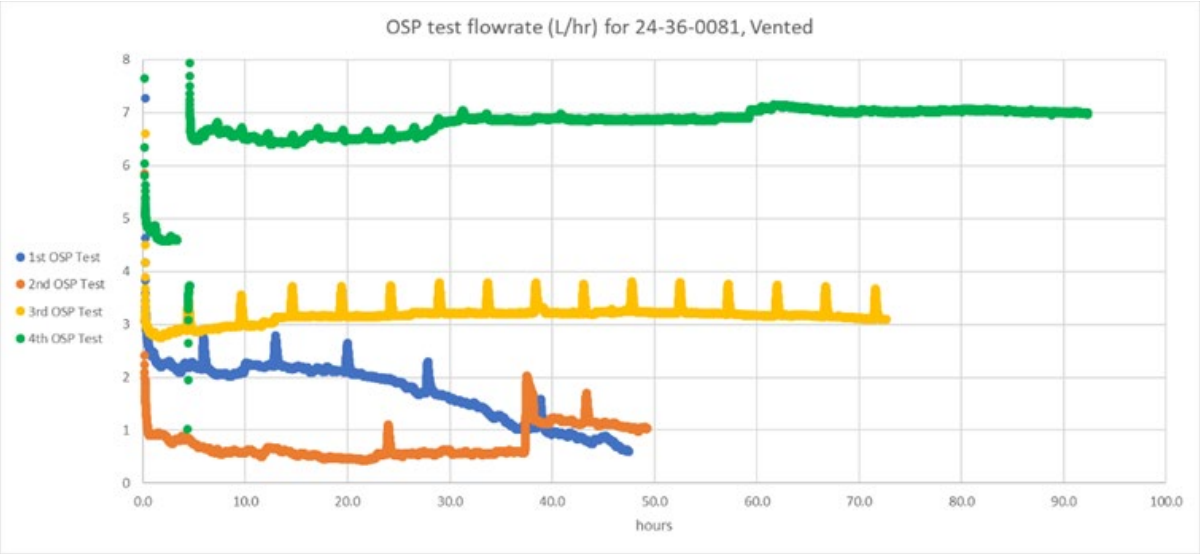
**Delamination testing was used to verify the structural integrity of the internal glue lines.**

Source: Porifera

    - **OSP Testing Standardization:** Quality control utilizing the custom OSP Test Station was employed to quantify baseline performance and check for micro-

leaks. After initially observing variability in test results over time, the team identified biological growth as a contributing factor. The installation of an ultraviolet (UV) light system to prevent bio-growth significantly increased the reliability and consistency of the OSP test results, establishing a reliable QA/QC baseline. This test continues to be in progress, and further improvements can be made to ensure consistent accuracy. See Figure 20 and Figure 21.

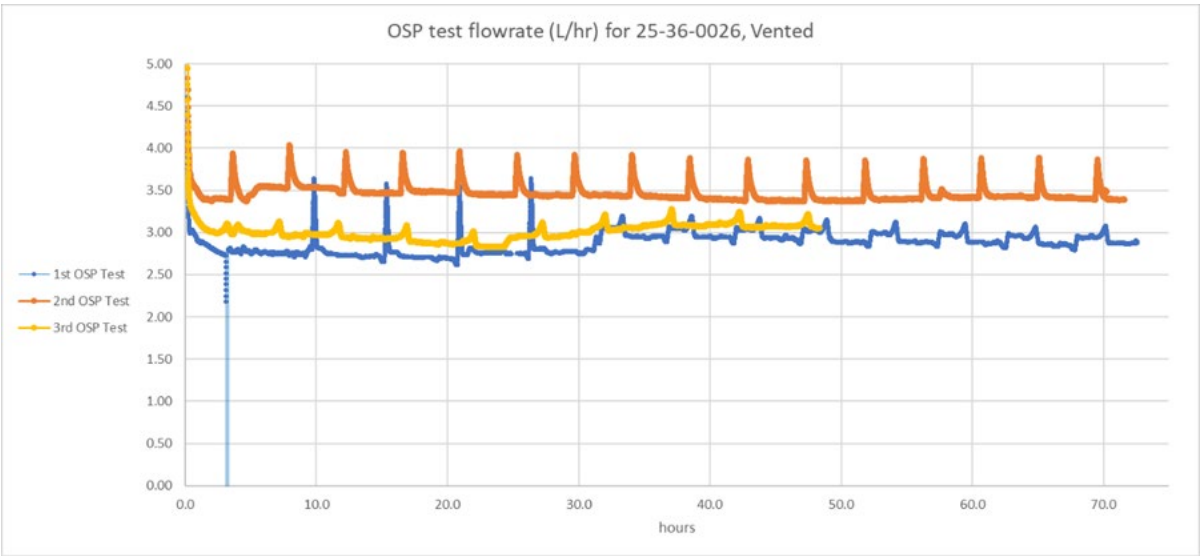
**Figure 20: Pre-UV vs. Post-UV OSP Test for Element 24-36-0081**




**Pre-UV and post-UV OSP test flowrate tracking over time for an assembled element, used to identify long-term leak rates and evaluate performance consistency.**

Source: Porifera

**Figure 21: Post-UV OSP Test for Element 25-36-0026**




**Additional post-UV OSP test flowrate evaluations were used to standardize testing parameters and ensure consistent quality assurance.**

Source: Porifera

**Objective 6:** Establish and validate a supply chain for production parts.

- **Result - Achieved:** A critical result of the supply chain validation was determining the most efficient and reliable methodology for producing the TFC membranes. The team compared a continuous, single-step high-speed process ("Supply Chain A") against a step-by-step modular process ("Supply Chain B").

  Test runs revealed that Supply Chain A was highly sensitive to single-parameter deviations, which caused cascading failures that resulted in severe material waste and production yields as low as 60 percent. Conversely, the modular Supply Chain B allowed granular parameter optimization at each stage, which contained failures to specific batches and dramatically improved production yields to between 86 percent and 93 percent. Table 3 shows this yield comparison.

**Table 3: Production Yield by Manufacturing Process Type**

| Production Type | Production Lots | Production Yield |
|---|---|---|
| Continuous process (Supply chain A) | 1719300 | 76% |
| | 1820100 | 77% |
| | 2012500 | 60% |
| Step-by-step process (Supply chain B) | 2204000 | 88% |
| | 2305000 | 86% |
| | 2415000 | 93% |

Source: Porifera

## Technical Barriers and Impact on Results

During the scale-up and testing phases, the team encountered specific technical barriers that threatened product viability. By systematically addressing these challenges, the team fundamentally improved the final manufacturing results.

**Component Warping and Rib Deformation:** During high-temperature endurance testing, the molded head and foot plates experienced thermal warping. This warping caused the external ribs to slide and deform into one another by ~0.8 millimeters, partially opening the element feed channels and causing leaks at the gasket seals.

- Resolution and Impact: The team halted production to remake the injection molds to improve rib alignment and thermal stability and deployed custom gaskets to eliminate seal thickness variability. This corrective action directly enabled the team to hit the failure rate target since subsequent elements maintained external integrity under stress.

**Internal Glue Line Failures:** Early endurance testing revealed internal glue line failures that compromised the structural integrity of the elements. Autopsies revealed this was caused by localized tackiness, uneven mixing, and the use of expired adhesive material (specifically the Part B hardener). See Figure 22.

**Figure 22: Failed Element Autopsy Revealing Uncured Glue Lines**

**An element autopsy revealing uncured and tacky glue lines. This technical barrier was traced to uneven mixing and the use of expired adhesive material.**

Source: Porifera

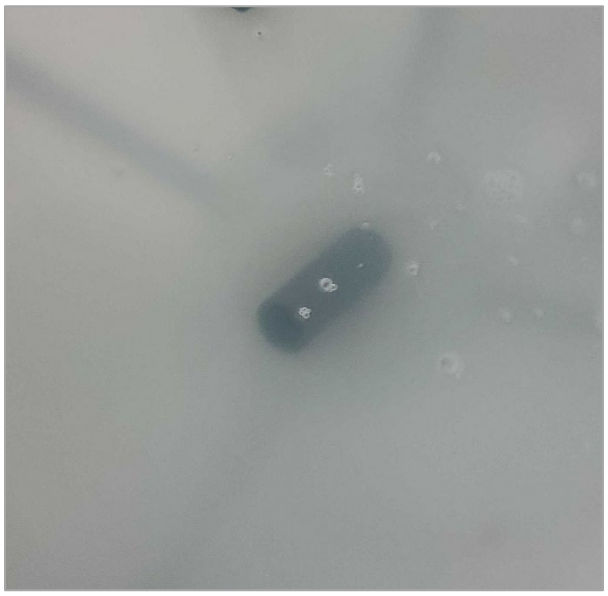
- **Resolution and Impact:** The team established strict material expiration protocols, implemented routine tank cleaning schedules to prevent crystallization, and retrofitted the glue dispensing robot to ensure proper mixing ratios. Resolving this barrier was critical; it allowed the elements to successfully pass the newly implemented delamination test and ensured consistent product quality.

**Membrane Manufacturing Sensitivity:** Initial attempts to manufacture the membranes using a continuous, single-step high-speed line (Supply Chain A) proved highly sensitive. A single deviation in parameters cascaded through the 500-foot line, making stabilization nearly impossible and resulting in material waste.

- **Resolution and Impact:** This barrier forced a shift in the manufacturing approach. The team pivoted to a step-by-step modular process (Supply Chain B), which allowed optimization at each independent stage. This pivot directly affected the results, elevating production yields from 60 percent to 93 percent.

**QA/QC Testing Variability:** While conducting tests on the OSP test station, the team observed unexplained variability in test results for elements evaluated over time. Furthermore, a "cloud-like" consistency was observed in the tank after allowing the system to run over the weekend. See Figure 23.

**Figure 23: "Cloud-Like" Consistency Observed in the Test Station Tank Over Time**



**Investigations revealed the source of this "cloud- like" appearance to be bio growth.**

Source: Porifera

- **Resolution and Impact:** An investigation revealed that biological growth within the test system was causing the result drift. The team installed a UV light system to eliminate bio-growth, which instantly stabilized the data and resulted in reliable QA/QC baseline testing.

# CHAPTER 4:
# Knowledge Transfer

In addition to successfully scaling up the manufacturing of the PFO-200 modules, the goal of this project was also to actively share these results with stakeholders. The project team engaged in extensive knowledge transfer activities to demonstrate the operational and economic benefits of the technology, specifically targeting food and beverage processing industries.

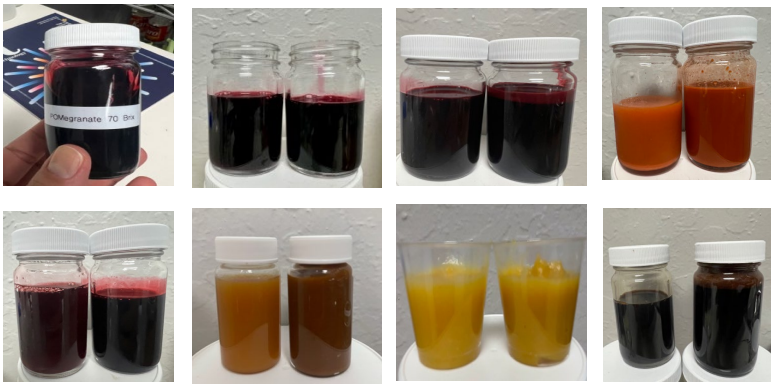
## Target Audience and Intended Use

This project aimed to showcase advanced FO membrane technology through real-world samples and techno-economic data. The primary target users are potential customers within the food and beverage processing sectors. For the food processing industry to adopt a new technology, processors required absolute confidence in both the technical efficacy and the commercial market potential of the system. Porifera's target customers span a variety of food processing industries including fruit and vegetable juice processors (for example, aronia berry [a genus of chokeberries], beet, carrot, cherry, peach, pomegranate, pineapple), coffee brewers, broth manufacturers, and dairy producers.

## Technology Transfer Activities

**Sample Generation and Demonstrations:** To physically demonstrate technical success, Porifera conducted in-house trials using the newly manufactured membrane elements to produce sample concentrates. These trials confirmed that product concentrations exceeding 65° Brix can be achieved. These physical samples were shared with prospective customers at trade shows and mailed directly to relevant industry contacts. Figure 24 shows the concentrates produced during these trials.

**Figure 24: Juice and Coffee Concentrates Produced via PFO-200 Elements**



**Produced samples of fruit and vegetable concentrates. Top row (left to right): pomegranate, aronia berry, beet, and carrot concentrates. Bottom row (left to right: cherry, peach, pineapple and coffee concentrates (60° Brix).**

Source: Porifera

**Techno-Economic Data Sharing:** To demonstrate market potential, the project team used operational data from the trials to generate detailed capital and operating cost estimates. These data were used to create customized business cases for specific food and beverage clients, providing them with the confidence necessary to adopt these energy-efficient systems.

**Marketing Collateral and Website Development:** The results of the manufacturing scale-up were integrated into Porifera's general marketing products. Banners and brochures were developed and distributed at major industry conferences. The company's website was also updated to reflect the capabilities of the current systems and their specific applicability to food and beverage industries. Website Link: www.porifera.com.

**Industry Outreach, Conferences, and Presentations:** To maximize public outreach, the Porifera team actively exhibited, attended, and presented at numerous high-profile industry conferences across the United States and internationally (Table 4).

**Table 4: Conference Attendance and Presentations**

| Event | Date | Location | Porifera Participation | Presentation Title |
|---|---|---|---|---|
| Specialty Coffee Expo 23 | April 22-23, 2023 | Portland, OR | Presented | Reinventing Membrane Processing: How to Make New Coffee Concentrate Products While Saving Energy and Water |
| Membrane Technology Forum | June 13-16, 2023 | Minneapolis, MN | Presented | Forward Osmosis Technology: Beer Concentration |
| IFT Nonthermal Processing Workshop & Short Course 23 | October 15-17, 2023 | Minneapolis, MN | Presented | Achieving High Concentrations Without Heat or Pressure with Porifera's Forward Osmosis Technology |
| Membrane Technology Forum | June 10-12, 2024 | St. Paul, MN | Presented | Porifera's New PFO200 Module and its Advantages for F&B Processing |
| Climate Week SF 25 | April 11, 2025 | San Francisco, CA | Presented | Designing Sustainable Live Events (panel discussion) |
| Juice Summit 25 | October 1-2, 2025 | Bruges, Belgium | Presented | Achieving High Juice Concentrations Without Heat or Pressure with Porifera's Forward Osmosis Technology |

| Event | Date | Location | Porifera Participation | Presentation Title |
|---|---|---|---|---|
| Unified Wine Symposium | January 24-26, 2023 | Sacramento, CA | Attended | N/A |
| Beverage Forum | May 2-3, 2023 | Chicago, IL | Attended | N/A |
| Specialty Coffee Expo 24 | April 12-14, 2024 | Chicago, IL | Attended | N/A |
| BevNet Live | June 11-12, 2025 | New York City, NY | Attended | N/A |
| Unified Wine Symposium | January 27–29, 2026 | Sacramento, CA | Attended | N/A |
| Future Food Tech | March 13-14, 2025 | San Francisco, CA | Attended | N/A |
| Low and No-Alcohol Wines Symposium | April 16, 2025 | Davis, CA | Attended | N/A |
| IFT FIRST 23 | July 16-19, 2023 | Chicago, IL | Exhibited | N/A |
| Craft Brewers Conference 24 | April 21-24, 2024 | Las Vegas, NV | Exhibited | N/A |
| IFT FIRST 24 | July 15-17, 2024 | Chicago, IL | Exhibited | N/A |
| Specialty Coffee Expo 25 | April 25-27, 2025 | Houston, TX | Exhibited | N/A |
| Drinktek 25 | September 15-19, 2025 | Munich, Germany | Exhibited | N/A |
| All Aboard 25 | September 28-30, 2025 | Half Moon Bay, CA | Exhibited | N/A |
| Food Processing Expo | February 4–5, 2026 | Sacramento, CA | Exhibited | N/A |

Source: Porifera, Inc.

**Industry Contacts and Policy Development**: Through the events listed here, the team made numerous direct industry contacts with food and beverage processors, evaluating customized FO implementation strategies. At this time, the project results are not intended to be cited in government policy publications or used to inform regulatory bodies. Public requests for project results or website downloads are not currently quantified.

**Case Study**: To further establish technical findings, Porifera developed a project case study evaluating the performance of the next-generation PFO-200 module compared with the legacy PFO-100. The study demonstrated that the PFO-200's improved parallel flow design achieved a 75-percent reduction in feed-side flow impedance and a 95-percent reduction in draw-side impedance. These fluid dynamic improvements allowed the system to operate with significantly less pump energy. Porifera presented these results to industry professionals and equipment providers at the Membrane Technology Forum in June 2024.

## Patents

Porifera filed a provisional patent application entitled "Pressurized Forward Osmosis Membrane Plates, Modules, and Systems Having Obliquely Angled Membrane Areas" with the United States patent office on December 5, 2023, and a subsequent patent cooperation treaty application with the International Bureau of World Intellectual Property Office on December 5, 2024. Porifera will pursue additional patents from these applications in key markets around the world.

## Energize Innovation

Information regarding this project, including its goals, approach, and outcomes, can be found on the CEC's Energize Innovation platform (https://www.energizeinnovation.fund/projects/manufacturing-large-format-osmotic-membrane-module).

# CHAPTER 5: Conclusion

The successful design, build-out, and optimization of the LRIP line marks a significant breakthrough for Porifera's new technology. By transitioning from the legacy PFO-100 to the large-format PFO-200, the project team overcame critical physical and economic limitations that previously hindered widespread commercial adoption of the technology.

The project advanced:

- **Production Targets:** The core semi-automated line engineered in Phase 1 performed exceptionally well, achieving up to 72 membrane packets per day and safely surpassing the project's 56-packet scope-of-work target.
- **Exceptional Quality Control:** By addressing multiple challenges, the team achieved an average failure rate of 4.6 percent across thousands of produced packets.
- **Supply Chain Resilience:** Strategically shifting to a step-by-step modular membrane manufacturing process isolated errors and drove production yields up to 93 percent.
- **Performance Improvements:** The PFO-200's redesigned 1.87-inch ports and parallel plate arrangements reduced feed impedance by 75 percent and draw impedance by 95 percent, enabling increases in flow rates.
- **Footprint and Cost Reduction:** By utilizing the PFO-200 elements in a modular system design, the parallel configuration enabled a reduced facility footprint compared with baseline configurations. Client analyses further validated that the system reduced shipping costs by nearly 50 percent, yielding over $36.7 million in annual savings at a commercial scale for processing 10,000 kg/h of juice.

## Next Steps

Building on the achievements of the manufacturing line, the project team recommends key next steps to sustain progress and fully transition the technology into broader commercial markets. First, the team will focus on continuous process optimization by refining the manufacturing and assembly processes, directly leveraging the insights and process controls developed during Phase 2. At the same time, the team will maintain and strengthen its collaboration with specialized vendors. Ensuring the long-term reliability of the supply chain for complex components (particularly the manufacturing of injection-molded spacer, head, and foot plates) remains vital for continuous mass production. The primary focus moving forward is the full-scale commercial implementation of PFO-200 systems to actively deliver these operational benefits and ratepayer cost savings to industrial clients.

## Benefits to California Ratepayers

The scaling and commercialization of the PFO-200 manufacturing line directly supports California's statutory energy and climate goals by providing a low-cost, small-footprint, and exceptionally reliable water reuse and treatment solution. It makes water reuse and near-ZLD

possible for industrial and agricultural projects where it was previously considered infeasible due to the massive energy demands of conventional thermal evaporation or high-pressure desalination.

Deploying these systems will provide significant benefits to ratepayers through improved grid reliability and reduced electricity costs. When implemented at scale, systems utilizing the PFO-200 modules are projected to yield annual electricity savings of 72,000 MWh by 2030, increasing to 1,467,000 MWh by 2040. Furthermore, they offer a 70-percent reduction in total power demand when compared with seawater desalination, and greenhouse gas emission reductions ranging from 30 percent (for industrial water reuse) up to 85 percent (for near-ZLD projects). Finally, it enables industries to capture and reuse more nutrients from waste streams while decreasing emissions, driving notable cost savings and environmental resilience throughout California.

# List of Terms/Glossary

| Term | Definition |
|---|---|
| BOM | bill of materials. A comprehensive list of parts, items, assemblies, and other materials required to build or manufacture a product |
| Brix (°Brix) | degrees Brix. A unit of measurement that represents the sugar content or concentration of dissolved solids in an aqueous solution (for example, fruit juice) |
| CAD | computer-aided design. The use of computers to aid in the creation, modification, analysis, or optimization of a design or mold |
| CEC | California Energy Commission |
| CIP | clean-in-place. A method of cleaning the interior surfaces of pipes, vessels, filters, and associated fittings without requiring the system to be disassembled |
| Delamination testing | A testing methodology used to verify the structural integrity of internal glue lines by applying pressurized water to detect seal failures |
| EPIC | Electric Program Investment Charge. A program funded by California utility customers that supports research to advance new energy solutions |
| FO | forward osmosis. A low-energy separation process that uses natural osmotic pressure to draw clean water across a semi-permeable membrane without the need for high heat or extreme pressure |
| kg/h | kilograms per hour. A standard metric unit of mass flow rate used to measure water processing capacity |
| LRIP | Low-rate initial production. The initial phase of producing a new product at a scaled-up, controlled commercial level to validate manufacturing lines |
| MWh | megawatt-hour. A unit of electrical energy representing 1-million watts of power sustained for one hour |
| OSP | Osmotic permeability. A wet-testing method developed by Porifera to quantify baseline flow performance and evaluate assembled elements for microscopic leaks |
| psi | Pounds per square inch. A standard unit of pressure |
| QA/QC | quality assurance/quality control. Manufacturing processes implemented to determine if a product meets strict structural and operational requirements |
| TFC | thin-film composite. A type of modular membrane used in osmosis systems, typically featuring a porous support layer and a highly selective active layer |
| UV | ultraviolet. A form of light radiation used within the testing systems to eliminate biological growth and ensure standardized performance results |

| Term | Definition |
| --- | --- |
| ZLD | zero liquid discharge. An advanced water treatment framework where nearly all water is recovered and reused, leaving virtually no liquid wastewater effluent |

# Project Deliverables

The following is a list of the key products and technical deliverables completed over the course of this project Agreement.

Task 2: Design and Build Manufacturing Equipment

- Phase 1: Manufacturing Report
- Phase 2: Manufacturing Report
- Critical Project Review (CPR) Report #1

Task 3: Product Manufacturing

- Supply Chain Validation Report

Task 4: Evaluation of Project Benefits

- Initial Project Benefits Questionnaire
- Annual surveys
- Final Project Benefits Questionnaire
- Documentation of project profile on EnergizeInnovation.fund
- Documentation of organization profile on EnergizeInnovation.fund

Task 5: Knowledge Transfer Activities

- Project Case Study Plan
- Summary of TAC comments
- Project Case Study
- High-quality digital photographs

Project deliverables, including interim project reports, are available upon request by emailing pubs@energy.ca.gov